After receipt of your corrections your article will be published initially within the online version of the journal.

**PLEASE NOTE THAT THE PROMPT RETURN OF YOUR PROOF CORRECTIONS WILL ENSURE THAT THERE ARE NO UNNECESSARY DELAYS IN THE PUBLICATION OF YOUR ARTICLE**

- **READ PROOFS CAREFULLY**
  - Once published online or in print it is not possible to make any further corrections to your article
  - This will be your only chance to correct your proof
  - Please note that the volume and page numbers shown on the proofs are for position only

- **ANSWER ALL QUERIES ON PROOFS** (Queries are attached as the last page of your proof.)
  - List all corrections and send back via e-mail to the production contact as detailed in the covering e-mail, or mark all corrections directly on the proofs and send the scanned copy via e-mail. Please do not send corrections by fax or post

- **CHECK FIGURES AND TABLES CAREFULLY**
  - Check sizes, numbering, and orientation of figures
  - All images in the PDF are downsampled (reduced to lower resolution and file size) to facilitate Internet delivery. These images will appear at higher resolution and sharpness in the printed article
  - Review figure legends to ensure that they are complete
  - Check all tables. Review layout, titles, and footnotes

- **COMPLETE COPYRIGHT TRANSFER AGREEMENT (CTA)** if you have not already signed one
  - Please send a scanned signed copy with your proofs by e-mail. Your article cannot be published unless we have received the signed CTA

- **AUTHOR SERVICES**
  - If you have registered this article in Wiley-Blackwell Author Services, the article's status will be updated shortly after you have returned your proof corrections (you will also receive an e-mail alert if you have opted to receive them). **You are entitled to free access to the PDF from Author Services when your article is published online.** This free access is considered your PDF offprint, and you will only have access from within Author Services; you will not be sent a PDF. You may also nominate up to 10 colleagues for free access. All accesses from Author Services count towards the usage of your article. For options to order print copies or additional electronic access, please see below.

- **OFFPRINTS**
  - Free access to the final PDF offprint of your article will be available via Author Services only. Please therefore sign up for Author Services if you would like to access your article PDF offprint and enjoy the many other benefits the service offers.

**Additional reprint and journal issue purchases**

- Should you wish to purchase a minimum of 100 copies of your article, please contact author_reprints@wiley.co.uk
- To purchase reprints in smaller quantities, please visit http://www3.interscience.wiley.com/aboutus/ppv-articleselect.html. Restrictions apply to the use of reprints – if you have a specific query, please contact permissionsuk@wiley.com.
- Corresponding authors are invited to inform their co-authors of the reprint options available
- To purchase a copy of the issue in which your article appears, please contact cs-journals@wiley.co.uk upon publication, quoting the article and volume/issue details
- Please note that regardless of the form in which they are acquired, reprints should not be resold, nor further disseminated in electronic or print form, nor deployed in part or in whole in any marketing, promotional or educational contexts without authorization from Wiley. Permissions requests should be directed to mailto: permissionsuk@wiley.com
Assessing the relative efficiency of energy use among similar manufacturing industries

Fernando Aguirre1, J. Rene Villalobos2,*,1, Patrick E. Phelan3 and Rafael Pacheco4,5

1US Airways, AZ 85281, U.S.A.
2International Logistics and Productivity Improvement Laboratory, School of Computing, Informatics and Decisions Systems Engineering, Arizona State University, Tempe, AZ 85287-8809, U.S.A.
3School of Mechanical, Aerospace, Chemical and Materials Engineering, Arizona State University, Tempe, AZ 85287-6106, U.S.A.
4School of Mathematical and Statistical Sciences, Arizona State University, Tempe AZ 85287, U.S.A.
5Environmental Fluid Dynamics Laboratories, The University of Notre Dame, South Bend, IN 46656, U.S.A.

SUMMARY

This article presents a methodology to measure relative industrial energy efficiency across plants within a manufacturing sector through the use of energy-production signatures (EPSs). Linear programming in combination with regression methods, benchmarking and simulation models are used to study the behavior of a representative manufacturing plant. The methodology is validated using data available from the Department of Energy database. The proposed EPSs can be used for proactive benchmarking and diagnostic purposes leading to improvements in energy consumption for individual companies. The results show that the proposed methodology successfully identifies energy and production inefficiencies within a manufacturing segment. Copyright © 2010 John Wiley & Sons, Ltd.

KEY WORDS

energy-production signatures; data envelopment analysis; aggregate efficiency decomposition model; manufacturing

Correspondence

*J. Rene Villalobos, International Logistics and Productivity Improvement Laboratory, School of Computing, Informatics and Decisions Systems Engineering, Arizona State University, Tempe, AZ 85287-8809, U.S.A.
E-mail: rene.villalobos@asu.edu

Contract/grant sponsor: US Department of Energy, through the Arizona State University Industrial Assessment Center

Received 1 September 2009; Revised 27 January 2010; Accepted 6 February 2010

1. INTRODUCTION

One of the main drivers for the most improvement projects across all industry segments is the desire to increase productivity of the processes used to manufacture or assemble a product so that the cost per unit produced is minimized and/or the revenues are maximized. These improvements can come in a variety of ways, including lowering costs, increasing yields and reducing energy-use costs. Some of the improvements can be identified as energy efficient because they reduce the use of energy per part processed. The implementation of energy-efficient improvement projects are usually subject to maintaining or increasing the productivity, in terms of dollars per part produced, of the underlying industrial process. However, the output level of a manufacturing facility is not set to a fixed value over time but varies over a range because of demand, raw materials scarcity, etc. For this reason, we believe that any energy-efficient improvement project should not just target energy-use improvements at a particular expected output but to consider all the range of production outputs expected of a given process. Thus, an energy-efficiency analysis should include the energy consumed at different levels of production before making decisions, such as the manufacturing technology to use. For instance the energy used at different production levels could be used to developed energy-production signatures (EPS) that could be compared with 'desired' signatures to identify efficiency gaps. In other words, current and desired EPSs for a particular process should be developed as a first step to identify the
proper technology used in the process to attain an overall 'efficiency'. Because developing the ideal EPS would be a difficult task, among other factors for lack of knowledge of the most advanced technologies, the EPS of known similar operations could be used instead to identify potential energy-use improvements. This is the underlying premise of this article, i.e. that there is enough information to compare the current EPS of a current operation (plant) with a real ‘best-in-class’ manufacturing plant. One of the problems with this approach is that companies are usually reluctant to share information with competitors. One way to circumvent this problem is by using data readily available to construct EPS for different manufacturing segments. Once these EPSs are available then each individual company could use it to benchmark its performance against the proper manufacturing segment.

