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Explaining the experience curve: Cost reductions of Brazilian ethanol from sugarcane

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ABSTRACT

Production costs of bio-ethanol from sugarcane in Brazil have declined continuously over the last three decades. The aims of this study are to determine underlying reasons behind these cost reductions, and to assess whether the experience curve concept can be used to describe the development of feedstock costs and industrial production costs. The analysis was performed using average national costs data, a number of prices (as a proxy for production costs) and data on annual Brazilian production volumes. Results show that the progress ratio (PR) for feedstock costs is 0.68 and 0.81 for industrial costs (excluding feedstock costs). The experience curve of total production costs results in a PR of 0.80. Cost breakdowns of sugarcane production show that all sub-processes contributed to the total, but that increasing yields have been the main driving force. Industrial costs mainly decreased because of increasing scales of the ethanol plants. Total production costs at present are approximately 340 US$/$m^3_{ethanol}$ (16 US$/GJ). Based on the experience curves for feedstock and industrial costs, total ethanol production costs in 2020 are estimated between US$ 200 and 260/m^3 (9.4–12.2 US$/GJ). We conclude that using disaggregated experience curves for feedstock and industrial processing costs provide more insights into the factors that lowered costs in the past, and allow more accurate estimations for future cost developments.

1. Introduction and rationale

With increasing concerns regarding the impact of greenhouse gas emissions on the climate, rising oil prices and the dependency of the global transportation sector on oil-derived fuels, many countries aim to diversify their energy supply and switch to more environmental friendly fuels. Biomass transportation fuels (biofuels) are an often-cited option to provide such an alternative. Both developed and developing countries are increasingly focusing research and development efforts and are introducing market development schemes for biofuels such as bio-ethanol and biodiesel [24].

A common argument against various biofuels for transportation is their high production costs, and in many countries, biofuels receive governmental support (such as subsidies or tax exemptions) to achieve economic competitiveness against oil-derived transportation fuels. One prominent example where this argument does not hold any longer

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is bio-ethanol produced from sugarcane in Brazil. In Brazil, anhydrous ethanol (96.6 GL[1]) is used as octane enhancer in all gasoline with blending rates up to 26%. Hydrated ethanol (99.7 GL) is used in neat-ethanol engines since 1980, and flex-fueled vehicles since 2003. Flex-fuel cars are not designed to run with neat gasoline but everything in between enhanced gasoline and hydrated ethanol.

In the state of Sao Paulo, average consumer prices for hydrated ethanol over the year 2005, were US$ 23.9/GJ (R$ 1.17/liter), compared to US$ 30.4/GJ (R$ 2.2/liter) for gasoline.[2] In general, it is estimated that ethanol can compete with gasoline without subsidies with an oil price higher than 38 US$/barrel [62].[3] Currently, 100% of the Brazilian passenger cars drive on (blended) ethanol, and 80% of all new cars sold are flexi-fuel cars, which allows the owner to drive on any mixture of gasoline and ethanol.

However, the success of bio-ethanol did not come out of nowhere. The production of bio-ethanol from sugarcane was stimulated between 1975 and 1999 by the national program ProÁlcool. During this program, ethanol production increased from 500 thousand m^3 up to 15 million m^3 annually year, nowadays contributing to 40% of the national gasoline demand. Over that period, ethanol prices paid to producers declined by about 70% due to technological advances in the production of ethanol. This decline of ethanol prices with cumulative production has been analyzed previously by Goldemberg et al. [25,26] using the experience curve approach.

In this approach, the production cost developments of a product or a technology are investigated as function of cumulative production (as a proxy for cumulative experience gained). Empirically, it has been observed that production costs of products tend to fall with a fixed percentage with every doubling of cumulative production [5]. This trend was shown in the past for many industrial products such as airplanes, computer chips, fluorescent light bulbs, various chemical compounds and many more products, see for an overview Dutton and Thomas [18] or McDonald and Schrattenholzer [37]. Within the field of renewable energy, this approach has been used to analyze e.g. the progress made in reducing the production costs of e.g. photovoltaic modules, onshore and offshore wind turbines, and several biomass combustion technologies in order to evaluate policies and predict future developments [31,34,35,36,43].

Studies investigating the advances and cost reductions of biomass technologies using the experience curve theory are relatively scarce. Junginger [34,35,36] presents several cases for solid biomass use in Scandinavia. For the Brazilian ethanol industry, Goldemberg described the cost reductions in 1996, and more recently in 2004 [25,26]. They state that there are ample indications that factors such as technological progress and upscaling have led to significant reductions in production costs in the past few decades. Moreira and Goldemberg [40] note that improvements in selected varieties of sugarcane, harvesting, transportation management of residues, general management improvements, juice extraction, juice treatment and distillation have been made. However, to our knowledge, no efforts have been made to quantitatively evaluate the influence of the different advances in production of the feedstock (sugarcane) and the industrial production costs of ethanol over a long period of time (e.g. 30 years).

The aims of this study are to determine underlying reasons behind the production cost reductions of Brazilian bio-ethanol, and to assess whether the experience curve concept can be used to describe separately the development of feedstock costs and industrial production costs. This would provide more insights into the factors that lowered costs in the past, and allow more accurate estimations for future cost developments. Furthermore, the study will address a number of methodological issues related to the application of the experience curve approach to Brazilian bio-ethanol production, which had little attention in earlier research on this topic. For example, we note that the use of prices instead of production costs is only valid under specific circumstances (when the margin between production costs and prices is constant) [31]. In addition, prices of Brazilian products plotted in US$ are heavily affected by fluctuating exchange rates. Also, the assumptions on the initial production volume can strongly influence the calculated slope of experience curves [57]. These methodological issues have barely been discussed for Brazilian bio-ethanol production.

