



HAL
open science

Metatechnology frontier and convexity: A restatement

Kristiaan Kerstens, Christopher O'donnell, Ignace van de Woestyne

► To cite this version:

Kristiaan Kerstens, Christopher O'donnell, Ignace van de Woestyne. Metatechnology frontier and convexity: A restatement. *European Journal of Operational Research*, 2019, 275 (2), pp.780-792. 10.1016/j.ejor.2018.11.064 . hal-02108502

HAL Id: hal-02108502

<https://hal.science/hal-02108502v1>

Submitted on 21 Oct 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

Metatechnology Frontier and Convexity: A Restatement*

Kristiaan Kerstens[†] Christopher O'Donnell[‡]

Ignace Van de Woestyne[§]

23rd February 2018

19th October 2018

Abstract

This article reconsiders the way metafrontiers and associated measures of efficiency are obtained from nonparametric estimates of underlying group-specific frontiers. **Both convex and non-convex metaset have been applied, but** the large majority of articles applying this popular methodology assume that the metafrontier envelops a convex metaset. We argue that associated estimates of efficiency are potentially unreliable. We develop a refined methodology for nonparametric envelopment of non-convex metaset. We apply our methodology to a secondary data set to illustrate the potential errors associated with the currently established methods. **Anticipating our main conclusion, we find that the convexification strategy consisting in assuming a convex metaset generally leads to erroneous results.**

Keywords: Data Envelopment Analysis, Free Disposal Hull, Metafrontier.

PRELIMINARY VERSION. DO NOT CITE WITHOUT PRIOR CONSENT.

*We are grateful to Sverre Kittelsen and Mikuláš Luptáčík as well as three referees of this journal for most useful comments. The usual disclaimer applies

[†]CNRS-LEM (UMR 9221), IESEG School of Management, 3 rue de la Digue, F-59000 Lille, France. k.kerstens@ieseg.fr, Corresponding author.

[‡]Centre for Efficiency and Productivity Analysis, School of Economics, University of Queensland, St Lucia, QLD 4072 Brisbane, Australia. c.odonnell11@uq.edu.au.

[§]KU Leuven, Research unit MEES, Warmoesberg 26, B-1000 Brussel, Belgium. ignace.vandewoestyne@kuleuven.be.

1 Introduction

Organisations in different industries, regions and countries can face different production possibilities at different points in time. Differences in so-called production possibilities sets may be due to differences in available technologies (i.e., differences in the methods that are available to transform inputs into outputs) and/or to differences in production environments (e.g., geography, climate, economic infrastructure). This article is concerned with one particular method for accounting for this type of heterogeneity when estimating production relationships.

The problem of accounting for heterogeneity when estimating production relationships is quite old. One solution that was initiated by Hayami and Ruttan (1970a) involves estimating some type of meta-production function. This meta-production function concept has been empirically applied in several agricultural studies comparing mainly country-level data (e.g., Binswanger, Yang, Bowers, and Mundlak (1987) and Lau and Yotopoulos (1989), among others). An empirical survey of this literature is provided by Trueblood (1989).

Hayami and Ruttan (1970a, p. 898) “call the envelope of all known and potentially discoverable activities a secular or “meta-production function”.” This secular production function, which is distinct from a long run production function, gives the maximum output possible using given inputs and a given amount of (existing and potentially discoverable) technical knowledge. It is implicitly assumed that all firm managers have access to the same set of input-output combinations, but each may choose a different input-output combination from that set depending on specific circumstances (i.e., government regulations, relative input prices, etc.). Cost-minimising adjustments in input mixes in response to changes in relative input prices, for example, can be viewed as movements along a secular isoquant. Trueblood (1989, Figure 1) and Hayami and Ruttan (1970b, Figure 5) draw figures depicting a secular isoquant enveloping a series of less elastic isoquants. At least part of this literature allows for inefficiency (e.g., Lau and Yotopoulos (1989)).

More recently, these basic ideas have been refined and transposed into a stochastic production frontier framework by Battese and Rao (2002) and Battese, Rao, and O’Donnell (2004). The seminal article refining the loose ends in the methodology and finalising the formal framework for making efficiency comparisons across groups of firms using both stochastic frontier analysis and nonparametric deterministic frontier analysis is O’Donnell, Rao, and Battese (2008). These authors consider a meta-production possibility set (or metaset for short) that is defined as the union of two or more underlying group-specific sets. They refer

to the boundary of the metaset as a metafrontier, and they refer to the boundaries of the group-specific sets as group-specific frontiers (or simply group frontiers).

Thereafter, this so-called metafrontier approach has been widely applied across sectors and disciplines. Nonparametric metafrontier models have been estimated for sectors varying from agriculture (e.g., Chen and Song (2008) and Latruffe, Fogarasi, and Desjeux (2012)) to banking (e.g., Casu, Ferrari, and Zhao (2013) and Kontolaimou and Tsekouras (2010)), fisheries (Lee and Midani (2015)), hotels (Assaf, Barros, and Josiassen (2012) and Huang, Ting, Lin, and Lin (2013), among others), schools (e.g., Thieme, Prior, and Tortosa-Ausina (2013)), water utilities (e.g., De Witte and Marques (2009)) and wastewater treatment plants (e.g., Sala-Garrido, Molinos-Senante, and Hernández-Sancho (2011)). Empirical metafrontier studies based on stochastic frontier analysis have been presented by Bos and Schmiedel (2007), Lee and Hwang (2011) and Moreira and Bravo-Ureta (2010), among others.

Meanwhile, this basic metafrontier framework has been extended in several directions: one example is the transposition to a cost (rather than production) frontier framework (e.g., Huang and Fu (2013)); another example is the estimation of the popular Malmquist productivity indices relative to metafrontiers (see, e.g., Casu, Ferrari, and Zhao (2013) or Oh and Lee (2010) for a primal index and Huang, Juo, and Fu (2015) for a dual approach); a final example is the introduction of more elaborate metafrontier efficiency decompositions (see Kounetas, Mourtos, and Tsekouras (2009) and Tsekouras, Chatzistamoulou, and Kounetas (2017)).¹

Note that some work in the literature does not refer explicitly to the metafrontier framework, but implicitly borrows the basic idea of an overall frontier defined as the envelope of different system or group-specific frontiers. Examples include Cooper, Seiford, and Tone (2007, Section 7.5) who talk about combining different “systems” and Kittelsen, Winsnes, Anthun, Goude, Hope, Häkkinen, Kalseth, Kilsmark, Medin, Rehnberg, and Rättö (2015) who pragmatically define a common frontier over several Nordic countries when comparing hospital productivity.

Reliable estimates of the metafrontier allow researchers to compute reliable estimates of performance measures (e.g., technical efficiency, productivity change). In practice, it is common to use assumptions about production possibilities sets to frame the estimation of the metafrontier. Basic nonparametric frontier models are most often underpinned by the assumption that all production possibilities sets are convex (C). Convexity of a production

¹Sometimes this Malmquist productivity index, which is most frequently estimated within a frontier-based framework, has been combined with the more traditional meta-production function approach: see, e.g., Fulginiti and Perrin (1998).

possibilities set means that if two input vectors x_1 and x_2 can produce two output vectors y_1 and y_2 respectively, then any positive linear combination $\alpha x_1 + (1 - \alpha)x_2$ with $\alpha \in [0, 1]$ of these input vectors can produce the output vector $\alpha y_1 + (1 - \alpha)y_2$. The convexity assumption is usually justified using a time divisibility argument (see Shephard (1970, p. 15) and Hackman (2008, p. 39)): the argument is that if production processes are time divisible, then a manager could use x_1 to produce y_1 a proportion α of the time, and then use x_2 to produce y_2 the rest of the time. There are two weaknesses in this argument. First, the argument is untenable in the case of production processes with positive setup times (e.g., in some manufacturing processes). Second, even if group specific sets are convex, **then** the metaset defined by their union need **normally** not be C (see O’Donnell, Rao, and Battese (2008)).²

Despite this mathematical fact that even convex group specific sets do not lead to a C metaset (defined as their union), O’Donnell, Rao, and Battese (2008) suggest estimating the metafrontier as the nonparametric boundary of a C metaset. Exactly the same **convexification strategy** is usually made when estimating parametric metafrontiers (e.g., Battese and Rao (2002), Battese, Rao, and O’Donnell (2004) and O’Donnell, Rao, and Battese (2008)). Since this **convexification strategy** is **normally** not true, then estimates of the metafrontier will be biased. The basic question addressed in this article is to which extent this **convexification strategy** yields estimates that are close to the true non-convex metaset defined as the union of group specific sets. If this approximation is close, then there is not much of a problem. However, if this approximation is poor, then potentially all articles that have so far adopted a convexification strategy when applying the metafrontier approach are **potentially wrong**.³ Therefore, associated measures of firm performance (e.g., technical efficiency, productivity change) will be unreliable. This could potentially undermine the credibility of policies (e.g., price cap (or RPI-X) regulation) where these performance measures are used.

To the best of our knowledge, these issues have not been fully investigated in the literature. De Witte and Marques (2009) and Thieme, Prior, and Tortosa-Ausina (2013), for example, consider nonparametric estimation of non-convex (NC) group specific-sets and metasets; they do not investigate the possibility that these sets may be convex. O’Donnell,

²Hung, Le Van, and Michel (2009) explore the complexities of optimal growth when the union of just two separate C production possibilities sets exhibits a basic non-convexity.

³A Google Scholar search on 11 October 2018 obtained 4420 results for the expression “metafrontier”. Furthermore, the key article of O’Donnell, Rao, and Battese (2008) has 736 cites on that same date. Obviously, not all of these articles involved have adopted a convexification strategy and are potentially wrong. Instead of listing culprits, we simply mention a few articles that do not adopt such a convexification strategy: examples include Breustedt, Francksen, and Latacz-Lohmann (2007), Huang, Ting, Lin, and Lin (2013), Sala-Garrido, Molinos-Senante, and Hernández-Sancho (2011), Tiedemann, Francksen, and Latacz-Lohmann (2011), Verschelde, Dumont, Rayp, and Merlevede (2016), among others.

Fallah-Fini, and Triantis (2017) consider nonparametric estimation of C group-specific sets and nonconvex metaset; they do not investigate the possibility that group-specific sets may be non-convex. Tiedemann, Francksen, and Latacz-Lohmann (2011) consider nonparametric estimation of C group-specific sets and NC metaset; they do not investigate the possibility that metaset may be C (see also Sala-Garrido, Molinos-Senante, and Hernández-Sancho (2011)). None of these authors conduct statistical tests concerning the effect of the [convexification strategy](#) on estimated efficiency scores.