In this article, data gathered during periodical assessments performed by the US Department of Energy Industrial Assessment Center (IAC; http://iac.rutgers.edu/) will be used to acquire the necessary time series and plant level production information needed to create EPSs as a first step to utilize them for productivity enhancement and energy-saving purposes. These EPSs will point specific industry sectors to a common direction and serve as a benchmark for analysis, prompt comparison and, if necessary, correction of malpractices [1]. With said EPSs essentially functioning as diagnostic tools, the relation between resource use (energy and production) is estimated and pre-evaluated. For instance, the energy use of a particular company could be compared with the ‘best practices’ to reveal energy-efficiency gaps. Our intention is to provide a tool to identify the existence of said gaps and set the basis for continuous improvement strategies for manufacturing plants regarding energy use. In particular, the objective of the research described in this article is the development of a diagnostic tool that will facilitate energy audits by revealing potential areas of improvement within a manufacturing facility before even visiting the manufacturing facility. For instance if historical production and energy consumption are available for a manufacturing site, the EPS of the site could be developed and compared with that of the corresponding signature of a ‘similar’ manufacturing segment. This comparison would be used as a benchmark and to alert energy-efficient concerned managers towards specific problems and possible continuous improvement strategies for the firm. Specifically, the existence of such signatures would help to determine at what production levels a particular operation is less efficient than their potential competitors. The identification of energy use–production efficiency gaps would trigger an investigation of the underlying reasons for the inefficiencies detected and eventually lead to an increase in efficiency after corrective measurements have been implemented. Consequently, the reduction in the plant’s energy intensity will result in minimizing energy consumption per unit produced. Furthermore, energy efficiency projects may increase competitiveness and may provide for the long-term health of the industry and its workers.

Figure 1 depicts how a tool based on the EPSs would work [1]. Using data from a specific industry sector, a signature would be created as shown by the solid line. This function describes the suggested energy intensity of an industry sector at different production levels. The signatures of two different manufacturing plants (represented by dotted and dashed lines) reveal their performance compared with the reference signature of an industry ‘x’. The plant represented by the dotted line signature is more energy efficient than the reference operation at low production levels, while its competitor (dashed line) transforms energy into production more efficiently at high production levels. Additionally, the existence of the proper EPS will aid a firm to benchmark itself against its top competitors. Thus, the firm will be able to see how efficient or inefficient it is compared with its competitors but, also, potentially will be able to identify the cause for that inefficiency.

2. BACKGROUND

The work presented in this article has practical and theoretical motivations. In this section we provide a brief review of previous works in areas related to the research presented in this article.

The work by Boyd and Pang [2] is recognized by several authors as the leading research effort related to industrial energy use. He suggests that it is desirable to have measures of energy intensity that indicate where a company or plant lies within a distribution of energy-use performance. Following his suggestions, the methodology presented in this article would ultimately reflect the position a given company belongs in terms of energy efficiency by benchmarking his operations to similar operations through the use of the appropriate EPSs.

The findings presented by Worrell et al. [3] illustrate the fact that productivity benefits can be obtained from energy-efficiency investments without making significant process changes. These types of improvements are collectively referred to as ‘productivity benefits’ or ‘non-energy benefits’, because in addition to reducing energy consumption they all increase the productivity of the firm. As a mean of comparison, Papadaratsakis et al. [4]
suggests that the ideal goal of any energy-use improvement program is to increase industrial productivity while at the same time decreasing energy consumption. He proposes an effective energy savings method in which energy accounting can be applied to yield an energy savings based on the plant’s current conditions and productivity recommendations. In his article, it is explained how a technical assistance program could aid industry on a plant-by-plant basis to reduce its energy intensity and generate potential effective energy savings.

Several authors, for instance [5,6], have explored the relationship between industrial productivity and energy efficiency. Their works suggest that making the appropriate energy-efficient investments can also provide a significant boost to overall industrial productivity. For instance, Boyd and Pang [5] maintains that identifying energy-efficient technologies as opportunities for productivity improvements has significant implications for conventional economic assessments. Given the difficulty in determining a causal or direct linkage, the experimental validation of how differences in energy efficiency are correlated with differences in productivity is still important. This empirical validation needs to be as general as possible, because there are important policy implications. However, it is reasonable to expect that any link between energy efficiency and productivity will be industry-specific, as is the case of energy use in those sectors.

Productivity benefits in the evaluation of energy-efficient measures leads to a more accurate understanding of cost-effective energy savings potential across an industry. However, as there are limitations and complicating factors that make the assessment of these productivity benefits and their incorporation into a quantitative analytical framework difficult [5], special attention should be paid to how these complications are addressed.

One complication is the uncertainty in evaluating certain productivity benefits. Within a cost curve methodology suggested by Worrell et al. [3], it is necessary to evaluate the monetary value of all productivity benefits but not all these benefits are easily quantified in financial terms. The previous literature review shows the relationship between production level and energy consumption has been recognized as important, but the construction of ‘signatures’ to explain and assess an efficient signature had not been attempted. This article provides the methodological framework to develop ‘EPSs’ for homogenous segments of industry for the identification of productivity improvement opportunities as a first step for the development of continuous energy-utilization improvement systems.

3. PROBLEM FORMULATION AND SOLUTION METHODOLOGY

The aim of this article is to present a methodology for the development of EPSs that relate total energy consumption to production output. The overall goal of the methodology is to provide a tool for benchmarking and diagnosis that would lead to a continuous improvement strategy for the firm.

A central premise of the development of the methodology is that there is enough information to build representative EPSs. We will make use of the assessment data collected through the years by the IAC program for the development of these signatures. For instance, the IAC database of Arizona State University contains data derived from around 400 industrial site visits and more than 3000 assessment recommendations. Each assessment includes total energy costs, production output, size of plant area and labor force (number of employees) among other important factors that will be used in the development of EPSs.

In general the methodology to be presented consists of the following steps:

1. Determine the general characteristics of the operation being analyzed and the manufacturing sector using the corresponding SIC code
2. Use the data envelopment analysis (DEA) to measure the relative efficiency of an operation within the manufacturing sector
3. Apply multivariate linear regression to determine the relevant factors determining the overall DEA efficiency score
4. Based on the relevant factors identified, build virtual producers and their corresponding EPSs
5. Compare the resulting EPSs against those of similar or virtual producers

In this article, we present focus on steps 1 through 5. The first step focuses on problem definition and establishing the boundaries of the problem to be studied. In this phase of the problem, the type of operation being analyzed and its corresponding SIC (or NAICS) is determined. Once this information is available, the second step determines a relative measure of the efficiency of the operation under analysis when compared with other companies within its sector. The third step focuses on determining those factors of the operation that impact the efficiency of the operation under study. The objective of this phase of the analysis is to create homogeneous groups of plants that can be directly compared in a single sector. The fourth factor aims to develop a range of values for the metric energy utilization/piece for a comparable operation. This comparable operation is a virtual producer developed by using the results of the DEA and the multiple regression analyses. Finally, the fifth step consists of comparing the signature of the operation under consideration against that of the virtual producer to determine opportunities for improvement of the operation under study.

The methodology to be presented is meant to be used with and will be exemplified through the use of
data for a particular industry sector (SIC 3354: Alumi

4. DETERMINATION OF THE

5. DEVELOPMENT OF DEA MODELS

Assessing the relative efficiency of energy
used to construct a virtual firm as a combination of 'efficient' plants against which particular plants can be compared. Table I presents the results of applying the DEA analysis to 38 extrusion plants audited by the IAC program. The data under the label 'ID' represent a coded identification number for each of the plants considered. The data under the label 'Efficiency' represent the overall efficiency score rendered by the DEA. As can be seen from this table different plants achieve a 'perfect' efficiency score of one. This score is only a relative score that represents that a particular plant is best-in-class, with the available data, in one or more dimensions measured by the DEA model. One of the problems in directly using the overall efficiency scores is that they do not provide by themselves, an indication of what particular input/output should be targeted for improvement. For instance, the plant 'SD0250' obtained a DEA efficiency score of 0.470. Although this score tells us that this plant is underperforming, it does not tell us anything about how to focus the efforts to improve this plant. The next phases of the study will shed light on this issue by dissecting the overall DEA score on components that are conducive to process improvement.