2. Brazilian background

The production of Brazilian bio-ethanol dates back to 1931 with the construction of the *Institution do Açúcar e do Álcool* (IAA) and a legislation requiring engine additions that would make ethanol blends possible up to 40% [23]. Due to availability of inexpensive oil up to the 1970s, the plan to decrease oil dependency was not put into practice. Increasing oil prices in the 1970s were the main reason that energy supply became a major politic priority, which led to a more serious federal ethanol program. The program became commonly known as ProÁlcool, which a lot has been written.[4]

2.1. *The sugar and ethanol market*

The state of São Paulo is the traditionally the largest sugar producing region, which is reflected in the national production trends. Fig. 1 displays the production trends of sugarcane, sugar and ethanol production in the state of São Paulo. Nowadays, approximately 300 industrial plants produce ethanol, most of them annexed plants.[5] Despite the increasing ethanol production over time (1975–1997), the amount of 300 plants remained almost unchanged. Recently a new wave of investments in industrial plants have taken place.

[1] GL is the indication used for volumetric percentage.

[2] Based on yearly average consumer prices for ethanol and gasoline prices over 2005 (Unica), a lower heating value (LHV) of ethanol of 21.3 GJ_{LHV}/m^3, and 32 GJ_{LHV}/m^3 for gasoline, and the exchange rate of 1 US$ = R$ 2.3, average over 2005 [65].

[3] For comparison, the oil price fluctuated between 45 and 70 US$/barrel in 2005.

[4] Rosillo-Calle and Cortez [54], Moreira and Goldemberg [40] and Puppim-de-Oliverio [50] provide good overviews on the governmental programme.

[5] Annexed plants produce sugar and ethanol. Autonomous plants produce only sugar or ethanol.

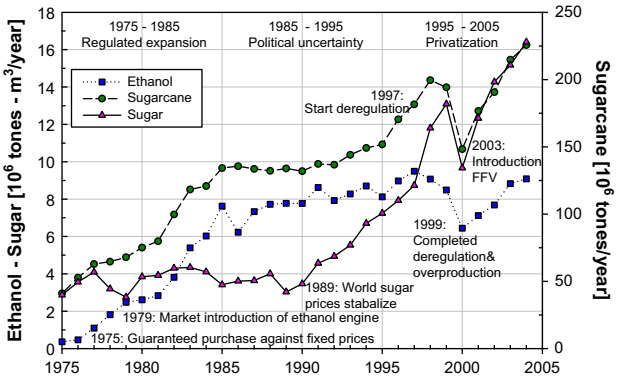

Fig. 1 – Yearly ethanol, sugarcane and sugar production in the state of Sao Paulo [58].

The first phase of ProAlcool (1975–1985) four major policy instruments were applied [22]:

- low-interest loans (compared to interest loans for similar-sized projects in the same time period) for the construction of ethanol distilleries offered by the Banco do Brasil;
- guaranteed purchase of ethanol against fixed prices set by Fundação Getulio Vargas (FGV);
- regulated pricing and production quotas of ethanol so could become competitive to gasoline and;
- production quota for sugar and export controls.

In this first phase traditional sugar producers expand the distillery capacity in order to fulfill the demand created by increased blending rates and ethanol engine. Three main incentives were created in order to stimulate demand: Fixed hydrated ethanol prices at 59% of that of gasohol, tax reduction on ethanol fueled cars, and annual license fee was reduced for ethanol cars [46].

During the second period (1985–1995) the great success of the program would face difficulties because of political uncertainties and fluctuating oil and sugar prices [40]. Financial incentives were necessary to save the program: R&D funding was diminished and guaranteed purchase prices were set below average production costs in the season 1986/1987 [25]. Meanwhile world market sugar prices recovered and sugar exports were increased, leading to significant shortage of ethanol in the season 1989/1990 [40].

In order to make an end of the permanent subsidies without destroying the built up capacity, four essential points had to be taken care of [40]: further cost reductions had to be pursued, guaranteeing a minimum price level for producers could only be possible if production costs could be evaluated properly with full accessibility to the cost spreadsheets, replacement of labor by equipments was to be considered, and better management skills were necessary to compete with the world market. The industry reacted by introducing highly modernized accounting systems and vertical integration of industrialists and farmers. The industry reacted by introducing highly modernized accounting systems and vertical integration of industrialists and farmers.

During the third phase (1995–2005) inflation rates were finally brought back to normal, creating a more stable economy. The government could reduce its interest in the sector and fulfill complete deregulation of anhydrous ethanol in March 1997 and hydrated ethanol in February 1999 [25]. From this point, the Brazilian government only had the gasohol blend ratio left as policy tool to directly affect the supply and demand of anhydrous ethanol in the market. Temporally overproduction in 1999 was the result of overestimated demand combined with a very good harvest year [41,51].

Rising oil prices were a welcome trend for ethanol producers as they were able to get higher profits on their ethanol. Production of hydrated ethanol was boosted by the introduction of the flex-fueled-vehicle (FFV).[6] As the oil prices kept on rising the sales of the FFV became a great success, with a market share of nearly 20 percent in the first year of introduction and nearly 80% in December 2005 [33].

2.2. *Sugarcane cultivation*

Sugarcane cultivation in Brazil is based on a ratoon system, which means that after the first cut the same plant is cut several times on a yearly basis (Fig. 2). Harvesting season in the state of São Paulo is approximately from May until November. Before planting in the first year, the soil is intensively prepared, nowadays mainly mechanical. After this the soil is furrowed and phosphate-rich fertilizers are applied, seeds are distributed and the furrows are closed and fertilizers and herbicides are applied once again. The stock is then treated with artificial fertilizers or 'filter cake'[7] once or twice again during cultivation in the first year. After 12–18 months the cane is ready for the first cut. For this it is (still) common to burn down the cane in order to simplify manual harvesting.[8] Mechanical harvesting is used for approximately 25% of all sugarcane in São Paulo [12]. Green cane harvesting is possible, but the (cellulosic) leaves have no use in the industry (yet), so leaves are generally left on the field as organic fertilizer. After cutting and sometimes chopping cane stalks by a chopped cane harvester, the cane stalks are loaded in trucks and transported by trucks to the industrial plant. Burning and delays before processing such as loading and transport lead to significant losses of the amount of sucrose per tonne total reducible sugars (TRS). Losses of 6–10 kg (TRS) per tonne of sugarcane within the first 72 h is normal, which stresses the importance of quick harvesting, loading and transportation [13].