Therefore, the main objectives of this article are three-fold. First, we recall some existing results and state some new results for general sets showing the potential bias of the “convexification” strategy that is used in the mainstream literature. To sharpen the focus, we consider cases where the metaset is the union of both C and NC group-specific sets. Second, to demonstrate the potential biases of the convexification strategy, we focus on the nonparametric frontier approach, since there the proper methodology to create the metafrontier from group-specific frontiers is easiest to establish (e.g., transposing and extending results from Afsharian and Ahn (2015), among others). [We thereby limit the discussion to the basic C and NC nonparametric frontier specifications of technologies. The transposition of our results to alternative nonparametric and other estimators is mentioned in the concluding section.](#) Third, using this nonparametric frontier approach, the similarities and differences between both C and NC group-specific sets and the resulting different NC metaset are empirically illustrated.

To achieve these objectives, this article is structured as follows. Section 2 explains how technologies can be represented using technology-specific production possibility sets and distance functions. Section 3 then explains how sets of technologies can be represented using technology-specific production possibility sets and distance functions. Section 4 explains how measures of technical efficiency can be written as the product of metatechnology ratios and measures of residual technical efficiency; these measures can be viewed as measures of how well technologies are chosen and used. Section 5 presents a number of results concerning hull operators. It then uses these results to establish relationships between technology-specific and metatechnology-specific production possibilities sets. Section 6 (resp. 7) explains how free disposal hull (resp. data envelopment analysis) estimators can be used to estimate C and NC technology-specific and metatechnology-specific production possibilities sets. These estimators can also be used to estimate metatechnology ratios and measures of residual technical efficiency. [Section 8 discusses related metafrontier models and methods.](#) Section 9 contains an empirical illustration based on a secondary data set. The focus here is on the [convexification strategy](#) that is common in the mainstream literature. We find evidence

that estimates of firm performance are significantly affected by this [convexification strategy](#). Section 10 summarises the article, [transposes the key results to alternative estimators](#) and makes a concluding recommendation.

In order to save space and avoid repetition, the remainder of this article is almost totally focused on estimating input distance functions and associated input-oriented measures of firm performance. Extending our work to output distance functions and associated output-oriented measures of performance is a trivial exercise that is left to the reader.

2 Technology and Technology-specific Frontier

In O’Donnell (2016, p.328), a *technology* is defined as “a technique, method or system for transforming inputs into outputs For most practical intents and purposes, it is convenient to think of a technology as a book of instructions, or recipe”. We adopt this definition here and we view a technology as a type of intellectual capital.⁴

Technology can be represented by a *technology-specific production possibilities set* (TPPS). A TPPS is a set containing all input-output combinations that are possible using a given technology. Let $x \in \mathbb{R}_+^M$ and $y \in \mathbb{R}_+^N$ denote vectors of inputs and outputs respectively. Mathematically, the set of all pairs of input and output vectors that can be produced using technology g is

$$t^g = \{(x, y) \in \mathbb{R}_+^{M+N} : x \text{ with technology } g \text{ can produce } y\}. \quad (1)$$

The boundary of this set is referred to as a *technology-specific frontier*. It is common to assume the following:⁵

(T.1) $(x, 0) \in t^g$ for all $x \in \mathbb{R}_+^M$.

(T.2) If $(0, y) \in t^g$, then $y = 0$.

⁴Other authors use the term “technology” quite differently. For example, Balk (1998, p.12) uses the term to describe a set of feasible input-output combinations; in this article, sets of feasible input-output combinations are referred to as production possibilities sets. As another example, Bresnahan and Trajtenberg (1995) use the term “general purpose technologies” to refer to goods that can be used for many purposes, e.g., “the steam engine, the electric motor, and semiconductors” (p. 83). In this article, goods are referred to as either inputs or outputs depending on whether they are used in or come out of a given production process.

⁵If only one technology exists, then the “ g ” notation can be suppressed and T.1 to T.6 collapse to the axioms found in most textbooks.

(T.3) t^g is a closed subset of \mathbb{R}_+^{M+N} .

(T.4) If $(x, y) \in t^g$ and $(x', -y') \geq (x, -y)$, then $(x', y') \in t^g$.

(T.5) t^g is a C set.

(T.6) If $(x, y) \in t^g$, then there exists $r > 0$ such that $(\lambda x, \lambda^r y) \in t^g$ for all $\lambda > 0$.

These rather traditional assumptions concerning technology g state that: (i) inactivity is possible, (ii) there is no free lunch, (iii) the set of feasible input-output combinations contains all the points on its boundary (closedness), (iv) inputs and outputs are freely (or strongly) disposable, (v) the production possibilities set is convex, and (vi) if inputs are increased by one percent, then outputs can be increased by approximately r percent. The frontier is said to exhibit decreasing returns to scale (DRS), constant returns to scale (CRS) or increasing returns to scale (IRS) as r is less than, equal to, or greater than one (respectively). For more details, see, for example, Hackman (2008). The first and last two assumptions (T.1, T.5 and T.6) are not always maintained in this article.

If assumption T.4 is true, then t^g can be represented using the following technology-specific input distance function:

$$d_I^g(x, y) = \sup_{\lambda \in \mathbb{R}_+} \{\lambda : (x/\lambda, y) \in t^g\}. \quad (2)$$

This function is non-negative, linearly homogeneous in inputs, and no less than unity for all $(x, y) \in t^g$.

3 Metatechnology and Metafrontier

We introduce the *technology set* or *metatechnology* Γ as the set of all technologies g (or recipes) that exist in a given period.⁶ If we view a technology as a recipe, then we can follow Caselli and Coleman (2006, p. 509) and view a technology set as “a library, containing blueprints, or recipes to turn inputs into outputs”. In this article, the set of all input and output vector pairs that are possible using a given technology set Γ (i.e., using some

⁶Other authors use the term “technology set” quite differently. For example, Färe and Primont (1995, p. 8), Coelli, Rao, O’Donnell, and Battese (2005, p. 42) and Afsharian and Ahn (2015, p. 6) use the term to describe a set of feasible input-output combinations. O’Donnell (2016) refers to the set of technologies that exist in a given period as a “metatechnology”.

technology that is contained in Γ) is referred to as a *metatechnology-specific production possibilities set* (MTPPS). Mathematically, this set of possible input-output combinations is

$$T^\Gamma = \{(x, y) \in \mathbb{R}_+^{M+N} : \exists g \in \Gamma : x \text{ and } g \text{ can produce } y\}. \quad (3)$$

Equivalently, $T^\Gamma = \cup_{g \in \Gamma} t^g$ where Γ is the technology set. The boundary of a MTPPS is referred to as a *metafrontier* in this article.

Note that the time dimension is not introduced in the above notions and corresponding notations. However, if relevant, this time dimension can be included quite straightforwardly. In this respect, we mention two natural implications. First, technologies can be identified at a given time period t . Then, the technology set Γ contains all technologies g that exist at that given time period. Consequently, all TPPSs and the corresponding MTPPS also depend on that given time period. Second, one technology in particular could be considered at different time periods (e.g., before, during, and after a crisis). Then, interpret this case as having different technologies available, each with their corresponding TPPS. The technology set Γ now contains these “different” technologies that determines the corresponding MTPPS.

If assumption T.4 is true, then T^Γ can be represented using the following metatechnology-specific input distance function:

$$D_I^\Gamma(x, y) = \max_{g \in \Gamma} \{d_I^g(x, y)\}. \quad (4)$$

Equivalently, $D_I^\Gamma(x, y) = \sup_{\lambda \in \mathbb{R}_+} \{\lambda : (x/\lambda, y) \in T^\Gamma\}$. This function is non-negative, linearly homogeneous in inputs, and no less than unity for all $(x, y) \in T^\Gamma$.

4 Technical Efficiency

In this article, the input-oriented metatechnology-specific technical efficiency (ITE) of a firm that uses inputs x to produce outputs y using some technology $g \in \Gamma$ is defined as the reciprocal of the metatechnology-specific input distance function:

$$\text{ITE}^\Gamma(x, y) = 1/D_I^\Gamma(x, y). \quad (5)$$

This measure goes back to the coefficient of resource utilisation defined by Debreu (1951, p. 285). It is a radial measure of efficiency that lies in the closed unit interval. It indicates the maximum equiproportionate reduction in x which still allows production of y by some

technology $g \in \Gamma$.

If Γ contains more than one technology, then the measure of ITE defined by (5) can be written as the product of an input-oriented metatechnology ratio (IMR) and a measure of residual input-oriented technical efficiency (RITE). Mathematically, the IMR relative to the technology set Γ of a firm that uses inputs x and technology g to produce outputs y is

$$\text{IMR}^{g\Gamma}(x, y) = d_I^g(x, y) / D_I^\Gamma(x, y). \quad (6)$$

This measure also lies in the closed unit interval. It can be viewed as an input-oriented measure of whether a firm has chosen the best technology that is available. The associated measure of RITE is

$$\text{RITE}^g(x, y) = 1 / d_I^g(x, y). \quad (7)$$

This measure also lies in the closed unit interval. It indicates the maximum equiproportionate reduction in x which still allows production of y when using technology g . It can also be viewed as the component of ITE that remains after accounting for the IMR (hence the term “residual”). Equations (4), (5) and (7) imply that

$$\text{ITE}^\Gamma(x, y) = \min_{g \in \Gamma} \{ \text{RITE}^g(x, y) \}. \quad (8)$$

An analogous definition of output-oriented technical efficiency (OTE) based on a similar enumeration over groups has recently been defined by Afsharian and Ahn (2015). Note that some of the components in (8) can be undefined for some input-output combinations that are not contained in the group technology composing the technology or metatechnology (see Briec and Kerstens (2009) for details on infeasibilities). Finally, equations (5), (6) and (7) imply that

$$\text{ITE}^\Gamma(x, y) = \text{IMR}^{g\Gamma}(x, y) \cdot \text{RITE}^g(x, y). \quad (9)$$

Thus, technical efficiency can be decomposed into the product of a metatechnology ratio (measuring how close a technology-specific frontier is to the metafrontier) and a measure of residual technical efficiency (measuring how close a firm is operating to the technology-specific frontier). Equation (9) is an input-oriented version of the output-oriented efficiency decomposition in O’Donnell, Rao, and Battese (2008, Eq. 10).

5 Different Hull Operators and Their Properties

To inform our discussion of convexification, we first establish some results concerning the monotonic hull, conical hull, and C hull of a general set $A \subseteq \mathbb{R}_+^{M+N}$.

Definition 5.1. For the set $A \subseteq \mathbb{R}_+^{M+N}$,

- (a) the monotonic hull of A is given by $mon(A) = \{z \in \mathbb{R}_+^{M+N} \mid \exists u \in A, \exists (x_+, y_-) \in \mathbb{R}_+^M \times \mathbb{R}_-^N \text{ such that } z = u + (x_+, y_-)\}$;
- (b) the conical hull of A is given by $cone(A) = \{z \in \mathbb{R}_+^{M+N} \mid \exists u \in A, \exists \lambda \in \mathbb{R}_{++} \text{ such that } z = \lambda u\}$;
- (c) the C hull of A is given by $conv(A) = \{z \in \mathbb{R}_+^{M+N} \mid \exists u_i \in A, \exists \alpha_i \in \mathbb{R}_+ \text{ with } \sum_i \alpha_i = 1 \text{ such that } z = \sum_i \alpha_i u_i\}$.