### Table I. Overall efficiency scores for 38 aluminum extrusion plants.

<table>
<thead>
<tr>
<th>ID</th>
<th>Efficiency</th>
<th>ID</th>
<th>Efficiency</th>
<th>ID</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>TN0492</td>
<td>1.00</td>
<td>GT0402</td>
<td>0.76</td>
<td>UF0323</td>
<td>0.43</td>
</tr>
<tr>
<td>AS0314</td>
<td>0.52</td>
<td>AS0032</td>
<td>0.36</td>
<td>HO0211</td>
<td>0.67</td>
</tr>
<tr>
<td>UM0227</td>
<td>0.46</td>
<td>ND0007</td>
<td>0.52</td>
<td>GT0674</td>
<td>0.57</td>
</tr>
<tr>
<td>SD0162</td>
<td>0.72</td>
<td>GT0681</td>
<td>0.58</td>
<td>AS0071</td>
<td>0.37</td>
</tr>
<tr>
<td>SD0032</td>
<td>0.51</td>
<td>MI0026</td>
<td>1.00</td>
<td>SD0276</td>
<td>0.82</td>
</tr>
<tr>
<td>AS0105</td>
<td>0.24</td>
<td>NC0251</td>
<td>0.25</td>
<td>AM0477</td>
<td>0.67</td>
</tr>
<tr>
<td>KU0245</td>
<td>0.23</td>
<td>SD0310</td>
<td>0.43</td>
<td>IC0400</td>
<td>0.47</td>
</tr>
<tr>
<td>MO0178</td>
<td>0.48</td>
<td>UL0174</td>
<td>0.53</td>
<td>AM0199</td>
<td>1.00</td>
</tr>
<tr>
<td>LT0030</td>
<td>0.18</td>
<td>UM0127</td>
<td>0.42</td>
<td>WV0226</td>
<td>0.53</td>
</tr>
<tr>
<td>OK0517</td>
<td>0.40</td>
<td>SD0313</td>
<td>0.90</td>
<td>AS0229</td>
<td>0.82</td>
</tr>
<tr>
<td>WV0036</td>
<td>0.32</td>
<td>AS0033</td>
<td>1.00</td>
<td>UF0233</td>
<td>0.82</td>
</tr>
<tr>
<td>UU0010</td>
<td>0.62</td>
<td>AS0292</td>
<td>1.00</td>
<td>UF0290</td>
<td>1.00</td>
</tr>
<tr>
<td>GT0253</td>
<td>0.39</td>
<td>AS0293</td>
<td>1.00</td>
<td>UF0302</td>
<td>0.97</td>
</tr>
<tr>
<td>UD0238</td>
<td>0.44</td>
<td>AS0291</td>
<td>1.00</td>
<td>GT0715</td>
<td>0.82</td>
</tr>
<tr>
<td>MI0033</td>
<td>0.90</td>
<td>SD0256</td>
<td>0.70</td>
<td>AT0039</td>
<td>1.00</td>
</tr>
<tr>
<td>DS0025</td>
<td>0.63</td>
<td>OD0167</td>
<td>1.00</td>
<td>MS0194</td>
<td>0.87</td>
</tr>
<tr>
<td>UU0042</td>
<td>0.70</td>
<td>SD0250</td>
<td>0.47</td>
<td>NC0045</td>
<td>1.00</td>
</tr>
<tr>
<td>UM0053</td>
<td>0.64</td>
<td>ND0361</td>
<td>0.81</td>
<td>CO0473</td>
<td>1.00</td>
</tr>
<tr>
<td>AM0330</td>
<td>0.48</td>
<td>SD0300</td>
<td>0.72</td>
<td>OR0274</td>
<td>1.00</td>
</tr>
</tbody>
</table>

being analyzed. However, the DEA results are the first step of a more precise analysis, which segments the overall efficiency analysis into a cluster of similar plants. To achieve this objective, the DEA relative efficiency is decomposed into more meaningful components through the use of a technique called the stochastic frontier regression analysis. The stochastic frontier analysis was first used by Aigner et al. [11] to assess productivity efficiency and very recently it has been used by Boyd [12] to estimate plant level energy efficiency. In our case, the stochastic frontier regression analysis separates the relative efficiency into three components: systematic economic effects, systematic productivity variables and a statistical random error. This is performed through the use of traditional linear regression models to obtain the relationship between these components. In particular, the linear regression model used in the analysis is given in Equation 5:

$$ A_i = \beta_0 + \beta_1 Y_{it} + \beta_2 Z_{it} + \epsilon_i $$

where \( A \) is the vector for the relative efficiency depicted from the DEA model, \( Y \) is the vector of systematic economic effects, \( Z \) is the vector of systematic productivity effects, \( \beta \) is the vector of parameters to be estimated, and \( \epsilon \) is a typical random error term \( \sim N(0, \sigma^2) \).

This model implies that the overall efficiency of an operation can be decomposed into economic and productivity factors. In general, economic factors are those that are part of the environment in which a firm operates and are difficult to change in the short term. Examples include physical infrastructure, such as buildings, or climate related, such as mean average temperature. On the other hand, productivity factors are those that are usually related to the day-to-day operation of a firm and are easier to change in the short term, such as production scheduling or frequency of maintenance operations. The method to follow to determine the values for each of the previous factors is explained next and the results can be seen in Figure 2.

### 7. DECOMPOSITION METHOD BASED ON MULTIVARIATE REGRESSION ANALYSIS

To determine the contribution of each economic and productivity factor to the overall efficiency of an operation it is necessary to use the aggregate efficiency, \( \text{Eff}_{tot} \). A manufacturing sector’s aggregate efficiency is a key parameter for describing and finding an overall industrial energy efficiency within an industry sector [13,14]. As mentioned earlier, the weight on the model of the systematic economic variables and productivity efficiency variables, the aggregate efficiency can also be disaggregated into clusters; all plants of any one cluster should have approximately similar aggregate efficiency. The decomposition analysis aims to breakdown the factors...
driving the results of the linear regression. The regression variables used in the DEA model are the following:

- Number of Employees (EM), Plant Area (PS), Production Hours (PH).
- Total Energy Cost (ES), Total Sales (P), Production Level (Q) and Number of Assessment Recommendations (AR) made by the IACs in the audits considered in the study.

Although there are potentially many factors that affect the relationship production/energy consumption, the reasons that the previous factors were selected include that they are readily available and that they were hypothesized to render enough explanatory power to be able to construct a reasonable relationship energy consumption versus production level. The level of explanatory power that these variables provide is explored later in this article through the use of an analysis of variance.