After the first harvest, the process is repeated excluding intensive soil treatments and planting. Depending on the rate

[6] The Flex-Fueled Vehicle is the result of a long lasting cooperative research project (since 1980s) by several research institutes in the US, Europe and Japan. The Brazilian ethanol market is the biggest in the world, and Volkswagen introduced the engine in March 2003 with great success.

[7] Filter cake is a rest product of sugar and ethanol production, it contains large amounts of nutrients, which are filtered out of the juice in the sedimentation process.

[8] The field is set to fire in order to get rid of the green residues such as leaves and kill dangerous species living in the field. Leaving the sugar containing stalks of cane in the field ready for relatively easy manual cutting. Introduction of mechanical harvesters makes unburned or green cane harvesting more and more applied nowadays. Also, burning of sugarcane is gradually being phased out.

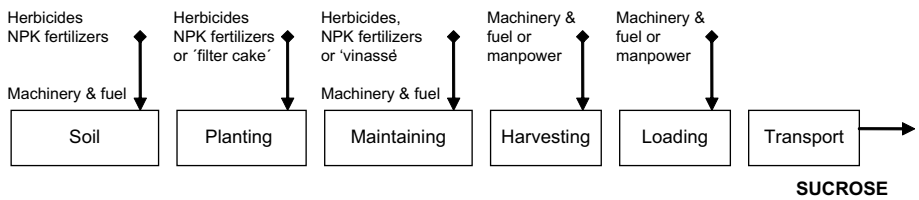

Fig. 2 – Simplified overview of sugarcane production.

of the declining yields[9] the same stock can be used up to 5–7 harvests nowadays. Yields decline with approximately 15% after the first harvest and 6–8% in the years that follow. Declining yields depend on treatment of the stock during maintenance and harvesting but are mainly determined by the combination of applied variety and type of soil [8,9].

2.3. *Ethanol production*

At the plant, the sugarcane is washed and shredded into smaller pieces of 20–25 cm (Fig. 3). The pieces are fed to and extracted by a set of 4–7 mill combinations into sugar containing juice and *bagasse*.[10] The main objective of the milling process is to extract the largest possible amount of sucrose from the cane, a secondary, and increasingly important objective is the production of bagasse with low moisture rates in order to feed the boilers. The boilers supply enough electricity and steam for the process to be self-sufficient, and in some cases to deliver excess electricity to the grid.

The chemical process in summary, the cane juice is filtered and treated by chemicals[11] and pasteurized. The sugar concentration in the juice is increased through evaporation and after that the juice is crystallized through heating. The product is a mixture of clear crystals surrounded by molasses[12] with a concentration of 91–93 Brix.[13] Molasses are removed by centrifugation where after it undergoes another pretreatment including pasteurization and addition of lime. This leads to a sterilized molasse free of impurities, ready to be fermented. In the fermentation process the sugars are transformed into ethanol by addition of yeast. Chemical fermentation efficiencies range from 80 to 90%, resulting in an alcohol content of 7–10 GL,[1] called fermented wine. The wine is centrifuged in order to recover the yeast. Making use of the different boiling points the alcohol in the fermented wine is separated from the yeast, non-fermentable sugars, minerals and gasses; CO_2 and SO_2. Hydrated ethanol with a concentration of 96 GL is the remaining product after intensive distillation. Further dehydration up to 99.7 GL in order to produce anhydrous ethanol, is normally done by addition of cyclohexane [38].

3. Methodology – the experience curve concept

3.1. *General experience curve theory*

The experience curve is based on the theory that cost reductions correlate with the level of experience. In literature the experience curve is mostly used to assess declining production costs as a result of the cumulative production, for an overview see McDonald and Schrattenholzer [39]. The power function can be used to demonstrate the relation between cumulative production and production costs. Equation (1) shows a power function, where C_0 is defined as the cost of the first unit of production; *CUM* is the cumulative unit production at present; *b* is the experience index; and C_{cum} is the cost per unit at present [5].

$$C_{cum} = C_0 CUM^b \tag{1}$$

Plotted on a log–log scale this function can be fitted by a straight line. The function can be rewritten as a progress ratio (PR), as a function of the experience index[14] (*b*), when doubling of cumulative production (see Equation (3)). A PR of 0.7 (or 70%) implies that with each doubling of cumulative production, production costs decline with 30%[15] compared with the costs before doubling.

$$PR = \frac{C_{cum_2}}{C_{cum_1}} = \frac{C_0 CUM_2^b}{C_0 CUM_1^b} \tag{2}$$

$$PR = 2^b (\text{when } CUM_2 = 2CUM_1) \tag{3}$$

The calculated PR is the result of minimization of the sum of squares. One should take into account the error of the fit, which gives an indication of the goodness fit of the power function. Different methods exist to define the goodness of fit, but mostly used is the coefficient of determination R^2, that

[9] The common unit for yield in the industry is [TC/ha/year], which is around 80–90 TC/ha/year. A more accurate unit for agricultural yields is [tonne TRS/ha/year], both will be used in this study.

[10] Bagasse is the name for the fibers which are left after milling.

[11] The juice is treated with sulphur (SO_2) and calcium in the form of hydrated lime ($Ca(OH)_2$) in order to eliminate colorants in the juice, neutralize organic acids and decrease the juice viscosity. After this, the juice is heated above 100 °C to stimulate coagulation and flocculation of non–sugar protein colloids, and emulsify fats, gum and waxes which are removed by sedimentation.