Obviously, the different hull operators of Definition 5.1 can be combined in several ways. To mention just a few possibilities for $A \subseteq \mathbb{R}_+^{M+N}$, the C conical hull of A is $conv(cone(A))$, the C monotonic hull of A is $conv(mon(A))$, the monotonic C hull of A is $mon(conv(A))$, and the conical C hull of A is $cone(conv(A))$. The following proposition says that the order in which these hull operators are applied on a given set does not matter.

Proposition 5.1. For the set $A \subseteq \mathbb{R}_+^{M+N}$,

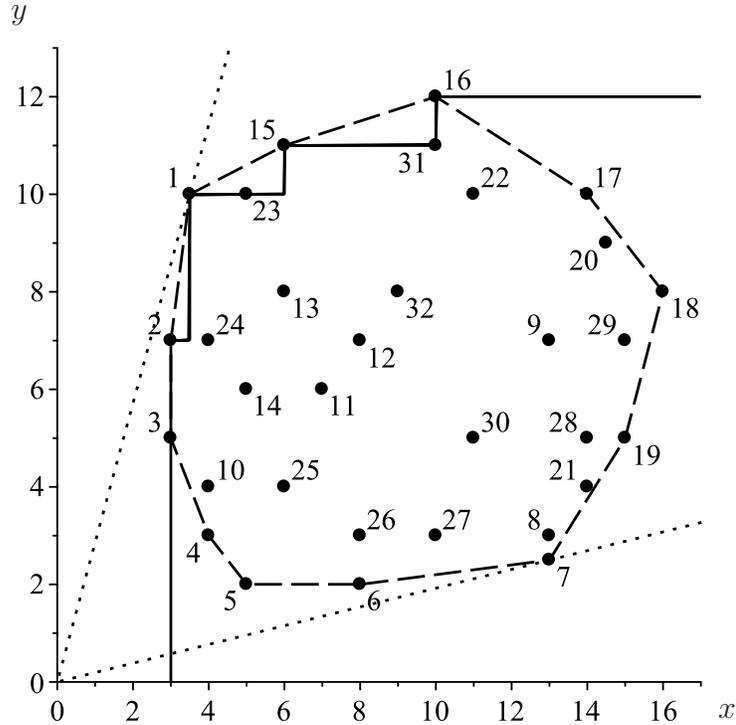
- (a) $mon(conv(A)) = conv(mon(A))$;
- (b) $cone(conv(A)) = conv(cone(A))$;
- (c) $mon(cone(A)) = cone(mon(A))$.

The proof of this proposition and all other propositions is found in Appendix 1.

Figure 1 illustrates the hull operators of Definition 5.1 on a set A containing 32 data points in \mathbb{R}_+^2 . The C hull $conv(A)$ is the region enclosed by the dashed polyline starting from observation 1 and continuing all the way round to observation 1 again. The monotonic hull $mon(A)$ consists of the region restricted to the first quadrant (i.e., the region with positive x - and y -coordinates) located below and to the right of the solid polyline starting vertical at the bottom towards observation 3 and then continuing to observations 2, 1, 23, 15, 31 and 16 using horizontal and vertical connections to end horizontally from observation 16

onwards. Unifying both these regions results in the C monotonic hull $conv(mon(A))$. This is the region restricted to the first quadrant below and to the right of the polyline starting with the vertical solid line to observation 2, then continuing via the dashed lines to observations 1, 15 and 16 to end with the horizontal solid line from observations 16 onwards. The C conical hull $conv(cone(A))$ consists of the region enclosed between the two dotted lines.

Figure 1: Different Hull operators Applied to the Same Set



The next proposition shows that a given set is contained in all hulls and that all hull operators preserve subset relationships.

Proposition 5.2. *For the sets $A, B \subseteq \mathbb{R}_+^{M+N}$ with $A \subseteq B$,*

- (a) $A \subseteq mon(A)$, $A \subseteq cone(A)$, and $A \subseteq conv(A)$;
- (b) $mon(A) \subseteq mon(B)$, $cone(A) \subseteq cone(B)$, and $conv(A) \subseteq conv(B)$.

In combination with the union operator on sets, we can establish the following results (to the best of our knowledge, these results are new):⁷

⁷Operations on sets (or composition rules) have to our knowledge been discussed theoretically only while

Proposition 5.3. For the sets $A, B \subseteq \mathbb{R}_+^{M+N}$,

(a) $mon(A) \cup mon(B) = mon(A \cup B)$;

(b) $cone(A) \cup cone(B) = cone(A \cup B)$;

(c) $conv(A) \cup conv(B) \subseteq conv(A \cup B)$.

Thus, the union of the monotonic (resp. conical) hulls of two sets is equal to the monotonic (resp. conical) hull of the union of these two sets. However, the union of the C hulls of two sets is only a subset of the C hull of the union of these two sets. The following result can now be stated.

Proposition 5.4. For the sets $A, B \subseteq \mathbb{R}_+^{M+N}$,

(a) $conv(mon(A)) \cup conv(mon(B)) \subseteq conv(mon(A \cup B))$;

(b) $conv(cone(A)) \cup conv(cone(B)) \subseteq conv(cone(A \cup B))$;

(c) $cone(mon(A)) \cup cone(mon(B)) = cone(mon(A \cup B))$.

Again, only the convexity operator yields subset relationships. Note that converse properties of (a) and (b) do not hold true. We leave it to the reader to illustrate this using a counterexample. The counterexample used in the proof of Proposition 5.3(c) can serve as inspiration.

All of the aforementioned hull operators and their properties can be applied to the production possibilities sets introduced in Sections 2 and 3. Propositions 5.3 and 5.4 imply:

Proposition 5.5. If $T^\Gamma = \cup_{g \in \Gamma} t^g$ for the technology set Γ , then

(a) $\cup_{g \in \Gamma} conv(mon(t^g)) \subseteq conv(mon(T^\Gamma))$;

(b) $\cup_{g \in \Gamma} conv(cone(t^g)) \subseteq conv(cone(T^\Gamma))$;

(c) $\cup_{g \in \Gamma} conv(cone(mon(t^g))) \subseteq conv(cone(mon(T^\Gamma)))$;

(d) $\cup_{g \in \Gamma} mon(t^g) = mon(T^\Gamma)$;

(e) $\cup_{g \in \Gamma} cone(mon(t^g)) = cone(mon(T^\Gamma))$.

maintaining convexity: see, e.g., Ruys (1974).

Proposition 5.5(a) says that the C monotonic hull of the MTPPS contains the union of all C monotonic hulls of each TPPS. Equality is only obtained in restrictive special cases. Proposition 5.5(b) says that the C conical hull of the MTPPS contains the union of all C conical hulls of each TPPS. Proposition 5.5(c) says that the C conical monotonic hull of the MTPPS contains the union of all C conical monotonic hulls of each TPPS. Proposition 5.5(d) says that the monotonic hull of the MTPPS equals the union of all monotonic hulls of each TPPS. Proposition 5.5(e) says that the conical monotonic hull of the MTPPS equals the union of all conical monotonic hulls of each TPPS.

The convexification strategy that is found in the mainstream efficiency literature is equivalent to assuming explicitly or implicitly that the subset relationships in Proposition 5.5(a-c) can be replaced for practical purposes by an equality relationship. To the best of our knowledge, the consequences of such a convexification strategy have not been thoroughly assessed in the literature.

In the next two sections, we consider the consequences of this convexification strategy for nonparametric estimators of technology-specific frontiers and associated metafrontiers. These estimators are all associated to initial observations. Therefore, we introduce the following notations. Assume that n observations $(x_1, y_1), \dots, (x_n, y_n)$ are available, and that technology g is determined by $n^g \leq n$ of these observations. To identify these particular observations, consider the one-to-one index function ϕ_g mapping the set $\{1, \dots, n^g\}$ into the set $\{1, \dots, n\}$. Then, $(x_{\phi_g(i)}, y_{\phi_g(i)})$ denotes the i -th generating observation of g . To illustrate these notations, consider the case where technology g is determined by the three observations (x_1, y_1) , (x_3, y_3) and (x_8, y_8) . Then, $n^g = 3$ and $\phi_g : \{1, 2, 3\} \rightarrow \{1, \dots, n\}$ with $\phi_g(1) = 1$, $\phi_g(2) = 3$ and $\phi_g(3) = 8$.

6 Free Disposal Hull Estimators

If every TPPS is NC and the associated technology exhibits variable returns to scale (VRS), then an asymptotically unbiased estimator for this TPPS is $t_{NC, VRS}^g = mon(s^g)$ with $s^g = \{(x_{\phi_g(i)}, y_{\phi_g(i)}) : i = 1, \dots, n^g\}$ the set of n^g initial observations determining technology g .

Equivalently,

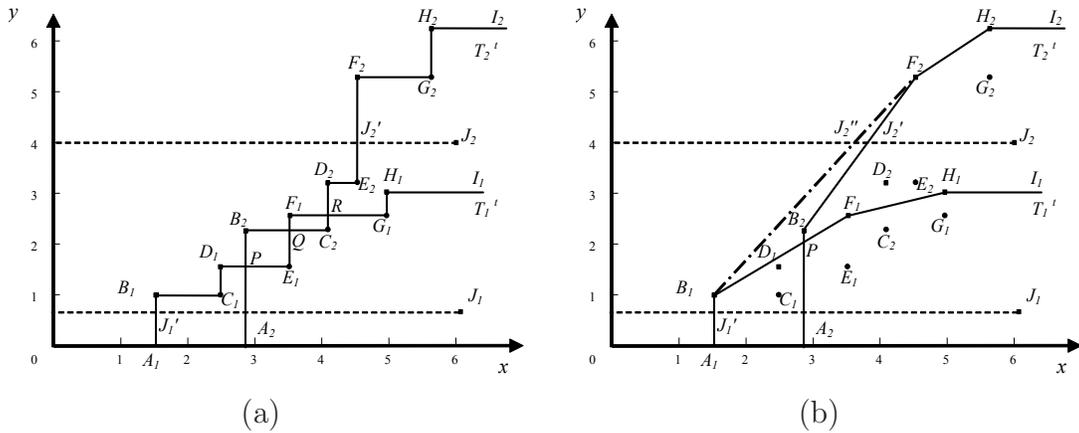
$$t_{NC, VRS}^g = \left\{ (x, y) \in \mathbb{R}_+^{M+N} : \sum_{i=1}^{n^g} \lambda_{\phi_g(i)} x_{\phi_g(i)} \leq x, \sum_{i=1}^{n^g} \lambda_{\phi_g(i)} y_{\phi_g(i)} \geq y, \right. \\ \left. \sum_{i=1}^{n^g} \lambda_{\phi_g(i)} = 1, \lambda_{\phi_g(i)} \in \{0, 1\} \right\}. \quad (10)$$