In particular, the following relation is used to estimate the productivity efficiency variables effect on the aggregate efficiency differential between plants 0 and n:

$$(\Delta \text{Eff}_{\text{prod}})_{0,n} = \sum_{j=0}^{j=n} \left[ \mu_j (P_j - P_{j-1}) + \mu_q (Q_j - Q_{j-1}) - \mu_{ar} (\text{AR}_j - \text{AR}_{j-1}) \right],$$

where $\mu_{j,em}, \mu_{q,ar}$, and $\mu_{ar}$ are the average productivity efficiency variable weights of the production output levels, $P$, $Q$, AR, for $N$ firms at the disaggregated level. Also notice that the last term is negative, this is because usually the more efficient the operation of a plant is, the less AR it gets. A more profound analysis into these recommendations, such as investment amount per DMU (S/DMU) could easily reveal more regarding any given plant’s operation, but for now the number of recommendations suffices to satisfy the scope of the research.

Alternatively, a second regression model is used to explain the relation between aggregate efficiency $\text{Eff}_{\text{tot}}$ of a plant and those factors likely to affect it. These variables are related to $\text{Eff}_{\text{tot}}$ through the following multivariate regression model:

$$(\text{Eff}_{\text{tot}})_z = \mu_0 + \mu_1 (\text{EM})_z + \mu_2 (\text{PS})_z + \mu_3 (\text{PH})_z + \mu_4 \times (\text{ES})_z + \mu_5 (P)_z + \mu_6 (Q)_z + \mu_7 (\text{AR})_z + \epsilon_z,$$ (7)

where $\mu_0$ is the regression model intercept, $\mu_j$ the regression model coefficient of the $j$th variable ($j = 1, 2, \ldots, m + s$) for energy cost (ES), number of AR’s (AR), plant size (PS), production hours (PH), sales (P), output level (Q) and number of employees (EM) variables, respectively and $\epsilon_z$ the difference between the actual efficiency and the predicted efficiency.

Using the data from the IAC database previously described, Equations 6 and 7 become:

$$(\Delta \text{Eff}_{\text{prod}})_{0,n} = \mu_\phi (P_n - P_0) + \mu_q (Q_n - Q_0) + \mu_{ar} \times [\text{AR}_n - \text{AR}_0],$$ (8)

and

$$(\text{Eff}_{\text{tot}})_1 = \mu_0 + \mu_1 (\text{EM})_1 + \mu_2 (\text{PS})_1 + \mu_3 (\text{PH})_1 + \mu_4 (\text{ES})_1 + \mu_5 (P)_1 + \mu_6 (Q)_1 + \mu_7 (\text{AR})_1 + \epsilon_1,$$

$$(\text{Eff}_{\text{tot}})_2 = \mu_0 + \mu_1 (\text{EM})_2 + \mu_2 (\text{PS})_2 + \mu_3 (\text{PH})_2 + \mu_4 (\text{ES})_2 + \mu_5 (P)_2 + \mu_6 (Q)_2 + \mu_7 (\text{AR})_2 + \epsilon_2,$$

$$(\text{Eff}_{\text{tot}})_n = \mu_0 + \mu_1 (\text{EM})_n + \mu_2 (\text{PS})_n + \mu_3 (\text{PH})_n + \mu_4 (\text{ES})_n + \mu_5 (P)_n + \mu_6 (Q)_n + \mu_7 (\text{AR})_n + \epsilon_n$$ (9)

where $\mu_{ph,em}$ represent the contribution of each of the independent variables to the regression function and $\mu_j (P_n - P_0) + \mu_q (Q_n - Q_0) + \mu_{ar} [\text{AR}_n - \text{AR}_0]$, the productivity efficiency variables’ output ratios of the gap between the best and the most inefficient firms, respectively.
The systematic economic variables are calculated as the difference between the actual aggregate efficiency change, \((\Delta \text{Eff}_\text{tot})_{h,n}\), (which is known, \(A_n - \lambda_0\)) and the estimated productivity efficiency variables effect (Equation 10), i.e.

\[
(\Delta \text{Eff}_\text{con})_{h,n} = (\Delta \text{Eff}_\text{tot})_{h,n} - (\Delta \text{Eff}_\text{prod})_{h,n} \quad (10)
\]

The model given by Equation 5 allows us to predict the degree of relative departure from the best practice. An example of the results of the frontier regression is depicted in Figure 3. The information presented in Figure 3 have been sorted from the lowest DEA efficiency score (left) to the highest score (right). The graph superimposes the efficiency scores obtained from the DEA analysis \(\lambda\), the efficiency scores obtained by the linear regression \(A\) and its decomposition into productivity \(Z\) and economic effects \(Y\), as well as an error term \(\epsilon\).

The choice of variables in the Y vector may include energy prices, plant scale (measured by output) and other output/input ratios, such as capital, materials and labor. Because energy consumption may be influenced by climate (e.g. as in Arizona), as well as production activity, state-level data on heating and cooling degree-days could be included in the energy intensity regression in the Y vector.

For instance in Figure 3 the third point from the left represents the operation of a plant with ID ‘AS0105’. This particular plant has an overall efficiency of 0.235, a systematic economic value of \(-0.33\) and a systematic productivity value of \(-0.07\). The resources being used by this plant are low, but the productivity is also very low compared with its peers. Thus, the model classifies the plant with a poor overall efficiency score. As expected, from an efficiency point of view, if the systematic economic effects \(Y\) become more negative and the productivity effects do not increase positively, the overall efficiency will be affected negatively as seen in this example. It is then intuitive that the value of the economic effects will be negative in the graph because all plants need to consume energy and resources to produce something. We also observe that this trend is almost a mirror image of its counterpart, the systematic productivity effects \(Z\). Thus, as production increases, usually more resources are needed and consequently \(Z\) and \(Y\) will grow apart in Figure 3.

### 8. AGGREGATE EFFICIENCY DECOMPOSITION MODEL

Once the overall efficiency of an operation has been determined, it is necessary to use the aggregate efficiency \(\text{Eff}_\text{tot}\) to determine if some plants can be clustered together. Doing this will reduce errors resulting from comparing two very different plants using the same ‘scale’ (e.g. measuring the efficiency of an outlet of a national chain against a pure local operation).

Ideally, in order to estimate the systematic economic variables and productivity efficiency variables, the aggregate level should be disaggregated into homogeneous clusters with similar aggregate efficiencies. The aggregate efficiency change between plant 0 and \(N\) may be expressed as follows:

\[
(\Delta \text{Eff}_\text{tot})_{h,n} = (\Delta \text{Eff}_\text{con})_{h,n} + (\Delta \text{Eff}_\text{prod})_{h,n} + (\Delta \text{Eff}_\text{err})_{h,n} \quad (11)
\]

where

\[
(\Delta \text{Eff}_\text{tot})_{h,n} = (\text{Eff}_\text{tot})_{h,n} - (\text{Eff}_\text{tot})_0, \quad (12)
\]

\[
(\text{Eff}_\text{tot})_2 = A \quad (13)
\]