[12] Molasse is the name for a sugar solution with remaining impurities. Molasse can be seen as the main feedstock for ethanol production.

[13] Degrees Brix is the amount of soluble solids, most fermentable sugars, in 100 parts of liquid.

[14] Experience indexes are directly related to progress ratios, Equation (4) shows how the standard error of the experience index is related to the standard error of the progress ratio.

[15] This can also be expressed by using the 'learning rate' (LR = 1 – PR) 0.3 or 30%. In literature the term progress ratio is used more often than LR the PR, the LR is defined as: 1 – PR. In most studies PR's between 0.7 and 0.9 are common, [39,18].

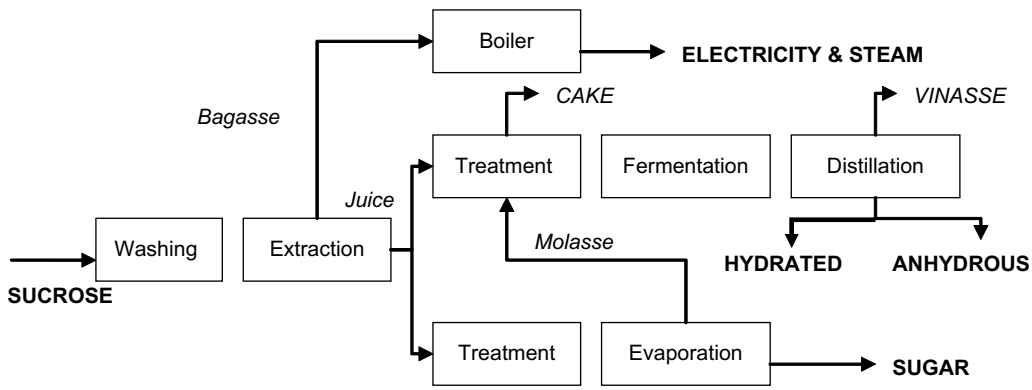

Fig. 3 – Simplified overview of the industrial ethanol production process.

defines the ratio of the regression sum of squares to the total sum of squares. Fitted data with $R^2 > 0.80$ are considered to be correlated, and fitted data with $R^2 < 0.25$ are very weak related [4]. The last and most important is the standard error in the PR, that is calculated from the propagation theory given by Bevington as:

$$\sigma_{PR} = \ln 2 \, PR \, \sigma_b \quad (4)$$

Here, σ_b is the standard error in b. The software tool Sigmaplot is used in this analysis to calculate the error σ_b and R^2 as problems occurred with the minimization of the sum of squares using logarithmic analysis, when using MS Excel [56].

Special methodological attention is paid to the influence of the initial cumulative production (CUM_1) as it can have significant influence on the PR[16] [57]. In earlier studies by Goldemberg et al. [25,26], the choice was made to choose a very low initial cumulative production before 1975, thus barely taking the effect of earlier experience into account. In this study the effect of the initial value on the calculated PR is analyzed by means of a sensitivity analysis.

In this study, costs are plotted in the local currency, corrected for national inflation and devaluation, and as a final step are converted to US$ (see Section 4.2).

3.2. *The experience curve approach applied to bio-energy systems*

When analyzing ethanol as a single product of one production process, no insight is given on the contribution of specific processes to the overall increased performance. IEA [31] gives some clear examples how supply chain systems can be split.

A useful subdivision to analyze the different advances for biofuel chains is the compound learning system presented by Junginger [34,35,36] and Rubin, Yeh, et al. [55]. For biomass-fueled power plants, the total learning system of producing electricity can be split up in three parts: the investment costs of the industrial plant, the operation and maintenance (O&M) costs of the plant, and the costs of the feedstock(s) (Fig. 4). For each of these parts, an experience curve can be defined, though in many cases the investment and O&M costs can be aggregated as industrial production costs. In this way, the black box of the entire learning system is opened, as more detailed insights can be obtained in the contributions of each sub-system to the overall cost reductions. This allows a better understanding of the mechanisms driving down the costs.

Several studies have shown that for industrial costs, it is difficult to devise meaningful experience curves due to a low degree of data availability and a large spread in the investment costs caused by variation in individual plant layout [34,35,36]. However, for biomass feedstock costs and for the costs of the final energy carrier (electricity or bio-ethanol) experience curves have been devised successfully in the past [25,34,35,36]. In case both data series are available, industrial costs can be calculated by subtracting the feedstock costs from the total production costs. We applied this strategy for estimating the annual industrial ethanol production costs for the Brazilian case study.

3.3. *Identifying mechanisms behind the cost reductions*

Cost reductions of new technologies do not come as manna from heaven . The way new technologies develop and diffuse is characterized by various stages from invention to wide spread implementation [64]. In each of these stages, different learning mechanisms play a role that cause technological change and cost reductions, such as: learning-by-searching, learning-by-doing, learning-by-using, learning-by-interacting, upsizing and economies of scale [43]. In our analysis, we attempt to quantify the cost reductions achieved in each sub-system.

Beforehand, it can be stated that one very important mechanism to reduce industrial production costs is the upscaling of production. For industrial processes, scale of production has significant influence on the costs per unit of capacity (i.e. $m^3_{ethanol}$/day). The effects of upscaling a production plant can be estimated using a scale factor [52].[17] Scale factors around 0.7–0.8 are quite commonly used. By applying the scale factor all plants can be converted to a reference size, thereby correcting the costs per unit of capacity [17].

[16] As follows from Equation (1) a low initial cumulative production (CUM) leads to a high experience index (b).

[17] $Cost_{Plantx}/Cost_{Referencesize} = (Capacity_{Plantx}/Capacity_{Referenceplant})^R$ where R is the scaling factor.