Proposition 5.5(d) implies that the associated asymptotically unbiased estimator for T^Γ is $T_{NC, VRS}^\Gamma = \text{mon}(\cup_{g \in \Gamma} s^g)$. Equivalently,

$$T_{NC, VRS}^\Gamma = \left\{ (x, y) \in \mathbb{R}_+^{M+N} : \sum_{g \in \Gamma} \sum_{i=1}^{n^g} \lambda_{\phi_g(i)} x_{\phi_g(i)} \leq x, \sum_{g \in \Gamma} \sum_{i=1}^{n^g} \lambda_{\phi_g(i)} y_{\phi_g(i)} \geq y, \right. \\ \left. \sum_{g \in \Gamma} \sum_{i=1}^{n^g} \lambda_{\phi_g(i)} = 1, \lambda_{\phi_g(i)} \in \{0, 1\} \right\}. \quad (11)$$

Figure 2(a) illustrates the relationship between the estimators (10) and (11) for the single-input-single-output case when only two technologies exist. In this figure, the estimated TPPS $t_{NC, VRS}^1$ (resp. $t_{NC, VRS}^2$) consists of all points between the polyline $A_1 B_1 C_1 D_1 E_1 F_1 G_1 H_1 I_1$ (resp. $A_2 B_2 C_2 D_2 E_2 F_2 G_2 H_2 I_2$) and the horizontal axis. The estimated MTPPS $T_{NC, VRS}^{\{1,2\}}$ consists of all points between the polyline $A_1 B_1 C_1 D_1 P B_2 Q F_1 R D_2 E_2 F_2 G_2 H_2 I_2$ and the horizontal axis. Notice the equality relationship of Proposition 5.5(d).

Figure 2: (a) NC and (b) C Group-Specific Technologies and NC Metatechnologies



If every TPPS is NC and the associated technology exhibits constant returns to scale (CRS), then an asymptotically unbiased estimator for this TPPS is $t_{NC,CRS}^g = \text{cone}(\text{mon}(s^g))$ with $s^g = \{(x_{\phi_g(i)}, y_{\phi_g(i)}) : i = 1, \dots, n^g\}$ the set of n^g initial observations determining technology g . Equivalently,

$$t_{NC,CRS}^g = \left\{ (x, y) \in \mathbb{R}_+^{M+N} : \sum_{i=1}^{n^g} \lambda_{\phi_g(i)} x_{\phi_g(i)} \leq x, \sum_{i=1}^{n^g} \lambda_{\phi_g(i)} y_{\phi_g(i)} \geq y, \lambda_{\phi_g(i)} \in \{0, 1\} \right\}. \quad (12)$$

Proposition 5.5(e) implies that the associated asymptotically unbiased estimator for T^Γ is $T_{NC,VCS}^\Gamma = \text{cone}(\text{mon}(\cup_{g \in \Gamma} s^g))$. Equivalently,

$$T_{NC,CRS}^\Gamma = \left\{ (x, y) \in \mathbb{R}_+^{M+N} : \sum_{g \in \Gamma} \sum_{i=1}^{n^g} \lambda_{\phi_g(i)} x_{\phi_g(i)} \leq x, \sum_{g \in \Gamma} \sum_{i=1}^{n^g} \lambda_{\phi_g(i)} y_{\phi_g(i)} \geq y, \lambda_{\phi_g(i)} \in \{0, 1\} \right\}. \quad (13)$$

The estimators (10), (11), (12) and (13) are commonly known as free disposal hull (FDH) estimators. Single output FDH estimators go back to Afriat (1972). If the technology-specific frontiers exhibit VRS (resp. CRS), then the estimator (10) (resp. (12)) can be used to construct an asymptotically unbiased estimator for the measure of RITE (7). The associated estimators (11) and (13) can be used to construct asymptotically unbiased estimators for the measure of ITE (5). FDH estimation of either a TPPS or MTPPS requires solving a mixed integer linear program for each evaluated observation. However, Leleu (2006) and Briec, Kerstens, and Vanden Eeckaut (2004) propose a linear programming (LP) solution and a closed form solution based on an implicit enumeration strategy, respectively.

7 Data Envelopment Analysis Estimators

If every TPPS is C and the associated technology exhibits VRS, then an asymptotically unbiased estimator for this TPPS is $t_{C,VRS}^g = \text{conv}(\text{mon}(s^g)) = \text{mon}(\text{conv}(s^g))$ with $s^g = \{(x_{\phi_g(i)}, y_{\phi_g(i)}) : i = 1, \dots, n^g\}$ the set of n^g initial observations determining technology g . Equivalently,

$$t_{C,VRS}^g = \left\{ (x, y) \in \mathbb{R}_+^{M+N} : \sum_{i=1}^{n^g} \lambda_{\phi_g(i)} x_{\phi_g(i)} \leq x, \sum_{i=1}^{n^g} \lambda_{\phi_g(i)} y_{\phi_g(i)} \geq y, \sum_{i=1}^{n^g} \lambda_{\phi_g(i)} = 1, \lambda_{\phi_g(i)} \in \mathbb{R}_+ \right\}. \quad (14)$$

This estimator is the convexified version of (10). It differs from (10) in that the nonnegative activity (or intensity) variables ($\lambda_{\phi_g(i)}$) are no longer restricted to be binary integers. The

associated asymptotically unbiased estimator for T^Γ is

$$T_{C,VRS}^\Gamma = \bigcup_{g \in \Gamma} \text{conv}(\text{mon}(s^g)). \quad (15)$$

This estimator goes back at least as far as Tiedemann, Francksen, and Latacz-Lohmann (2011, p. 578). Proposition 5.5(a) implies that it is not necessarily equal to the convexified version of (11). The convexified version of (11) is $H_{C,VRS}^\Gamma = \text{conv}(\text{mon}(\bigcup_{g \in \Gamma} s^g))$. Equivalently,

$$H_{C,VRS}^\Gamma = \left\{ (x, y) \in \mathbb{R}_+^{M+N} : \sum_{g \in \Gamma} \sum_{i=1}^{n^g} \lambda_{\phi_g(i)} x_{\phi_g(i)} \leq x, \sum_{g \in \Gamma} \sum_{i=1}^{n^g} \lambda_{\phi_g(i)} y_{\phi_g(i)} \geq y, \sum_{g \in \Gamma} \sum_{i=1}^{n^g} \lambda_{\phi_g(i)} = 1, \lambda_{\phi_g(i)} \in \mathbb{R}_+ \right\}. \quad (16)$$

O'Donnell, Rao, and Battese (2008, p. 238) use an estimator of this type⁸ to construct an estimator of OTE. Proposition 5.5(a) implies that $H_{C,VRS}^\Gamma \supseteq T_{C,VRS}^\Gamma$. Thus, except in restrictive special cases (e.g., only one technology exists), it is an asymptotically biased estimator of the MTPPS. The basic question we address in this article is whether it yields efficiency estimates that are close to the estimates obtained using the asymptotically unbiased estimator (15).

To the best of our knowledge, no single study has ever documented this bias issue. Tiedemann, Francksen, and Latacz-Lohmann (2011) only compare C TPPSs to the correct NC MTPPS defined as the union of these TPPSs, but they ignore the bias issue (see also Sala-Garrido, Molinos-Senante, and Hernández-Sancho (2011)). This bias issue is only partly documented in Huang, Ting, Lin, and Lin (2013) and in the unpublished paper of Breustedt, Francksen, and Latacz-Lohmann (2007): the former article lists the units whose efficiency measure is different on the true NC compared to the biased convexified MTPPSs (see their Table 4), the latter study illustrates these same differences in metafrontier efficiency measures mainly graphically. But, none of these studies reports any test statistic regarding these differences in metafrontier efficiency measures.

Figure 2(b) illustrates the relationship between the estimators (14), (15) and (16) for the single-input-single-output case when only two technologies exist.⁹ In this figure, the

⁸O'Donnell, Rao, and Battese (2008) effectively estimate OTE under the assumption that there is no technical change.

⁹The data points in this figure are, in fact, the data points that were depicted earlier in Figure 2. However, each TPPS is now assumed to be convex.

estimated TPPS $t_{C, VRS}^1$ (resp. $t_{C, VRS}^2$) consists of all points between the horizontal axis and the polyline $A_1B_1F_1H_1I_1$ (resp. $A_2B_2F_2H_2I_2$). The estimated MTPPS $T_{C, VRS}^{\{1,2\}}$ consists of all points between the horizontal axis and the polyline $A_1B_1PB_2F_2H_2I_2$. While each estimated TPPS is convex, the estimated MTPPS is clearly non-convex. The estimator (16) convexifies this NC set by adding the region $B_1PB_2F_2B_1$; the resulting set $H_{C, VRS}^{\{1,2\}}$ consists of all points between the horizontal axis and the polyline $A_1B_1F_2H_2I_2$. If we were to add an additional technology, then the set $T_{C, VRS}^\Gamma$ may still not equal the C set $H_{C, VRS}^\Gamma$; an additional TPPS might fill up part of the region determined by $B_1PB_2F_2B_1$, but it could easily create further non-convexities to the left or to the right of the existing one. Notice in Figure 2(b) the subset relationship in Proposition 5.5(a). Obviously, one must realize that in a multiple-input-multiple-output setting (rather than in a single-input-single-output setting), the union of more than two TPPSs is only by sheer coincidence going to end up yielding a C set. The most likely outcome is simply that the resulting MTPPS is non-convex.

If every TPPS is C and the associated technology exhibits CRS, then an asymptotically unbiased estimator for this TPPS is $t_{C, CRS}^g = \text{conv}(\text{cone}(\text{mon}(s_g)))$ with $s^g = \{(x_{\phi_g(i)}, y_{\phi_g(i)}) : i = 1, \dots, n^g\}$ the set of n^g initial observations determining technology g . Equivalently,

$$t_{C, CRS}^g = \left\{ (x, y) \in \mathbb{R}_+^{M+N} : \sum_{i=1}^{n^g} \lambda_{\phi_g(i)} x_{\phi_g(i)} \leq x, \sum_{i=1}^{n^g} \lambda_i y_{\phi_g(i)} \geq y, \lambda_{\phi_g(i)} \in \mathbb{R}_+ \right\}. \quad (17)$$

This estimator is the convexified version of (12). Again, it differs from (12) in that the nonnegative activity variables are no longer restricted to be binary integers. The associated asymptotically unbiased estimator for T^Γ is

$$T_{C, CRS}^\Gamma = \cup_{g \in \Gamma} \text{conv}(\text{cone}(\text{mon}(s^g))). \quad (18)$$

Proposition 5.5(c) implies that this is not necessarily equal to the convexified version of (13). The convexified version of (13) is $H_{C, CRS}^\Gamma = \text{conv}(\text{cone}(\text{mon}(\cup_{g \in \Gamma} s^g)))$. Equivalently,

$$H_{C, CRS}^\Gamma = \left\{ (x, y) \in \mathbb{R}_+^{M+N} : \sum_{g \in \Gamma} \sum_{i=1}^{n^g} \lambda_{\phi_g(i)} x_{\phi_g(i)} \leq x, \sum_{g \in \Gamma} \sum_{i=1}^{n^g} \lambda_{\phi_g(i)} y_{\phi_g(i)} \geq y, \lambda_{\phi_g(i)} \in \mathbb{R}_+ \right\}. \quad (19)$$

Proposition 5.5(c) implies that $H_{C, CRS}^\Gamma \supseteq T_{C, CRS}^\Gamma$. Thus, once again, except in restrictive special cases, it is an asymptotically biased estimator of the MTPPS. Again, the basic question is whether it yields efficiency estimates that are close to the estimates obtained using the asymptotically unbiased estimator (18).