![Figure 3. Decomposition of regression analysis of DEA results.](Image)
in which \( \Delta \text{Eff}_{\text{tot},0} \) is the total change in the aggregate efficiency between plant \( n \) and the company or plant that is being compared to \( 0 \). \( \Delta \text{Eff}_{\text{prod}} \) is the contribution of the systematic economic variables to the efficiency differential, \( \Delta \text{Eff}_{\text{err}} \) is the contribution of the productivity variables and \( \Delta \text{Eff}_{\text{res}} \) is the residual. \( \text{Eff}_{\text{tot}} \) is the total aggregate efficiency for plant \( z \), and \( \lambda \) is the efficiency measure found by the DEA method for plant \( z \). While Equation 11 represents an individual segment decomposition that uses only the data of the target and base plants, the same equation can be modified to represent a series of efficiency decompositions for the cumulative efficiency change of each plant. For instance, the cumulative efficiency change between plants \( 0 \) and \( n \) can be decomposed as:

\[
(C_{\text{tot}})_{0,n} = (C_{\text{ecn}})_{0,n} + (C_{\text{prod}})_{0,n} + (C_{\text{err}})_{0,n},
\]

where

\[
(C_{\text{tot}})_{0,n} = (\Delta \text{Eff}_{\text{tot}})_{0,1} + (\Delta \text{Eff}_{\text{tot}})_{1,2} + \cdots + (\Delta \text{Eff}_{\text{tot}})_{n-1,n},
\]

\[
(C_{\text{ecn}})_{0,n} = (\Delta \text{Eff}_{\text{ecn}})_{0,1} + (\Delta \text{Eff}_{\text{ecn}})_{1,2} + \cdots + (\Delta \text{Eff}_{\text{ecn}})_{n-1,n},
\]

\[
(C_{\text{prod}})_{0,n} = (\Delta \text{Eff}_{\text{prod}})_{0,1} + (\Delta \text{Eff}_{\text{prod}})_{1,2} + \cdots + (\Delta \text{Eff}_{\text{prod}})_{n-1,n},
\]

\[
(C_{\text{err}})_{0,n} = (\Delta \text{Eff}_{\text{err}})_{0,1} + (\Delta \text{Eff}_{\text{err}})_{1,2} + \cdots + (\Delta \text{Eff}_{\text{err}})_{n-1,n},
\]

where \( (C_{\text{tot}})_{0,n} \) is the cumulative efficiency total change between plants \( 0 \) and \( n \), \( (C_{\text{ecn}})_{0,n} \) the cumulative systematic economic variable change between plants \( 0 \) and \( n \), \( (C_{\text{prod}})_{0,n} \) the productivity efficiency variable change between plants \( 0 \) and \( n \) and \( (C_{\text{err}})_{0,n} \) the cumulative residual factor change between plants \( 0 \) and \( n \).

Decomposition analysis based on a multivariate regression model is then used to estimate the contribution of \( \Delta \text{Eff}_{\text{ecn}} \), \( \Delta \text{Eff}_{\text{prod}} \) and \( \Delta \text{Eff}_{\text{err}} \) for each plant.

As mentioned earlier, in order to estimate the contribution of the systematic economic variables and productivity efficiency variables fairly, the aggregate level should be disaggregated into clusters; all plants belonging to any one cluster should have approximately similar aggregate efficiency signatures.

Figure 3 shows how each plant’s aggregate efficiency is broken down into their corresponding systematic economic variables Eff_Econ and Y and productivity efficiency variables Eff_Prod or Z. This figure also shows that the graph can be decomposed into three homogenous regions. The following observations can be derived from Figure 4.

1. As the value of productivity efficiency variables increase, the aggregate efficiency does not necessarily follow that trend. It is clear how the industry is segmented into different regions as \( \text{Eff}_\text{prod} = 0 \) (separated by purple vertical lines). Each change is characterized by a drop in the aggregate efficiency. As seen in Figure 4, segmentation occurs when a steep change takes place in the Eff_Econ. In both cases, the vertical line lies at the point where the largest negative change occurs. The first segmentation occurs when Eff_Econ drops from \(-55\%\) and the second by a drop from \(-34\%\) to \(-58\%\). A reasonable assumption for this decrease in aggregate efficiency is the saturation of resources at a given production output level (beginning of each segment), thus resulting in lower efficiencies.

2. At the same break points that are illustrated below, the Eff_Econ variable can be seen gradually decreasing and their means becoming somewhat stationary over those specific regions (green hor-
Horizontal bars show the mean. This can be interpreted in conjunction with the previous statement in point number 1. At each segment, it can be predicted that firms are using on average the same amount of resources (systematic economic variables are \(-38\%\) for the segment in the left, \(-44\%\) for the segment in the middle and \(-60\%\) for the segment in the right).

Note that each segment has now at least one firm with 100\% relative efficiency. All the other firms in each segment can now be benchmarked against the ‘most efficient’ in their group.

3. Figure 4 also shows that the relation of Eff_Econ, Eff_Prod and Eff_Tot holds for Equation 5 and Equation 13. Eff_Tot is then the relation of its systematic economic and productivity efficiency variables and is directly related to the real efficiency value calculated by the DEA \(\lambda\). The difference between Eff_Tot and \(\lambda\) is characterized by the error generated by the regression model.

9. CUMULATIVE EFFICIENCY DECOMPOSITION MODEL

Although the previous section represents a firm-by-firm decomposition that uses only the data for each specific firm, the same equation can be modified to represent the relative efficiency differential between consecutive firms which in this case is called the cumulative efficiency change, \((C_{\text{tot}})_{i,i+1}\) between firms \(i\) and \(i+1\). \((C_{\text{econ}})_{i,i+1}\) then describes the cumulative systematic economic change between firms \(i\) and \(i+1\) and \((C_{\text{prod}})_{i,i+1}\) the cumulative productivity efficiency change between firms \(i\) and \(i+1\).

Figure 4 depicts the behavior of the relative change of efficiencies between firms sorted from decreasing to increasing order of productivity efficiency. This graph simply depicts the gradual increase in the gap between firms as efficiency starts to increase. This gap is the reflection of the difficulty to jump from a lower efficiency level to a higher one.

On the other hand, Figure 5 shows another but equally important point. If the same data are ordered in a different manner, it is clear that the differential between adjacent firms have on average the same value:

- \(\pm 22\%\) Mean change in cumulative systematic economic variables (dotted line ~ Figure 5)
- \(\pm 25\%\) Mean change in cumulative productivity efficiency variables (dashed line ~ Figure 5).

Thus, it can be concluded that on average the cumulative total value change is \(\pm 3\%\) (\(\pm 25\%\) to \(\pm 22\%\)). The calculated real value of efficiency change between adjacent firms is \(\pm 1.4\%\). The difference between these two numbers is due to the cumulative error factor in our original model. This information supports the hypothesis of segmentation proposed in the previous section. That is, the analysis shows a gradual change in the nature of the industries, rather than a radical one. If this were not true, then every firm would be in a segment by itself and therefore a direct benchmark using the proposed methodology would not be feasible.

10. DEA OF ALUMINUM EXTRUSION RESULTS

In this section we present a case study of the overall methodology applied to the aluminum extrusion industry. This industry was selected because it is energy intensive and there is an abundance of audit data in the
IAC database. Specifically, for this case study we use information of 38 audits conducted by several IAC sites.

The relative efficiency of each plant was calculated using LP and the results were already presented in Table I. This table shows in the shaded columns labeled Efficiency the corresponding value for each corresponding firm. Using this result will be the starting point of the analysis that will further extend our understanding of this particular industry.