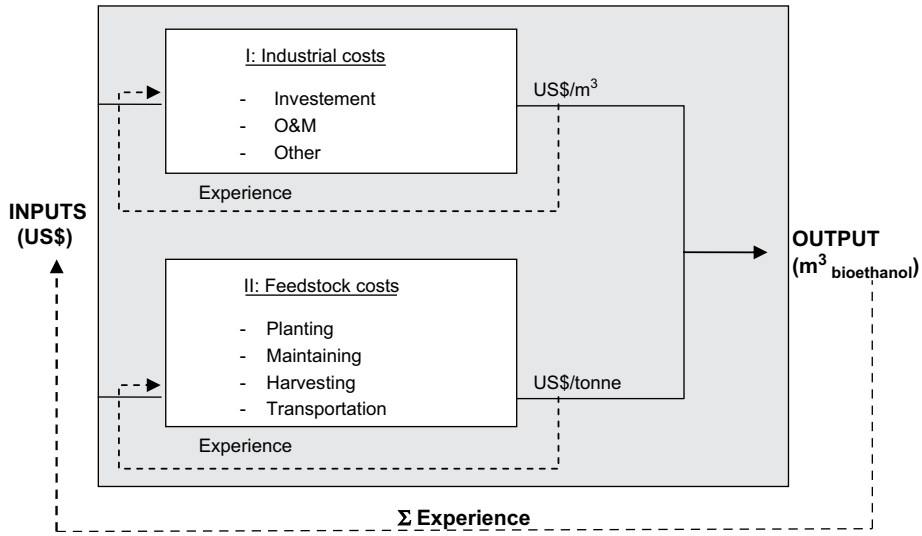

Fig. 4 – Compound learning system for the Brazilian bio-ethanol production chain (based on Junginger [34,35,36]).

4. Data collection and processing

4.1. *Data collection*

Data on the average production costs, market prices and production volumes of ethanol, sugar and sugarcane in Brazil were collected by various editions of divers Brazilian journals (*Brasil Açucareiro*, *Usineiro* and *Saccharum*) and statistics from UNICA (largest cooperation of sugar and ethanol producers). The outcomes were reviewed by a number of interviews with experts in the field.

Cumulative production volumes of sugarcane and ethanol were taken from UNICA. Initial cumulative production for sugarcane for the period before 1975 had to be estimated. This was done calculating the sum of national sugarcane production from 1941 to 1974, numbers collected by UNICA [63]. Cumulative production of ethanol for the period before 1975 was estimated by taking the sum of national production from 1930 to 1974 taken from UNICA.

Production costs of sugarcane have been collected from different sources. Historical data were collected from publications in (historical) journals (1975–1986) Brasil Açucareiro (BA), the journal of the IAA, who monitored the production costs for policy purposes. Most production costs (1986–1997) were taken from the Fundação Getulio Vargas (FGV), the main national economic institute, who monitored the production costs during the ProÁlcool program. Data were presented by Nastari and Macedo [42]. After market deregulation in 1999 no data on production costs was found and prices, presented by UNICA, were used as proxy[18] as the market was completely deregulated by 1999.

Total production costs of hydrated and anhydrous ethanol were collected from several different sources. Indications of costs before 1986 had to be estimated from all available data collected from various Brazilian journals; *Brasil Açucareiro*, *Usineiro* and *Saccharum*; scientific studies on this subject done by *Instituto de Economia Agrícola* (IEA), Copersucar Technology Centre (CTC), ESALQ and IAC. For the period 1986–1997 Nastari and Macedo [42] present total production costs for hydrated and anhydrated ethanol. We chose to use hydrated ethanol instead of anhydrous ethanol, because a longer time series for production costs was available. After deregulation of hydrated ethanol in February 1999 average market prices of sugarcane and hydrated ethanol in São Paulo, presented by ESALQ, are used as proxy for production costs for the same reason as for sugarcane.

Detailed cost breakdowns of sugarcane and ethanol production were found in a number of studies in literature which specify the cost structure sugarcane and ethanol at various point in time (see next section for references).

For assessment and as a quality check, the time series for production costs of sugarcane and ethanol were presented to a panel of professionals in the industry and scientists. This panel was composed of a number of professionals with different backgrounds and positions, all related to the ethanol industry (Prof. Braunbeck, W. Burnquist, I. Chaves, P. Delfini, J.L. Oliverio, J. Finguerut, R. Ionta, Prof. I. Macedo, P. Nastari, J.S. Nunez Gago, M. Regis). Experts were also used for to explain observed cost reductions and cost breakdowns (see Section 5).

4.2. *Data processing*

All costs were corrected for inflation using the IGP-DI deflator[19] and several devaluations [61]. Because of the extreme inflation rates during the 1980s and beginning of 1990s, costs have been corrected on a monthly basis. Publications during that period without exact notation of month of calculation were assumed to be a yearly average. In this manner all nominal costs, prices etc. were expressed to

[18] Experience curve theory allows the use of prices as proxy for production costs in cases of a well-established market where prices are likely to follow the same trend as production costs [5].

[19] The IGP-DI is the Brazilian general price index, it is calculated taking prices of agricultural and industrial raw materials, intermediates and final use products into account.

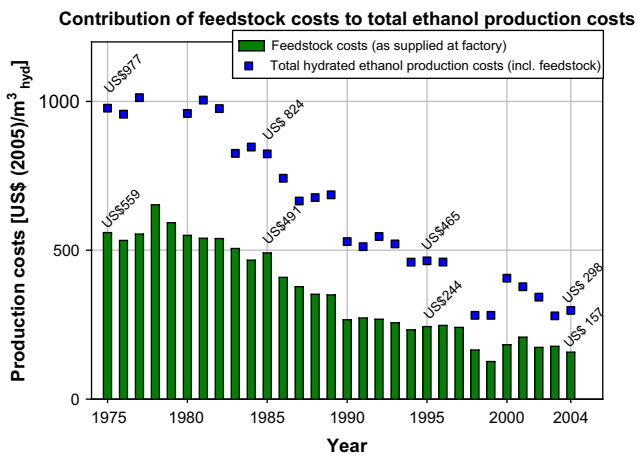

Fig. 5 – Compound cost structure of bio-ethanol from sugarcane (1975–2004), mainly based on Nastari and Macedo [42], see van den Wall Bake [61] for detailed overview.