The estimators (14), (16), (17) and (19) are commonly known as data envelopment analysis (DEA) estimators. Single output DEA estimators also go back to at least Afriat (1972). Multi-output DEA estimators appear to have been introduced to the literature by Banker, Charnes, and Cooper (1984) and Färe, Grosskopf, and Lovell (1983). If the TPPS exhibit VRS (resp. CRS), then the estimator (14) (resp. (17)) can be used to construct an asymptotically unbiased estimator for the measure of RITE (7). This requires solving an LP problem for each evaluated observation (see Hackman (2008) or Ray (2004)). The associated estimators (15) and (18) can be used to construct asymptotically unbiased estimators for the measure of ITE (5). Recently, Afsharian and Podinovski (2018) demonstrate that this can be achieved in both cases by solving a single LP problem. For the reasons given earlier, the estimators (16) and (19) cannot generally be used to construct an asymptotically unbiased estimator for the measure of ITE.

8 Related Metafrontier Models and Methods

This article has focused on metafrontier methods for estimating the gaps between TPPSs and the MTPPS. Metafrontier methods can also be used to estimate the gaps between other types of production possibilities sets. For example, they can be used to estimate the gaps between period-and-state-contingent production possibilities sets and period-specific production possibilities sets. A period-and-state-contingent production possibilities set is a set containing all input-output combinations that are possible in a given period in a given state of the production environment (or state of nature). Suppose there are $S \in \mathbb{Z}_+$ possible states of nature. Mathematically, the set of all input and output vector pairs that are possible in period t in state s is $T^t(s) = \{(x, y) \in \mathbb{R}_+^{M+N} : x \text{ can produce } y \text{ in period } t \text{ in state } s\}$. The boundary of this set is a period-and-state-contingent frontier. The associated period-specific production possibilities set is $T^t = \cup_{s \in \Omega} T^t(s)$ where $\Omega = \{1, \dots, S\}$. If inputs are freely disposable, then $T^t(s)$ can be represented using the following period-and-state-contingent input distance function:

$$D_I^t(x, y, s) = \sup_{\lambda \in \mathbb{R}_+} \{\lambda : (x/\lambda, y) \in T^t(s)\}. \quad (20)$$

This distance function gives the largest factor by which it is possible to reduce x and still produce y in period t in state s . The associated period-specific input distance function is

$$D_I^t(x, y) = \max_{s \in \Omega} \{D_I^t(x, y, s)\}. \quad (21)$$

This distance function gives the largest factor by which it is possible to reduce x and still produce y in period t . An associated input-oriented measure of firm and environmental performance is the following input-oriented technical efficiency and environmental effect (ITEEE):

$$ITEEE^t(x, y) = 1/D_I^t(x, y). \quad (22)$$

This is a radial measure of performance that lies in the closed unit interval. If there is only one state of nature (i.e., there are no environmental effects), then it is equivalent to the measure of ITE defined by (5). If $S > 1$, then it can be written as the product of an input-oriented environmental effect (IEE) and a measure of ITE. Mathematically, the IEE a firm that uses inputs x to produces outputs y in period t in state s is

$$IEE^t(x, y, s) = D_I^t(x, y, s)/D_I^t(x, y). \quad (23)$$

This measure also lies in the closed unit interval. It can be viewed as an input-oriented measure of whether a firm is operating in the best production environment. The ITE of the firm is

$$ITE^t(x, y, s) = 1/D_I^t(x, y, s). \quad (24)$$

This measure also lies in the closed unit interval. It can still be viewed as a measure of how well the firm makes use of the technologies that exist in period t . Equations (21), (22) and (24) imply that

$$ITEEE^t(x, y) = \min_{s \in \Omega} \{ITE^t(x, y, s)\}. \quad (25)$$

Finally, equations (22), (23) and (24) imply that

$$ITEEE^t(x, y) = ITE^t(x, y, s) \cdot IEE^t(x, y, s). \quad (26)$$

Equations (22) to (26) are analogous to equations (5) to (9). Associated FDH and DEA estimators of these quantities are analogous to the estimators discussed in Sections 6 and 7.

The message to take from this discussion is that various functions and measures of performance associated with different production environments have the same mathematical structure, but not necessarily the same interpretation, as those associated with the selection and use of technologies. From a mathematical viewpoint, the distinction between technologies and environments is immaterial. The distinguishing feature of metafrontier models is that firms can be classified into groups. If the classification is not obvious, then there are several multivariate statistical methods that can be used to classify the units in a sample into either some natural groups (e.g., using some variant of cluster analysis) or a set of existing

groups (e.g., using discriminant analysis and its variations). Examples include Samoilenko and Osei-Bryson (2010) and Llorca, Orea, and Pollitt (2014), among others. Along similar lines, frontier estimates have been used in a variety of ways to distinguish strategic groups (e.g., Athanassopoulos (2003), Warning (2004), among others). As long as groups can be identified, the metafrontier framework is applicable.

The short article of Pastor and Lovell (2005) proposes a global Malmquist productivity index based upon the specification of a single global technology constructed by taking a convex cone over all data for all observations and all time periods simultaneously. It has the key attractive feature of being circular (just like any fixed base index). However, Afsharian and Ahn (2015) analyse this proposal in detail and fundamentally criticize the Pastor and Lovell (2005) proposal for adopting -in our parlance- a convexification strategy that is unwarranted. In particular, these authors point out that this strategy (1) neglects the role of each contemporaneous technology in the determination of the global benchmark technology; (2) assumes that convex combinations of observations across time periods are feasible; and (3) previously computed results by the global Malmquist index can change significantly when a new time period is incorporated. Therefore, Afsharian and Ahn (2015) plea to use a proper union of convex cones defined per contemporaneous technology (instead of the convex cone over the union of all observations).

9 Empirical Illustration: Hydroelectric Power Plants

In this section, we illustrate the implications of convexification using data that have previously been used by Atkinson and Dorfman (2009) to assess the performance of Chilean hydroelectric power plants.

There are two main techniques (or technologies) used to generate hydroelectric power in Chile. The first technology (given index 1) involves building a large dam on a river to store water. Water is then released from the dam to spin turbines that generate electricity. The advantage of so-called dam systems is that electricity generation is de-coupled from river flows. The second type of hydroelectric power technology (given index 2) involves merely diverting river flows through turbines. The advantage of so-called run-of-river (ROR), or diversion, systems is that they are relatively inexpensive and have relatively little impact on the environment. A disadvantage of these systems is that they cannot be used to match electricity generation with consumer demand.¹⁰

¹⁰A third hydroelectric power technology, called pumped storage, can be used to match electricity gener-

By construction, the technology set $\Gamma = \{1, 2\}$. The sample comprises data on $M = 3$ inputs and $N = 1$ output for 16 Chilean hydroelectric power plants over the 12 months of the year 1997. There are 5 dam plants and 11 ROR plants in our sample. The data are publicly available on the web site of the *Journal of Applied Econometrics*.¹¹ The single output is electricity generated (in gigawatt hours). The three inputs are labor (thousands of workers), capital (real pesos), and water (cubic meters). More details concerning the data can be accessed from Atkinson and Dorfman (2009) and Atkinson and Halabí (2005).

Our knowledge of hydroelectric power generation in Chile leads us to believe that it *may* be possible for the manager of a given (dam or ROR) plant to use a given input vector to produce a given level of output for some of the time, and then use a different input vector to produce a different level of output the rest of the time. This suggests that each TPPS *may* be convex. Consequently, we began by estimating these TPPSs t^1 and t^2 using the “convexifying” DEA estimator (14). It is also our understanding that, given the different types of capital involved in constructing different plants, the manager of a given plant cannot operate a dam system for some of the time and then operate an ROR system the rest of the time. This suggests that the MTPPS should not be convexified. Consequently, we estimated the MTPPS using the DEA estimator (15). Descriptive statistics for the associated estimates of ITE, RITE and IMR are reported in the columns labelled C-NC in Table 1 (the acronym C-NC indicates that the TPPSs have been convexified, but the MTPPS has not been convexified). Of course, TPPSs may *not* be convex. Consequently, we also estimated the TPPSs using the non-convexifying FDH estimator (10). The associated estimator of the period-specific production possibilities set is the non-convexifying FDH estimator (11). Descriptive statistics for the associated estimates of ITE, RITE and IMR are reported in the columns labelled NC-NC in Table 1 (the acronym NC-NC indicates that neither the TPPSs nor the MTPPS have been convexified). In Table 1, both C-NC and NC-NC results are reported in two blocks of three columns each. The last column contains the number of infeasible solutions.¹²

Explaining the rows in Table 1, the first block of numbers in Table 1 contains summary statistics for all $16 \times 12 = 192$ observations in the sample. The next two blocks of numbers contain summary statistics for the $n^1 = 5 \times 12 = 60$ dam observations and the $n^2 = 11 \times 12 = 132$ ROR observations. The first row in each block reports the number of efficient observations (i.e., the number of times the relevant measure of performance is estimated to be

ation with daily or weekly consumer demand. However, there are no pumped storage plants in our dataset.

¹¹See: <http://qed.econ.queensu.ca/jae/>

¹²See Bricc and Kerstens (2009) for an extensive discussion on the occurrence of infeasibilities for general distance functions.

1). The next three rows in each block report the geometric averages,¹³ standard deviations, and minima of the relevant estimates.