The next step of the methodology consists of fitting a first-order multivariate regression model to further analyze the disaggregated data rendered by the DEA results. The results of the regression model are then used to predict the relative efficiency of a plant using the parameters given in the IAC database. The distribution of the random error exhibits a normal distribution pattern with a standard deviation of 0.15 or 15%. Table II presents the summary of the results of the analysis of variance.

The variables *Employees* and *Energy* were the only independent variables found to be not significant at the 0.05 level. This was somewhat expected, as both variables have the largest relative standard deviations of the sample (24.99% and 24.15%, respectively). These two variables were removed from the final linear regression model.

Most importantly they will not serve as overall predictor factors when the model becomes decomposed into its systematic economic and productivity efficiency effects.

### 11. FIRM SIGNATURES

As shown in the previous sections, using information from other plants and feeding it into the model will tell us a good deal of how well another plant is managed. Performing such analysis effectively establishes that a plant is relatively efficient in comparison with its competitors in the corresponding industry segment or cluster. EPSs can provide that relative efficiency that can indicate exactly where a candidate is more or less efficient than its competitors.

To illustrate the development of EPSs, we have further applied the methodology to each segmented cluster found in the aluminum industry. Figure 6 shows two EPSs for two clusters of firms in the Aluminum Industry. The EPSs in this example are based on the total sales of a plant (production) versus energy costs. The crosses in the figure represent the real data points used to develop the signatures.

These signatures can be used for individual plants to assess their standing against others in their corresponding industry segment or cluster and as a first step of a continuous improvement process of the way energy is converted into production. For a more detailed explanation of the results, the reader is referred to [1].

### 12. ERROR ANALYSIS AND VALIDATION

To verify the regression models, three different tests were conducted on the models and the experimental errors or residuals: underlying assumptions validation, outlier analysis and multicollinearity. Each of these tests is summarized next.

#### 12.1. Assumptions validation

Multivariate regression analysis uses the ANalysis Of Variance (ANOVA) tool to testify the validity and significance of the model. ANOVA is based on some assumptions, such as the residuals being normally distributed and having constant variance. A graphical analysis of the residuals was carried out for each of the regression models to check these assumptions, giving satisfactory results. For example, Figure 7 shows the residuals versus the fitted values for the DEA model. Because the residuals are contained within a horizontal band, the constant variance assumption is satisfied. Figure 8 shows the normal probability plot for the DEA model. Figure 8 shows a standard error analysis in which the residuals are plotted in normal (Gaussian) scale where the straight line represents a perfect match.
Because the cumulative normal distribution is approximately a straight line, there are no reasons to suspect that the normality assumption is violated.

12.2. Outlier, leverage and influence points diagnosis (unusual points)

Only three leverage and influence points were detected in the regression model. On further analysis it was determined that these outliers caused no significant changes in the model if deleted from the model.

12.3. Multicollinearity

The analysis of variation inflation factor on the regression model gave values of less than 10 as shown in Table II. Thus, it was deemed that there was not a significant multicollinearity problem [15].

13. CONCLUSIONS AND FUTURE RESEARCH

The results presented indicate that a great potential exists for the creation of EPSs that relate total energy consumption to production output. These signatures can be used as a benchmark and to point energy-efficient concerned managers towards a continuous improvement strategy for the firm. This tool reaches its maximal potential when the data from a specific industry is readily available and accurate in sources such as but not limited to the IAC database.

The methodology developed classified all the plants in the Aluminum Extrusion industry sample with their relative efficiency. EPSs were created for this industry to avoid the large gap between lower production level plants and larger ones. Potentially, there can be more than two EPSs for any given industry.

In conclusion, we believe that the article presented can be of great benefit to any kind of industry to identify gaps and potential areas for improvement.

In terms of future research, there is extensive work that can be done in the area of tool development for energy efficiency benchmarking and continuous improvement. This is especially true now in that renewed attention is being paid to the existing energy-efficiency gap between actual and optimal energy use in most industries. EPSs can serve as a useful tool to quickly identify the range of efficiency in which a plant can operate. These signatures can be further analyzed and broken down into lower levels that can potentially identify new sources of inefficient practices.

The use of the IAC database provides any scholar, researcher, manager or anyone who is interested with a wide range of information that can be filtered according to one’s needs. This article focused on a limited amount of information, but further factors can be added to the analysis or can be interchanged given the needs and characteristics of the industry in study.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the partial support provided by the US Department of Energy, through the Arizona State University Industrial Assessment Center. This material was based in part on work supported by the National Science Foundation, while one of the authors (P. E. P.) was working at the Foundation. Any opinion, findings and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

REFERENCES


<table>
<thead>
<tr>
<th>Query No.</th>
<th>Details required</th>
<th>Author’s response</th>
</tr>
</thead>
<tbody>
<tr>
<td>AQ1</td>
<td>Please check whether the affiliations are OK as typeset.</td>
<td></td>
</tr>
<tr>
<td>AQ2</td>
<td>The abbreviations “PA” and “PS” both have been used for the spelled-out form “plant size”. Please check.</td>
<td></td>
</tr>
</tbody>
</table>
COPYRIGHT TRANSFER AGREEMENT

Date: ____________________________  Contributor name: ____________________________

Contributor address: ____________________________

Manuscript number (Editorial office only): ____________________________

Re: Manuscript entitled ____________________________ (the "Contribution")

for publication in ____________________________ (the "Journal")

published by ____________________________ ("Wiley-Blackwell").

Dear Contributor(s):

Thank you for submitting your Contribution for publication. In order to expedite the editing and publishing process and enable Wiley-Blackwell to disseminate your Contribution to the fullest extent, we need to have this Copyright Transfer Agreement signed and returned as directed in the Journal’s instructions for authors as soon as possible. If the Contribution is not accepted for publication, or if the Contribution is subsequently rejected, this Agreement shall be null and void. **Publication cannot proceed without a signed copy of this Agreement.**

A. COPYRIGHT

1. The Contributor assigns to Wiley-Blackwell, during the full term of copyright and any extensions or renewals, all copyright in and to the Contribution, and all rights therein, including but not limited to the right to publish, republish, transmit, sell, distribute and otherwise use the Contribution in whole or in part in electronic and print editions of the Journal and in derivative works throughout the world, in all languages and in all media of expression now known or later developed, and to license or permit others to do so.

2. Reproduction, posting, transmission or other distribution or use of the final Contribution in whole or in part in any medium by the Contributor as permitted by this Agreement requires a citation to the Journal and an appropriate credit to Wiley-Blackwell as Publisher, and/or the Society if applicable, in form and content as follows: (Title of Article, Author, Journal Title and Volume/Issue, Copyright © [year], copyright owner as specified in the Journal). Links to the final article on Wiley-Blackwell’s website are encouraged where appropriate.

B. RETAINED RIGHTS

Notwithstanding the above, the Contributor or, if applicable, the Contributor’s Employer, retains all proprietary rights other than copyright, such as patent rights, in any process, procedure or article of manufacture described in the Contribution.

C. PERMITTED USES BY CONTRIBUTOR

1. Submitted Version. Wiley-Blackwell licenses back to the Contributor the following rights with respect to the final published version of the Contribution:

   a. The right to transmit, print and share copies with colleagues.

   b. The right to transmit, print and share copies with colleagues.