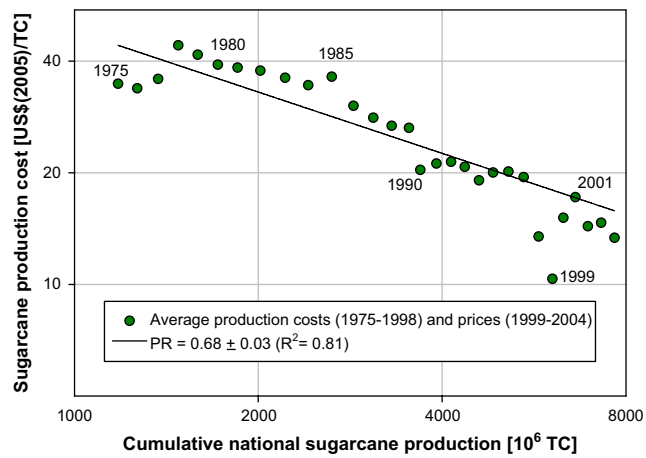

Fig. 6 – Experience curve of sugarcane production 1975–2004. Data mainly based on Nastari and Macedo [42]; see van den Wall Bake [61] for a detailed overview.

comparable R$ values as in December 2005.[20] All data presented in US$ were calculated by applying an exchange rate for December 2005 of US$ = R$ 2.3.[21]

Total industrial costs were obtained by deducting the average feedstock costs as delivered at the plant, from the total production costs. For this calculation we required the average industrial yield [lit_{hyd}/tonne cane] that was converted from [lit_{anh}/TC] by a factor 1.05 [58]. A three year average was taken to compensate seasonal influence, (see Ref. [61] for exact numbers and a detailed overview).

In most plants, both sugar and ethanol are produced., which poses the issue of allocating production costs over both products. Nastari and Macedo [42] already provided separate ethanol and sugar production costs. As we did not get permission to gain detailed insight in the calculations of FGV, we had no other option than to assume that allocation was taken care off.

Annual investment costs are calculated by converting the total turn-key investment costs into annual costs by means of the annuity factor.[22] The annuity factor is assumed constant over the past 30 years to make analysis and comparison possible.

5. Results

As a first overview, Fig. 5 shows the decline of both the total hydrated ethanol costs[23] and the sugarcane feedstock costs. Total ethanol costs declined from approximately US$980/$m^3_{hyd}$ in 1975 (R$ 2250/m^3) down to 260–305 US$/$m^3_{hyd}$ in 2004 (R$ 600–700/m^3). Costs of sugarcane have declined in a similar way, showing that the contribution of feedstock around 60% of the total costs has remained relatively stable over the last three decades. This was also widely confirmed by experts in the industry. However, this does not automatically imply that the agricultural and industrial systems learned at the same speed, as we show in the next sections.

5.1. *Experience curves for sugarcane production costs*

Fig. 6 shows the relation of sugarcane production and national average production costs by means of an experience curve. The initial cumulative production from 1941 to 1974 was determined to be 1.110×10^6 TC. The sugarcane production costs were reduced by more than 60%, from approximately US$ 35 to about US$ 13 in 2004. The PR of this curve is given 0.68 ± 0.03 over nearly three cumulative doublings (see gridlines). The goodness of fit is reliable with an R^2 of 0.81, just like the error in the progress ratio (σ_{pr}) of 0.03. Next to the experience curve base on the cost of a tonne of cane, also an experience curve for costs and production of sucrose was devised (not shown here, for more details, see Ref. [61]). This curve shows an even slightly lower progress ratio of 0.67 ± 0.02 ($R^2 = 0.85$), which can be explained by the increased sucrose yield over time per tonne of sugarcane.

The initial rise of feedstock production costs during the late 1970s is somewhat odd. However this trend was also observed by Vegro and Ferreira [60]. A likely explanation are high oil prices and an unfavorable US$–R$ exchange rate, strongly affecting the costs on imported fertilizers. Another remarkable year was 1999. Complete market deregulation in February 1999 and optimal climate conditions lead to a large overproduction of sugarcane, and thus the lowest reported costs so far observed. When the exceptionally low sugarcane costs of 1999 are left out, the PR increases only slightly to 0.69 ($R^2 = 0.82$).

[20] All nominal values and the IGP-DI can be found in van den Wall Bake [61].

[21] Note that this is rather low and that costs presented in US$ are very sensitive to the fluctuating exchange rate [41]. The average exchange rate for 2004 for example was US$ = R$3,6.

[22] The annuity factor and is defined as: $(dr/1-(1+dr)^{-lt})$ applying a discount rate (*dr*) of 15% [41] and an average economic lifetime *lt* of 25 years. The assumed lifetime of the total investment is possibly too pessimistic as boilers easily have lifetimes of 50 years and cylinder mills that have a lifetime of 20–30 years [66].

[23] All costs are presented in the national Brazilian currency Reais (R$) and corrected for devaluations and inflation to the year 2005. Costs provided in US$ are calculated by applying the average exchange rate for 2005, US$–R$ 2.3.