Table 1: C-NC and NC-NC Estimates of ITE, RITE and the IMR

		C-NC			NC-NC			Inf.
		ITE	RITE	IMR	ITE	RITE	IMR	
All 192	#Eff. Obs.	21	24	163	154	168	175	
Observations	Geom. Mean	0.7582	0.8046	0.9424	0.9391	0.9629	0.9752	
	Stand. Dev.	0.2009	0.1791	0.1260	0.1378	0.1076	0.0878	
	Min.	0.1325	0.2094	0.3740	0.3154	0.3154	0.3866	
Li-test†		34.15	37.15	2.13				
<i>p</i> -value		(0.000)	(0.000)	(0.022)				
60 Dam	#Eff. Obs.	1	4	31	39	52	44	
Observations	Geom. Mean	0.6751	0.8163	0.8271	0.8811	0.9547	0.9229	29
	Stand. Dev.	0.2141	0.1645	0.1896	0.1867	0.1181	0.1495	
	Min.	0.1325	0.2681	0.3740	0.3212	0.3212	0.3866	
132 ROR	#Eff. Obs.	20	20	132	115	116	131	
Observations	Geom. Mean	0.7994	0.7994	1.0000	0.9667	0.9667	≈1.000	0
	Stand. Dev.	0.1853	0.1853	0.0000	0.1024	0.1024	0.0004	
	Min.	0.2094	0.2094	1.0000	0.3154	0.3154	0.9953	

† Li test: **exact *p* values are reported in round brackets underneath.**

Four observations can be made with regard to Table 1. First, by construction, estimates of ITE obtained using the estimators (14) and (15) can be no higher than the estimates obtained using the estimators (10) and (11) (i.e., estimates of ITE obtained using the C-NC model can be no higher than those obtained using the NC-NC model). Table 1 reveals that, in the case of Chilean hydroelectric power generators, estimates of ITE obtained using (14) and (15) are on average $1 - 0.7582/0.9391 = 19.3\%$ lower than estimates obtained using (10) and (11).

Second, also by construction, estimates of RITE obtained using the estimator (14) can be no higher than the estimates obtained using the estimator (10) (i.e., estimates of RITE obtained using the C-NC model can also be no higher than those obtained using the NC-NC model). Table 1 reveals that, in our application, estimates of RITE obtained using (14) are on average $1 - 0.8046/0.9629 = 16.4\%$ lower than estimates obtained using (10).

Third, in theory, estimates of the IMRs obtained using the estimators (14) and (15) can be either higher or lower than the estimates obtained using the estimators (10) and (11) (i.e.,

¹³The use of geometric averages guarantees that the multiplicative decomposition (9) holds exactly.

estimates of the IMRs obtained using the C-NC model can be either higher or lower than those obtained using the NC-NC model). Table 1 reveals that, in our application, estimates of the IMRs obtained using (14) and (15) are on average $1 - 0.9424/0.9752 = 3.4\%$ lower than estimates obtained using (10) and (11). The minima reported for the ROR observations reveal that there was at least one observation where the IMR obtained using the estimators (14) and (15) was higher than the IMR obtained using the estimators (10) and (11).

Finally, the IMR estimates obtained using the C-NC (resp. NC-NC) model and the 132 ROR observations are all (resp. nearly all) equal to one. This indicates that ROR hydroelectric power systems are superior to dam systems. Indeed, we estimate that approximately half of the observed input-output combinations of ROR plants would not even have been feasible using dam plants (i.e., they lie outside the estimated dam-specific production possibilities set). As far as we know, there are only a handful of other studies that use metafrontier methods to determine the inferiority or superiority of different technologies. For example, Sala-Garrido, Molinos-Senante, and Hernández-Sancho (2011) compare four wastewater treatment technologies and find that one technology dominates all others.

Fourth, among dam plants there are 29 instances of infeasible solutions when computing some of the distances to the C TPPSs in determining ITE. This amounts to about 15% of the sample. By contrast, ROR plants do not encounter any infeasible solutions at all.

Figure 3(a) displays the kernel densities of the ITE estimates that were summarised at the top of Table 1.¹⁴ The two densities appear to be quite different. For a formal assessment of this difference, we employ a nonparametric test initially proposed by Li (1996). This test has been refined by Fan and Ullah (1999) and others: the most recent development is by Li, Maasoumi, and Racine (2009). This nonparametric test analyzes the differences between entire distributions instead of focusing on, for instance, first moments (as, e.g., the Wilcoxon signed-ranks test). It tests the statistical significance of differences between two kernel-based estimates of density functions, f and g , of a random variable x . The null hypothesis states the equality of both density functions almost everywhere ($H_0 : f(x) = g(x)$ for all x). The alternative hypothesis negates the equality of both density functions ($H_1 : f(x) \neq g(x)$ for some x). This test is valid for both dependent and independent variables: observe that dependency is a characteristic of frontier estimators (i.e., efficiency levels depend on sample size, among others). Simar and Zelenyuk (2006) fine tune this test statistic further for nonparametric frontier estimators to circumvent the problem of spurious mass at the boundary: their Algorithm I ignores the boundary estimates and their Algorithm

¹⁴Each density was estimated using $N = 192$ observations. For reasons of comparability, a common Sheather and Jones plug-in bandwidth was used (see, e.g., Sheather (2004)).

II smooths boundary estimates by adding uniform noise of an order of magnitude less than the order of magnitude of noise added by the specific estimator. Monte Carlo evidence suggests that Algorithm II performs slightly better overall, though the power of the test statistic decreases with the dimensionality of the production specification.¹⁵ In short, we adopt the Li, Maasoumi, and Racine (2009) version of this test amended with Algorithm II from Simar and Zelenyuk (2006). For this test statistic, we report on the next line the exact p value using 2000 bootstrap replications starting from a conventional 5% significance level (i.e., $\alpha = 0.05$). The test statistic was calculated to be 34.15. The p value indicates that we can reject the null hypothesis and conclude that the two distributions are significantly different.

Figure 3: Kernel Density Estimates of (a) ITE, (b) RITE, and (c) IMRs

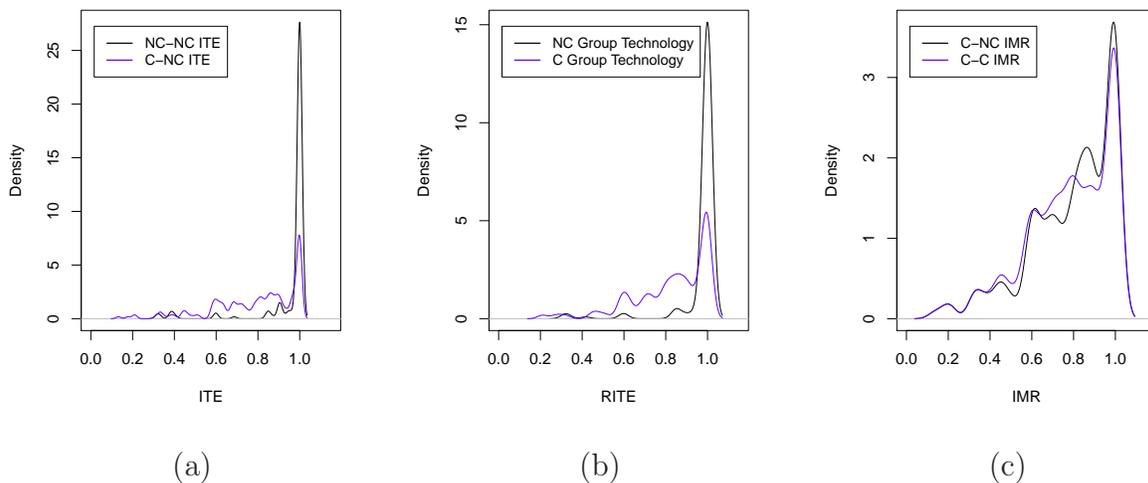


Figure 3(b) displays the kernel densities of the RITE estimates that were summarised at the top of Table 1. Again, the two densities seem quite different. In this case, the Li test statistic amounts to 37.15. The p value indicates that we can again reject the null hypothesis and conclude that the two distributions are significantly different.

Figure 3(c) displays the kernel densities of the IMRs that were summarised at the top of Table 1. In this case, the two densities appear to be quite similar. The Li test statistic

¹⁵In fact, there is not much theoretical argument to adopt either algorithm. Simar and Zelenyuk (2006, p. 508) concede: “Although these ways of curing the discontinuity problem by smoothing or deleting the efficiency scores equal to unity is somewhat ad hoc, at this point they seem to be the only two approaches that work well.”

was calculated to be only 2.13. The large p value indicates that we do not reject the null hypothesis that the two distributions are equal.

The estimates reported in Table 1 and Figures 3(a) to 3(c) are perfectly consistent with what we understand about the different types of physical capital used in Chilean hydroelectric power generation. Engineering considerations have led us to understand that it is not possible for the manager of a given (dam or ROR) plant to produce electricity using a linear combination of the physical capital used in a dam system and the physical capital used in an ROR system. This implies that it is not appropriate to follow common practice and convexify the MTPPS. To assess the impact of (inappropriately) convexifying this set, we estimated the MTPPS using the convexifying DEA estimator (16). Descriptive statistics for the associated estimates of ITE and IMR are reported in the columns labelled C-C in Table 2 (the acronym C-C indicates that the TPPSs and MTPPS have all been convexified).¹⁶

Table 2: C-NC and C-C Estimates of ITE and the IMR

		ITE			IMR		
		C-NC	C-C	Difference	C-NC	C-C	Difference
All 192	# Eff. Obs.	21	23	88	163	71	88
Observations	Arith. Mean.	0.7940	0.7770	0.0170	0.9541	0.9335	0.0206
	Stand. Dev.	0.2009	0.2030	0.0470	0.1260	0.1317	0.0554
	Min.	0.1325	0.1325	0.0000	0.3740	0.3740	0.0000
Li-test†				-1.32			15.21
p -value				(0.951)			(0.000)
60 Dam	# Eff. Obs.	1	2	18	31	1	18
Observations	Arith. Mean.	0.7205	0.6820	0.0385	0.8530	0.8080	0.0450
	Stand. Dev.	0.2141	0.2025	0.0760	0.1896	0.1776	0.0890
	Min.	0.1325	0.1325	0.0000	0.3740	0.3740	0.0000
132 ROR	# Eff. Obs.	20	21	70	132	70	70
Observations	Arith. Mean.	0.8274	0.8202	0.0072	1.0000	0.9905	0.0095
	Stand. Dev.	0.1853	0.1879	0.0170	0.0000	0.0217	0.0217
	Min.	0.2094	0.2094	0.0000	1.0000	0.9036	0.0000

† Li test: exact p values are reported in round brackets underneath.

Most of the column and row labels in Table 2 are self explanatory. The columns labelled “Difference” report the differences between the C-NC and the C-C results. For example, the average difference between the C-NC and C-C estimates of ITE is $0.7940 - 0.7770 = 0.0170$. A Li test was once again applied to all 192 observations to test the null hypothesis that

¹⁶Descriptive statistics for the associated RITE estimates were already reported in the C-NC column in Table 1.

the two ITE (resp. IMR) distributions are equal. The test statistic obtained is [-1.32 \(resp. 15.21\)](#). [The large \(resp. small\) \$p\$ value indicates that](#) we do not reject (resp. reject) the null hypothesis that the two ITE (resp. IMR) distributions are equal.