2. Accepted Version. Re-use of the accepted and peer-reviewed (but not final) version of the Contribution shall be by separate agreement with Wiley-Blackwell. Wiley-Blackwell has agreements with certain funding agencies governing reuse of this version. The details of those relationships, and other offerings allowing open web use, are set forth at the following website: http://www.wiley.com/go/funderstatement. NIH grantees should check the box at the bottom of this document.

3. Final Published Version. Wiley-Blackwell hereby licenses back to the Contributor the following rights with respect to the final published version of the Contribution:

   a. Copies for colleagues. The personal right of the Contributor only to send or transmit individual copies of the final published version in any format to colleagues upon their specific request provided no fee is charged, and further-provided that there is no systematic distribution of the Contribution, e.g. posting on a listserve, website or automated delivery.

   b. Re-use in other publications. The right to re-use the final Contribution or parts thereof for any publication authored or edited by the Contributor (excluding journal articles) where such re-used material constitutes less than half of the total material in such publication. In such case, any modifications should be accurately noted.

   c. Teaching duties. The right to include the Contribution in teaching or training duties at the Contributor’s institution/place of employment including in course packs, e-reserves, presentation at professional conferences, in-house training, or distance learning. The Contribution may not be used in seminars outside of normal teaching obligations (e.g. commercial seminars). Electronic posting of the final published version in connection with teaching/training at the Contributor’s institution/place of employment is permitted subject to the implementation of reasonable access control mechanisms, such as user name and password. Posting the final published version on the open Internet is not permitted.

   d. Oral presentations. The right to make oral presentations based on the Contribution.

4. Article Abstracts, Figures, Tables, Data Sets, Artwork and Selected Text (up to 250 words).

   a. Contributors may re-use unmodified abstracts for any non-commercial purpose. For on-line uses of the abstracts, Wiley-Blackwell encourages but does not require linking back to the final published versions.

   b. Contributors may re-use figures, tables, data sets, artwork, and selected text up to 250 words from their Contributions, provided the following conditions are met:

      (i) Full and accurate credit must be given to the Contribution.

      (ii) Modifications to the figures, tables and data must be noted. Otherwise, no changes may be made.

      (iii) The reuse may not be made for direct commercial purposes, or for financial consideration to the Contributor.

      (iv) Nothing herein shall permit dual publication in violation of journal ethical practices.

CTA-A
D. CONTRIBUTIONS OWNED BY EMPLOYER

1. If the Contribution was written by the Contributor in the course of the Contributor's employment (as a “work-made-for-hire” in the course of employment), the Contribution is owned by the company/employer which must sign this Agreement (in addition to the Contributor's signature) in the space provided below. In such case, the company/employer hereby assigns to Wiley-Blackwell, during the full term of copyright, all copyright in and to the Contribution for the full term of copyright throughout the world as specified in paragraph A above.

2. In addition to the rights specified as retained in paragraph B above and the rights granted back to the Contributor pursuant to paragraph C above, Wiley-Blackwell hereby grants back, without charge, to such company/employer, its subsidiaries and divisions, the right to make copies of and distribute the final published Contribution internally in print format or electronically on the Company's internal network. Copies so used may not be resold or distributed externally. However the company/employer may include information and text from the Contribution as part of an information package included with software or other products offered for sale or license or included in patent applications. Posting of the final published Contribution by the institution on a public access website may only be done with Wiley-Blackwell's written permission, and payment of any applicable fee(s). Also, upon payment of Wiley-Blackwell's reprint fee, the institution may distribute print copies of the published Contribution externally.

E. GOVERNMENT CONTRACTS

In the case of a Contribution prepared under U.S. Government contract or grant, the U.S. Government may reproduce, without charge, all or portions of the Contribution and may authorize others to do so, for official U.S. Government purposes only, if the U.S. Government contract or grant so requires. (U.S. Government, U.K. Government, and other government employees: see notes at end)

F. COPYRIGHT NOTICE

The Contributor and the company/employer agree that any and all copies of the final published version of the Contribution or any part thereof distributed or posted by them in print or electronic format as permitted herein will include the notice of copyright as stipulated in the Journal and a full citation to the Journal as published by Wiley-Blackwell.

G. CONTRIBUTOR'S REPRESENTATIONS

The Contributor represents that the Contribution is the Contributor's original work, all individuals identified as Contributors actually contributed to the Contribution, and all individuals who contributed are included. If the Contribution was prepared jointly, the Contributor agrees to inform the co-Contributors of the terms of this Agreement and to obtain their signature to this Agreement or their written permission to sign on their behalf. The Contribution is submitted only to this Journal and has not been published before. If excerpts from copyright-owned works owned by third parties are included, the Contributor will obtain written permission from the copyright owners for all uses as set forth in Wiley-Blackwell's permissions form or in the Journal's Instructions for Contributors, and show credit to the sources in the Contribution.) The Contributor also warrants that the Contribution contains no libelous or unlawful statements, does not infringe upon the rights (including without limitation the copyright, patent or trademark rights) or the privacy of others, or contain material or instructions that might cause harm or injury.

CHECK ONE BOX:

- [ ] Contributor-owned work

  ATTACH ADDITIONAL SIGNATURE PAGES AS NECESSARY

  Contributor's signature ________________________________ Date ________________________________

  Type or print name and title ________________________________

  Co-contributor's signature ________________________________ Date ________________________________

  Type or print name and title ________________________________

- [ ] Company/Institution-owned work

  (made-for-hire in the course of employment)

  Company or Institution (Employer-for-Hire) ________________________________ Date ________________________________

  Authorized signature of Employer ________________________________ Date ________________________________

- [ ] U.S. Government work

  Note to U.S. Government Employees
  A Contribution prepared by a U.S. federal government employee as part of the employee's official duties, or which is an official U.S. Government publication, is called a “U.S. Government work,” and is in the public domain in the United States. In such case, the employee may cross out Paragraph A.1 but must sign (in the Contributor's signature line) and return this Agreement. If the Contribution was not prepared as part of the employee's duties or is not an official U.S. Government publication, it is not a U.S. Government work.

- [ ] U.K. Government work

  Crown Copyright

  Note to U.K. Government Employees
  The rights in a Contribution prepared by an employee of a U.K. government department, agency or other Crown body as part of his/her official duties, or which is an official government publication, belong to the Crown. U.K. government authors should submit a signed declaration form together with this Agreement. The form can be obtained via http://www.opsi.gov.uk/advice/crown-copyright/copyright-guidance/publication-of-articles-written-by-ministers-and-civil-servants.htm

- [ ] Other Government work

  Note to Non-U.S., Non-U.K. Government Employees
  If your status as a government employee legally prevents you from signing this Agreement, please contact the editorial office.

- [ ] NIH Grantees

  Note to NIH Grantees
  Pursuant to NIH mandate, Wiley-Blackwell will post the accepted version of Contributions authored by NIH grant-holders to PubMed Central upon acceptance. This accepted version will be made publicly available 12 months after publication. For further information, see www.wiley.com/go/nihmandate.
WILEY AUTHOR DISCOUNT CARD

As a highly valued contributor to Wiley’s publications, we would like to show our appreciation to you by offering a unique 25% discount off the published price of any of our books*.