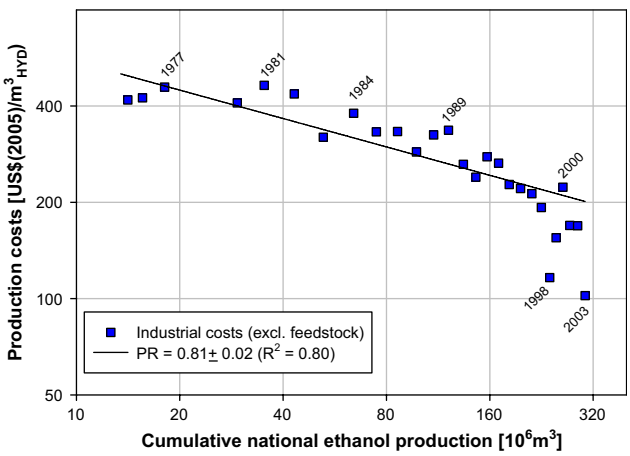

Fig. 7 – Experience curve for hydrated ethanol (1975–2004) excluding feedstock costs, mainly based on Nastari and Macedo [42]; see van den Wall Bake [61] for a detailed overview.

5.2. *Experience curves for industrial ethanol production costs*

Fig. 7 shows the experience curve for the industrial ethanol production costs.[24] For ethanol production, excluding feedstock costs, we determined an initial cumulative national production of 12.9×10^6 $m^3_{ethanol}$ during the period 1931–1974. Industrial processing costs were reduced by approximately 70% during the past 30 years, from over US$ 440 to US$ 110–150/m^3_{hyd}. Over nearly five cumulative doublings, the PR is higher than the PR of the sugarcane and TRS experience curves [61]. Correlation and significance are both good with a PR of 0.81 ± 0.02 and an R^2 of 0.80.

From 1975 to 1999, the scatter around the trend line is relatively small. The increased spread of the scatter after complete market regulation in 1999 may be caused by the use of prices instead of production costs. In addition, the extreme over-supply of sugarcane in 1999 lead to very low ethanol prices. For a detailed description on data quality, see van den Wall Bake [61].

5.3. *Experience curve for total ethanol production costs*

Fig. 8 shows the experience curve for ethanol production including feedstock costs, we determined the same initial cumulative production of 12.9×10^6 $m^3_{ethanol}$ (as in Fig. 7). Total production costs also declined around 70%, as in costs excluding feedstock costs, over the same five cumulative doublings. The PR is slightly higher (i.e. less benign) than the PR of costs excluding feedstock costs, and can be explained by fact that over time, sugarcane costs decreased slightly faster than industrial processing costs (see Fig. 6).

A general discussion of these results including a sensitivity analysis and a comparison with the results from previous studies is provided in Section 7.

[24] As no comprehensive time series on industrial production were available for the period 1975–2005, we used three different data sources (see Section 4.1).

5.4. *Detailed analysis of the sugarcane production cost breakdowns*

The agricultural production costs of sugarcane consist of a number of components, for example soil preparation, harvesting and transportation to the ethanol plant. All these steps have been continuously improved during the past 30 years. Table 1 and Fig. 9 show the varying contribution of all processes to the total cost reduction over time.

The data shown in Fig. 9 was derived from various studies analyzing the sugarcane production cost breakdowns in Sao Paulo [1,2,6,7,59]. However, for some studies a number of assumptions had to be made, e.g. yields (TC/ha) and number of harvests of the same crop. These are essential parameters, but were not always provided in the individual studies. These parameters were estimated based on the values used in other studies and on expert judgment. The ranges given in Fig. 9 indicate these uncertainties. Detailed calculations are presented in van den Wall Bake [61].

The presented breakdowns show a similar trend as the costs given by FGV. The error bars give an indication of the influence of two parameters; agricultural yields [TC/ha] and length of the ratoon system [harvests/stock]. Compared with national average yields, applied yields and the number of harvests could easily differ up to 30% (detailed calculations can be found in van den Wall Bake [61]).

Cost reductions for and rent, soil preparation and crop maintenance, were highly influenced by the increasing length of the ratoon system and the rising agricultural yields (see Table 2). Improved strength of new varieties and application of management systems form the main explanations. Harvesting costs declined mainly because of increasing yields in the manual process. Yields increased from 4.5 to 6 TC/man/day in 1977 to over 9 TC/man/day[25] in 2004. Due to increasing ethanol plant sizes, average transportation distances doubled from 10 km in 1977 up to 20 km in 2004, but loads increased significantly from 10 TC/truck to 40 TC/truck. Transportation costs declined mainly because of upscaling, introduction of automated logistic systems and improved infrastructure. These data are mainly based on BA [7] and CTC [12]. All processes are described in more detail in van den Wall Bake [61].

5.5. *Detailed analysis of the industrial ethanol production cost breakdowns*

As with the agricultural costs, different cost components can be distinguished. Unfortunately, less production cost studies were found for the case of industrial costs. In total, 5 studies were used to assess the reduction of investment costs [6,11,15,27,32].[26] However, for some studies a number of assumptions had to be made, e.g. on the load factors, the number of processing days and the scale of the installation, as these parameters were not always provided in the studies. These parameters were estimated based on the values used in

[25] Both numbers indicate the manual harvesting yields, excluding the affects of manual harvesting.

[26] Other studies such as Eid [19] and Hemerly [30] also present cost breakdowns but as most of the studies, do not use clear definitions in their cost breakdown.