By construction, estimates of ITE obtained using the convexifying DEA estimator (16) can be no higher than the estimates obtained using the asymptotically unbiased estimator (15) (i.e., estimates of ITE obtained using the C-C model can be no higher than those obtained using the C-NC model). Table 2 reveals that, in the case of Chilean hydroelectric power generators, estimates of ITE obtained using (16) are on average 1.70 percentage points lower than those obtained using (15). This represents a $0.017/0.794 = 2.1\%$ decrease in estimated average ITE. For the subset of firms that use the dam (resp. ROR) technology, using the estimator (16) instead of the estimator (15) results in a $0.0385/0.7205 = 5.3\%$ (resp. $0.0072/0.8274 = 0.9\%$) decrease in estimated average ITE. By construction,¹⁷ qualitatively similar conclusions can be drawn regarding the IMRs.

10 Conclusions

In their seminal paper, O’Donnell, Rao, and Battese (2008) consider a metaset that is defined as the union of two or more underlying group-specific sets. They refer to the boundary of the metaset as a metafrontier, and they refer to the boundaries of the group-specific sets as group frontiers. They suggest estimating the metafrontier under the assumption that the metaset is convex. If this assumption is false, then their “convexifying” estimator is biased. Our key result, Proposition 5.5, shows that both C and NC group-specific sets can (and generally do) yield NC metaset. This suggests that the [convexification strategy](#) should not be maintained *a priori*. In any case, it should be empirically tested.

We used secondary data on Chilean hydroelectric power plants to explore the consequences of making incorrect assumptions about the convexity or nonconvexity of TPPSs and MTPPS. We focused on the consequences of [a convexification strategy](#) for input-oriented estimates of metatechnology ratios and associated measures of technical efficiency. Estimates of input-oriented technical efficiency (ITE), residual input-oriented technical efficiency (RITE) and input-oriented metatechnology ratios (IMRs) were moderately sensitive to these assumptions. While we could have engaged in a data mining exercise to scan for a variety

¹⁷The RITE estimates obtained using the C-C and C-NC models are identical (both were obtained using the convexifying DEA estimator (14)). If the ITE estimates obtained from the C-C model can be no higher than those obtained from the C-NC model, then the decomposition (9) implies that IMR estimates obtained from the C-C model can be no higher than those obtained from the C-NC model.

of data sets that would have supported our basic hypotheses more strongly, we have simply taken a data set that is publicly available so that readers can easily duplicate our results. Since one counterexample is sufficient to invalidate an hypothesis, our results can be safely taken to reject the assumption that the convexification strategy suggested by O'Donnell, Rao, and Battese (2008) is empirically innocuous.

We recommend that users of metafrontier methods should form MTPPS as the (possibly non-convex) union of either C or NC TPPSs. The shortcut suggested in the seminal article of O'Donnell, Rao, and Battese (2008) (i.e., convexify the metaset) generally leads to erroneous results. This critical conclusion that convexity need not be an innocuous assumption is in line with some earlier results in the literature. Briec, Kerstens, and Vanden Eeckaut (2004) already illustrated how the measurement of technical and scale efficiencies is affected by the convexity axiom. Kerstens and Managi (2012) show how the Luenberger productivity indicator as well as its decomposition into technical change and efficiency change are affected by convexity. Finally, Briec, Kerstens, and Vanden Eeckaut (2004) establish theoretically, and illustrate empirically, how the convexity axiom not only affects technologies, but also affects the level of the cost function derived from it (see also Balaguer-Coll, Prior, and Tortosa-Ausina (2007) for another empirical illustration).¹⁸ Thus, convexity seems to matter both from a theoretical and empirical perspective.

Furthermore, we can briefly indicate whether and how these results based on general technologies and on a nonparametric approach using data envelopment analysis and free disposal hull estimators can be transposed to alternative frontier methodologies. First, [the transposition to alternative nonparametric frontier methods \(e.g., conditional C and NC models, C and NC order-m models \(see Daraio and Simar \(2007\)\)\) is straightforward by definition.](#) Second, adopting this meticulous construction of a MTPPS should be rather straightforward in a deterministic parametric approach: it is just a matter of properly transposing the constructive results from the nonparametric approach. Third, the implications for a proper construction of a MTPPS in the far more popular stochastic frontier model have just recently been explored in Amsler, O'Donnell, and Schmidt (2017). Unfortunately, simulation methods must generally be used to construct a stochastic metafrontier that correctly envelops two or more stochastic group frontiers (for details, see Amsler, O'Donnell, and Schmidt (2017)). Finally, transposing this construction of a MTPPS in a stochastic non-parametric approach seems rather straightforward (see, e.g., Afsharian (2017) who focuses on the StoNED method).

¹⁸In fact, WACM is implicitly based on an FDH technology: see Ray (2004).

Finally, it is clear that further research is needed to assess how the many different meta-frontier applications discussed in Section 1 are affected by the possibly incorrect assumption that the MTPPS is convex. We encourage researchers to test this assumption in their empirical work. Some first steps seem to have been taken by Afsharian and Ahn (2015) and Afsharian, Ahn, and Harms (2017) when developing some variation on the primal Malmquist productivity index. Furthermore, empirical testing of the impact of assuming an equality in Proposition 5.5 property (c) in contrast to an approach in part (e) remains to be done: this boils down to redoing our empirical analysis using cone technologies. Furthermore, while we have used a rather generally valid test statistic, specific statistical tests of convexity versus non-convexity have been proposed in a theoretical framework developed by Kneip, Simar, and Wilson (2016). Implementing such a specific test approach may eventually sharpen our results. In a similar vein, there have been a variety of alternative proposals around to account for heterogeneity in frontier models. Popular methods include the use of latent class models (e.g., Orea and Kumbhakar (2004) in a stochastic frontier context), or aggregation over groups or industries (e.g., Zelenyuk (2006) or Mayer and Zelenyuk (2014), but see Balk (2016) for some caveats). There are also alternative proposals around to handle heterogeneity: Simar, Vanhems, and Van Keilegom (2016) or Tsekouras, Chatzistamoulou, and Kounetas (2017) to give some examples. In fact, to the best of our knowledge no theoretical or empirical review has ever compared some let alone all of these different methods to account for heterogeneity in a frontier framework. Obviously, there is a lot of scope for future work.

References

- AFRIAT, S. (1972): “Efficiency Estimation of Production Functions,” *International Economic Review*, 13(3), 568–598.
- AFSHARIAN, M. (2017): “Metafrontier Efficiency Analysis with Convex and Non-Convex Metatechnologies by Stochastic Nonparametric Envelopment of Data,” *Economics Letters*, 160, 1–3.
- AFSHARIAN, M., AND H. AHN (2015): “The Overall Malmquist Index: A New Approach for Measuring Productivity Changes over Time,” *Annals of Operations Research*, 226(1), 1–27.
- AFSHARIAN, M., H. AHN, AND S. HARMS (2017): “A Non-Convex Meta-Frontier Malm-

- quist Index for Measuring Productivity over Time,” *IMA Journal of Management Mathematics*, p. forthcoming.
- AFSHARIAN, M., AND V. PODINOVSKI (2018): “A Linear Programming Approach to Efficiency Evaluation in Nonconvex Metatechnologies,” *European Journal of Operational Research*, 268(1), 268–280.
- AMSLER, C., C. O’DONNELL, AND P. SCHMIDT (2017): “Stochastic Metafrontiers,” *Econometrics Reviews*, 36(6–9), 1007–1020.
- ASSAF, A., C. BARROS, AND A. JOSIASSEN (2012): “Hotel Efficiency: A Bootstrapped Metafrontier Approach,” *International Journal of Hospitality Management*, 31(2), 621–629.
- ATHANASSOPOULOS, A. (2003): “Strategic Groups, Frontier Benchmarking and Performance Differences: Evidence from the UK Retail Grocery Industry,” *Journal of Management Studies*, 40(4), 921–953.
- ATKINSON, S., AND J. DORFMAN (2009): “Feasible Estimation of Firm-Specific Allocative Inefficiency Through Bayesian Numerical Methods,” *Journal of Applied Econometrics*, 24(4), 675–697.
- ATKINSON, S., AND C. HALABÍ (2005): “Economic Efficiency and Productivity Growth in the Post-Privatization Chilean Hydroelectric Industry,” *Journal of Productivity Analysis*, 23(2), 245–273.
- BALAGUER-COLL, M., D. PRIOR, AND E. TORTOSA-AUSINA (2007): “On the Determinants of Local Government Performance: A Two-Stage Nonparametric Approach,” *European Economic Review*, 51(2), 425–451.
- BALK, B. (2016): “Various Approaches to the Aggregation of Economic Productivity Indices,” *Pacific Economic Review*, 21(4), 445–463.
- BANKER, R., A. CHARNES, AND W. COOPER (1984): “Some Models for Estimating Technical and Scale Inefficiencies in Data Envelopment Analysis,” *Management Science*, 30(9), 1078–1092.
- BATTESE, G., AND D. RAO (2002): “Technology Gap, Efficiency and a Stochastic Metafrontier Function,” *International Journal of Business and Economics*, 1(2), 87–93.

- BATTESE, G., D. RAO, AND C. O'DONNELL (2004): "A Metafrontier Production Function for Estimation of Technical Efficiencies and Technology Gaps for Firms Operating Under Different Technologies," *Journal of Productivity Analysis*, 21(1), 91–103.
- BINSWANGER, H., M.-C. YANG, A. BOWERS, AND Y. MUNDLAK (1987): "On the Determinants of Cross-country Aggregate Agricultural Supply," *Journal of Econometrics*, 36(1–2), 111–131.
- BOS, J., AND H. SCHMIEDEL (2007): "Is There a Single Frontier in a Single European Banking Market?," *Journal of Banking & Finance*, 31(7), 2081–2102.
- BRESNAHAN, T., AND M. TRAJTENBERG (1995): "General Purpose Technologies - Engines of Growth?," *Journal of Econometrics*, 65(1), 83–108.
- BREUSTEDT, G., T. FRANCKSEN, AND U. LATA CZ-LOHMANN (2007): "Estimating Non-Concave Metafrontiers Using Data Envelope Analysis," Discussion paper, Department of Agricultural Economics, Christian-Albrechts University, Kiel (Germany).
- BRIEC, W., AND K. KERSTENS (2009): "Infeasibilities and Directional Distance Functions with Application to the Determinateness of the Luenberger Productivity Indicator," *Journal of Optimization Theory and Applications*, 141(1), 55–73.
- BRIEC, W., K. KERSTENS, AND P. VANDEN EECKAUT (2004): "Non-convex Technologies and Cost Functions: Definitions, Duality and Nonparametric Tests of Convexity," *Journal of Economics*, 81(2), 155–192.
- CASELLI, F., AND W. COLEMAN (2006): "The World Technology Frontier," *American Economic Review*, 93(3), 499–522.
- CASU, B., A. FERRARI, AND T. ZHAO (2013): "Regulatory Reform and Productivity Change in Indian Banking," *Review of Economics and Statistics*, 95(3), 1066–1077.
- CHEN, Z., AND S. SONG (2008): "Efficiency and Technology Gap in China's Agriculture: A Regional Meta-Frontier Analysis," *China Economic Review*, 19(2), 287–296.
- COELLI, T., D. RAO, C. O'DONNELL, AND G. BATTESE (2005): *An Introduction to Efficiency and Productivity Analysis*. Springer, New York, 2nd edn.
- COOPER, W., L. SEIFORD, AND K. TONE (2007): *Data Envelopment Analysis: A Comprehensive Text with Models, Applications, References and DEA-Solver Software*. Springer, Berlin, 2 edn.