To take advantage of this offer, all you need to do is apply for the Wiley Author Discount Card by completing the attached form and returning it to us at the following address:

The Database Group
John Wiley & Sons Ltd
The Atrium
Southern Gate
Chichester
West Sussex PO19 8SQ
UK

In the meantime, whenever you order books direct from us, simply quote promotional code S001W to take advantage of the 25% discount.

The newest and quickest way to order your books from us is via our new European website at:

http://www.wileyeurope.com

Key benefits to using the site and ordering online include:
• Real-time SECURE on-line ordering
• The most up-to-date search functionality to make browsing the catalogue easier
• Dedicated Author resource centre
• E-mail a friend
• Easy to use navigation
• Regular special offers
• Sign up for subject orientated e-mail alerts

So take advantage of this great offer, return your completed form today to receive your discount card.

Yours sincerely,

Verity Leaver
E-marketing and Database Manager

*TERMS AND CONDITIONS
This offer is exclusive to Wiley Authors, Editors, Contributors and Editorial Board Members in acquiring books (excluding encyclopaedias and major reference works) for their personal use. There must be no resale through any channel. The offer is subject to stock availability and cannot be applied retrospectively. This entitlement cannot be used in conjunction with any other special offer. Wiley reserves the right to amend the terms of the offer at any time.
To enjoy your special discount, tell us your areas of interest and you will receive relevant catalogues or leaflets from which to select your books. Please indicate your specific subject areas below.

<table>
<thead>
<tr>
<th>Area</th>
<th>[ ]</th>
<th>Area</th>
<th>[ ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accounting</td>
<td></td>
<td>Architecture</td>
<td></td>
</tr>
<tr>
<td>• Public</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Corporate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chemistry</td>
<td>[ ]</td>
<td>Business/Management</td>
<td>[ ]</td>
</tr>
<tr>
<td>• Analytical</td>
<td>[ ]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Industrial/Safety</td>
<td>[ ]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Organic</td>
<td>[ ]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Inorganic</td>
<td>[ ]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Polymer</td>
<td>[ ]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Spectroscopy</td>
<td>[ ]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Encyclopedia/Reference</td>
<td></td>
<td>Engineering</td>
<td>[ ]</td>
</tr>
<tr>
<td>• Business/Finance</td>
<td>[ ]</td>
<td>• Civil</td>
<td></td>
</tr>
<tr>
<td>• Life Sciences</td>
<td>[ ]</td>
<td>• Communications Technology</td>
<td>[ ]</td>
</tr>
<tr>
<td>• Medical Sciences</td>
<td>[ ]</td>
<td>• Electronic</td>
<td></td>
</tr>
<tr>
<td>• Physical Sciences</td>
<td>[ ]</td>
<td>• Environmental</td>
<td></td>
</tr>
<tr>
<td>• Technology</td>
<td>[ ]</td>
<td>• Industrial</td>
<td></td>
</tr>
<tr>
<td>• Technology</td>
<td>[ ]</td>
<td>• Mechanical</td>
<td></td>
</tr>
<tr>
<td>Earth &amp; Environmental Science</td>
<td>[ ]</td>
<td>Finance/Investing</td>
<td>[ ]</td>
</tr>
<tr>
<td>Hospitality</td>
<td>[ ]</td>
<td>• Economics</td>
<td></td>
</tr>
<tr>
<td>Genetics</td>
<td>[ ]</td>
<td>• Institutional</td>
<td></td>
</tr>
<tr>
<td>• Bioinformatics/Computational</td>
<td>[ ]</td>
<td>• Personal Finance</td>
<td>[ ]</td>
</tr>
<tr>
<td>• Biology</td>
<td>[ ]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Proteomics</td>
<td>[ ]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Genomics</td>
<td>[ ]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Gene Mapping</td>
<td>[ ]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Clinical Genetics</td>
<td>[ ]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medical Science</td>
<td></td>
<td>Life Science</td>
<td>[ ]</td>
</tr>
<tr>
<td>• Cardiovascular</td>
<td>[ ]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Diabetes</td>
<td>[ ]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Endocrinology</td>
<td>[ ]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Imaging</td>
<td>[ ]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Obstetrics/Gynaecology</td>
<td>[ ]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Oncology</td>
<td>[ ]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Pharmacology</td>
<td>[ ]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Psychiatry</td>
<td>[ ]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-Profit</td>
<td>[ ]</td>
<td>Psychology</td>
<td>[ ]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Clinical</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Forensic</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Social &amp; Personality</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Health &amp; Sport</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Cognitive</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Organizational</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Developmental and Special Ed</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Child Welfare</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Self-Help</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Physics/Physical Science</td>
<td>[ ]</td>
</tr>
</tbody>
</table>
[ ] I confirm that I am a Wiley Author/Editor/Contributor/Editorial Board Member of the following publications:

SIGNATURE: …………………………………………………………………………………………………………………………………………………

PLEASE COMPLETE THE FOLLOWING DETAILS IN BLOCK CAPITALS:

TITLE AND NAME: (e.g. Mr, Mrs, Dr) …………………………………………………………………………………………………………………

JOB TITLE: …………………………………………………………………………………………………………………………………………………

DEPARTMENT: ……………………………………………………………………………………………………………………………………………

COMPANY/INSTITUTION: ……………………………………………………………………………………………………………………………

ADDRESS: …………………………………………………………………………………………………………………………………………………

TOWN/CITY: ……………………………………………………………………………………………………………………………………………

COUNTY/STATE: ………………………………………………………………………………………………………………………………………

COUNTRY: ……………………………………………………………………………………………………………………………………………

POSTCODE/ZIP CODE: ………………………………………………………………………………………………………………………………

DAYTIME TEL: ……………………………………………………………………………………………………………………………………………

FAX: ………………………………………………………………………………………………………………………………………………………

E-MAIL: …………………………………………………………………………………………………………………………………………………

YOUR PERSONAL DATA
We, John Wiley & Sons Ltd, will use the information you have provided to fulfil your request. In addition, we would like to:

1. Use your information to keep you informed by post, e-mail or telephone of titles and offers of interest to you and available from us or other Wiley Group companies worldwide, and may supply your details to members of the Wiley Group for this purpose.

[ ] Please tick the box if you do not wish to receive this information

2. Share your information with other carefully selected companies so that they may contact you by post, fax or e-mail with details of titles and offers that may be of interest to you.

[ ] Please tick the box if you do not wish to receive this information.

If, at any time, you wish to stop receiving information, please contact the Database Group (databasegroup@wiley.co.uk) at John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex PO19 8SQ, UK.

E-MAIL ALERTING SERVICE
We offer an information service on our product ranges via e-mail. If you do not wish to receive information and offers from John Wiley companies worldwide via e-mail, please tick the box [ ].

This offer is exclusive to Wiley Authors, Editors, Contributors and Editorial Board Members in acquiring books (excluding encyclopaedias and major reference works) for their personal use. There should be no resale through any channel. The offer is subject to stock availability and may not be applied retrospectively. This entitlement cannot be used in conjunction with any other special offer. Wiley reserves the right to vary the terms of the offer at any time.

Ref: S001W