- DARAIIO, C., AND L. SIMAR (2007): “Conditional Nonparametric Frontier Models for Convex and Nonconvex Technologies: A Unifying Approach,” *Journal of Productivity Analysis*, 28(1–2), 13–32.
- DE WITTE, K., AND R. MARQUES (2009): “Capturing the Environment, A Metafrontier Approach to the Drinking Water Sector,” *International Transactions in Operational Research*, 16(2), 257–271.
- DEBREU, G. (1951): “The Coefficient of Resource Utilization,” *Econometrica*, 19(3), 273–292.
- FAN, Y., AND A. ULLAH (1999): “On Goodness-of-fit Tests for Weakly Dependent Processes Using Kernel Method,” *Journal of Nonparametric Statistics*, 11(1), 337–360.
- FÄRE, R., S. GROSSKOPF, AND C. LOVELL (1983): “The Structure of Technical Efficiency,” *Scandinavian Journal of Economics*, 85(2), 181–190.
- FÄRE, R., AND D. PRIMONT (1995): *Multi-output Production and Duality: Theory and Applications*. Kluwer Academic Publishers, Boston.
- FULGINITI, L., AND R. PERRIN (1998): “Agricultural Productivity in Developing Countries,” *Agricultural Economics*, 19(1), 45–51.
- HACKMAN, S. (2008): *Production Economics: Integrating the Microeconomic and Engineering Perspectives*. Springer, Berlin.
- HAYAMI, Y., AND V. RUTTAN (1970a): “Agricultural Productivity Differences among Countries,” *American Economic Review*, 60(5), 895–911.
- (1970b): “Factor Prices and Technical Change in Agricultural Development: The United States and Japan, 1880-1960,” *Journal of Political Economy*, 78(5), 1115–1141.
- HUANG, C.-W., C.-T. TING, C.-H. LIN, AND C.-T. LIN (2013): “Measuring Non-Convex Metafrontier Efficiency in International Tourist Hotels,” *Journal of the Operational Research Society*, 64(2), 250–259.
- HUANG, M.-Y., AND T.-T. FU (2013): “An Examination of the Cost Efficiency of Banks in Taiwan and China using the Metafrontier Cost Function,” *Journal of Productivity Analysis*, 40(3), 387–406.

- HUANG, M.-Y., J.-C. JUO, AND T.-T. FU (2015): “Metafrontier Cost Malmquist Productivity Index: An Application to Taiwanese and Chinese Commercial Banks,” *Journal of Productivity Analysis*, 44(3), 321–335.
- HUNG, N., C. LE VAN, AND P. MICHEL (2009): “Non-convex Aggregate Technology and Optimal Economic Growth,” *Economic Theory*, 40(3), 457–471.
- KERSTENS, K., AND S. MANAGI (2012): “Total Factor Productivity Growth and Convergence in the Petroleum Industry: Empirical Analysis Testing for Convexity,” *International Journal of Production Economics*, 139(1), 196–206.
- KITTELSEN, S., B. WINSNES, K. ANTHUN, F. GOUDE, Ø. HOPE, U. HÄKKINEN, B. KALSETH, J. KILSMARK, E. MEDIN, C. REHNBERG, AND H. RÄTTÖ (2015): “Decomposing the Productivity Differences between Hospitals in the Nordic Countries,” *Journal of Productivity Analysis*, 43(3), 281–293.
- KNEIP, A., L. SIMAR, AND P. WILSON (2016): “Testing Hypotheses in Nonparametric Models of Production,” *Journal of Business & Economic Statistics*, 34(3), 435–456.
- KONTOLAIMOU, A., AND K. TSEKOURAS (2010): “Are Cooperatives the Weakest Link in European Banking? A Non-Parametric Metafrontier Approach,” *Journal of Banking & Finance*, 34(8), 1946–1957.
- KOUNETAS, K., I. MOURTOS, AND K. TSEKOURAS (2009): “Efficiency Decompositions for Heterogeneous Technologies,” *European Journal of Operational Research*, 199(1), 209–218.
- LATRUFFE, L., J. FOGARASI, AND Y. DESJEUX (2012): “Efficiency, Productivity and Technology Comparison for Farms in Central and Western Europe: The Case of Field Crop and Dairy Farming in Hungary and France,” *Economic Systems*, 36(2), 264–278.
- LAU, L., AND P. YOTOPOULOS (1989): “The Meta-production Function Approach to Technological Change in World Agriculture,” *Journal of Development Economics*, 31(2), 241–269.
- LEE, D., AND J. HWANG (2011): “Network Neutrality and Difference in Efficiency among Internet Application Service Providers: A Meta-Frontier Analysis,” *Telecommunications Policy*, 35(8), 764–772.
- LEE, S.-G., AND A. MIDANI (2015): “Comparison of Efficiency Levels Using Meta-Frontier Analysis of Global Fisheries for the Period 1960-2010,” *Fisheries Science*, 81(2), 247–254.

- LELEU, H. (2006): “A Linear Programming Framework for Free Disposal Hull Technologies and Cost Functions: Primal and Dual Models,” *European Journal of Operational Research*, 168(2), 340–344.
- LI, Q. (1996): “Nonparametric Testing of Closeness between Two Unknown Distribution Functions,” *Econometric Reviews*, 15(1), 261–274.
- LI, Q., E. MAASOUMI, AND J. RACINE (2009): “A Nonparametric Test for Equality of Distributions with Mixed Categorical and Continuous Data,” *Journal of Econometrics*, 148(2), 186–200.
- LLORCA, M., L. OREA, AND M. POLLITT (2014): “Using the Latent Class Approach to Cluster Firms in Benchmarking: An Application to the US Electricity Transmission Industry,” *Operations Research Perspectives*, 1(1), 6–17.
- MAYER, A., AND V. ZELENYUK (2014): “Aggregation of Malmquist Productivity Indexes Allowing for Reallocation of Resources,” *European Journal of Operational Research*, 238(3), 774–785.
- MOREIRA, V., AND B. BRAVO-URETA (2010): “Technical Efficiency and Metatechnology Ratios for Dairy Farms in Three Southern Cone Countries: A Stochastic Meta-Frontier Model,” *Journal of Productivity Analysis*, 33(1), 33–45.
- O’DONNELL, C. (2016): “Using Information About Technologies, Markets and Firm Behaviour to Decompose a Proper Productivity Index,” *Journal of Econometrics*, 190(2), 328–340.
- O’DONNELL, C., S. FALLAH-FINI, AND K. TRIANTIS (2017): “Measuring and Analysing Productivity Change in a Metafrontier Framework,” *Journal of Productivity Analysis*, 47(2), 117–128.
- O’DONNELL, C., D. RAO, AND G. BATTESE (2008): “Metafrontier Frameworks for the Study of Firm-Level Efficiencies and Technology Ratios,” *Empirical Economics*, 34(1), 231–255.
- OH, D.-H., AND J.-D. LEE (2010): “A Metafrontier Approach for Measuring Malmquist Productivity Index,” *Empirical Economics*, 38(1), 47–64.
- OREA, L., AND S. KUMBHAKAR (2004): “Efficiency Measurement Using a Latent Class Stochastic Frontier Model,” *Empirical Economics*, 29(1), 169–183.

- PASTOR, J. T., AND C. K. LOVELL (2005): “A Global Malmquist Productivity Index,” *Economic Letters*, 88(1), 266–271.
- RAY, S. (2004): *Data Envelopment Analysis: Theory and Techniques for Economics and Operations Research*. Cambridge University Press, Cambridge.
- RUYS, P. (1974): “Production Correspondences and Convex Algebra,” in *Production Theory: Proceedings of an International Seminar Held at the University at Karlsruhe May-July 1973*, ed. by W. Eichhorn, R. Henn, O. Opitz, and R. Shephard, pp. 231–252. Springer, Berlin.
- SALA-GARRIDO, R., M. MOLINOS-SENANTE, AND F. HERNÁNDEZ-SANCHO (2011): “Comparing the Efficiency of Wastewater Treatment Technologies through a DEA Meta-frontier Model,” *Chemical Engineering Journal*, 173(3), 766–772.
- SAMOILENKO, S., AND K.-M. OSEI-BRYSON (2010): “Determining Sources of Relative Inefficiency in Heterogeneous Samples: Methodology using Cluster Analysis, DEA and Neural Networks,” *European Journal of Operational Research*, 206(2), 479–487.
- SHEATHER, S. (2004): “Density Estimation,” *Statistical Science*, 19(4), 588–597.
- SHEPHARD, R. (1970): *The Theory of Cost and Production Functions*. Princeton University Press, Princeton.
- SIMAR, L., A. VANHEMS, AND I. VAN KEILEGOM (2016): “Unobserved Heterogeneity and Endogeneity in Nonparametric Frontier Estimation,” *Journal of Econometrics*, 190(2), 360–373.
- SIMAR, L., AND V. ZELENYUK (2006): “On Testing Equality of Distributions of Technical Efficiency Scores,” *Econometric Reviews*, 25(4), 497–522.
- THIEME, C., D. PRIOR, AND E. TORTOSA-AUSINA (2013): “A Multilevel Decomposition of School Performance Using Robust Nonparametric Frontier Techniques,” *Economics of Education Review*, 32, 104–121.
- TIEDEMANN, T., T. FRANCKSEN, AND U. LATA CZ-LOHMANN (2011): “Assessing the Performance of German Bundesliga Football Players: A Non-Parametric Metafrontier Approach,” *Central European Journal of Operations Research*, 19(4), 571–587.
- TRUEBLOOD, M. (1989): “Agricultural Production Function Estimates from Aggregate Inter-country Observations: A Selected Survey,” *Canadian Journal of Agricultural Economics*, 37(4), 1045–1060.

- TSEKOURAS, K., N. CHATZISTAMOULOU, AND K. KOUNETAS (2017): “Productive Performance, Technology Heterogeneity and Hierarchies: Who to Compare with Whom,” *International Journal of Production Economics*, 193, 465–478.
- VERSCHELDE, M., M. DUMONT, G. RAYP, AND B. MERLEVEDE (2016): “Semiparametric Stochastic Metafrontier Efficiency of European Manufacturing Firms,” *Journal of Productivity Analysis*, 45(1), 53–69.
- WARNING, S. (2004): “Performance Differences in German Higher Education: Empirical Analysis of Strategic Groups,” *Review of Industrial Organization*, 24(4), 393–408.
- ZELNYUK, V. (2006): “Aggregation of Malmquist Productivity Indexes,” *European Journal of Operational Research*, 174(2), 1076–1086.