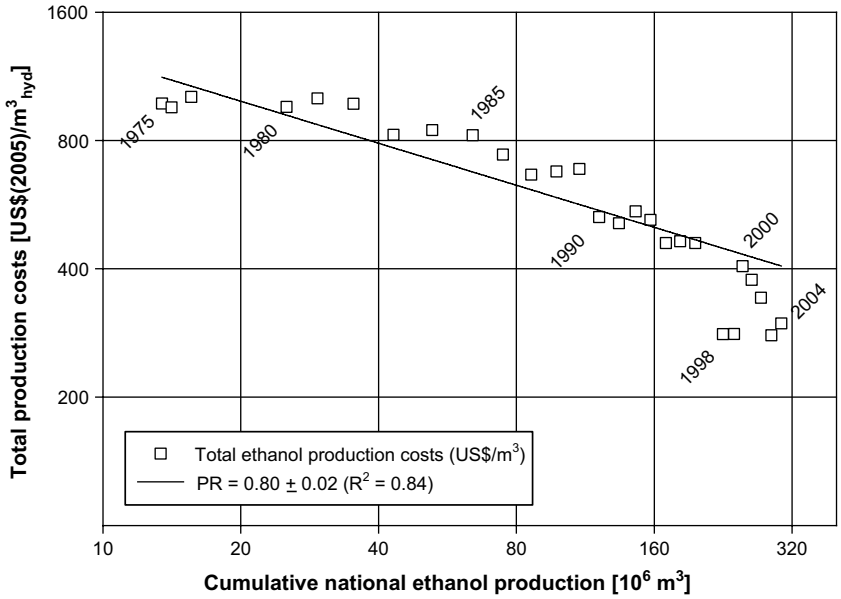

Fig. 8 – Experience curve for total hydrated ethanol (1975–2004) including feedstock costs, mainly based on Nastari and Macedo [42].

other studies and on expert judgment. See van den Wall Bake [61] for detailed calculations.

The stacked bars in Fig. 10 show a clear declining trend of all the costs, i.e. investment costs, O&M costs and administrative and other costs. Error bars show the uncertainty of the calculations, mainly the result of assumed average scales. Other assumptions given in the methodology could explain the differences between our calculations and those based on FGV and IAA. For comparison, the industrial cost curve is based on the same data as the experience curve (Fig. 7).

O&M data are defined as the operational costs of labor and materials in the industry itself during the maintenance and processing phases. Fixed costs such as administrative costs and insurances, taxes etc are included in the other category.

Industrial yields [$lit_{ethanol}$/kg TRS] are normally higher with increasing scales, resulting in lower costs per unit of product, affecting all types of costs. Investment costs are mainly lower because of costs of lower costs on materials and lower design costs, calculated per unit of capacity. Operational costs are mainly lower because of higher levels of automation. Table 3 shows the development of scales and investment costs, reflecting operational costs.

Using all available studies with reliable data on investment costs for autonomous plants (y-axes) and corresponding sizes (x-axes), we calculated a scale factor of 0.67 ($R^2 = 0.71$) (for more details see van den Wall Bake [61]). This scale factor is in the range of scale factors found in literature for similar equipment, often between 0.6 and 0.8 [17,39,44]. We also calculated a scale factor for annexed distilleries based on turn-key investments given by Dedini [47]. Using this data, we obtained a perfect fit of 0.997, but the calculated scale factor of 0.34 is much lower than normal ranges found in literature. A possible explanation might be the allocation of costs between the ethanol and sugar production,[27] but this could not be confirmed. Still, the scale effects found were confirmed by experts in the field. Olivério [47] and Nastari [41] underlined the importance of scale in the industry. More research is recommended to clarify this matter.

On the other hand, next to the effects of upscaling, it is clear that all kinds of process and material improvement also reduced the specific investment costs (described in more detail below). As a result, it is estimated that the investment costs of a 2 million tonne cane processing plant ($\pm$1000 m^3/day) nowadays costs US$ 78 million, around 1975 this would have been nearly twice as much, US$ $<$ 130 million [47].

Strongly correlated to scale, increasing the load factor during the milling season played an important role in cost reductions. A load factor of 90% during the operational season was typically found in the late 1970s, while nowadays load factors are usually around 95%, mainly because the number of crushing stops was decreased as a result of introduction of automated feeding and milling processes. In addition, the amount of operational days per year was raised from 160 in 1975, up to 190 days/year in 2005. This extension of the milling season was mainly the result of the use new varieties, but also of a well-organized planting and harvesting logistics. Due to further development of new varieties and optimization of the harvesting logistic systems, the amount of operational days is expected to reach 200 days/year in the near future [51].

Industrial performance showed strong growth during the 1970s and some steady growth until 1995. Increasing mill capacities, extraction and fermentation performance were the main drivers behind increasing industrial efficiencies as is highlighted in the section below.

[27] Possibly, all costs of components jointly used for sugar and ethanol production, such as the mills, may have been allocated 100% to sugar production.

Table 1 – Comparison of cost breakdowns 1976 and 2005.

	Costs [US$(2005)/TC]		Cost reduction (%)
	1976	2005	1976–2005
Land rent	7.33 (20%)	2.60 (21%)	64%
Soil Preparation	9.78 (27%)	2.33 (19%)	76%
Stock Maintenance	7.47 (21%)	3.31 (27%)	58%
Harvest – Loading	5.97 (17%)	2.47 (20%)	59%
Transport	5.22 (15%)	1.66 (13%)	68%
Total	**35.77** (100%)	**13.09** (100%)	**65%**

Table 4 shows how increased capacities of the two dominantly applied mills (with a radius of 54″ and 78″) developed simultaneously with higher efficiencies.

Three key factors led to increased capacities, and thus higher efficiencies of the mills: continuous feeding of the mills, increased pressure on the mills, and advanced juice recovery systems. Higher load factors required semi-automated systems, which became normal investments in the 1990s and are still an ongoing trend today [16].

Up until 1975, the fermentation process had remained unchanged for decennia and was running with low ethanol yields ($6\%_{vol}$), low overall efficiencies (80%) and slow fermentation times (15 h). From 1975, significant improvements have been achieved, as shown in Table 5. The first major step in order to increase efficiency was to increase juice purity. Secondly, new yeasts made continuous fermentation possible and speeded up the fermentation process. This also allowed for lower investments in tanks, simpler cooling systems, less required area and lower operational costs, mainly because of less frequent intensive tank cleaning. Continuous fermentation required continuous feedstock supplies, thus more reliable milling and juice treatment processes, which seriously affected the developments described earlier [20].

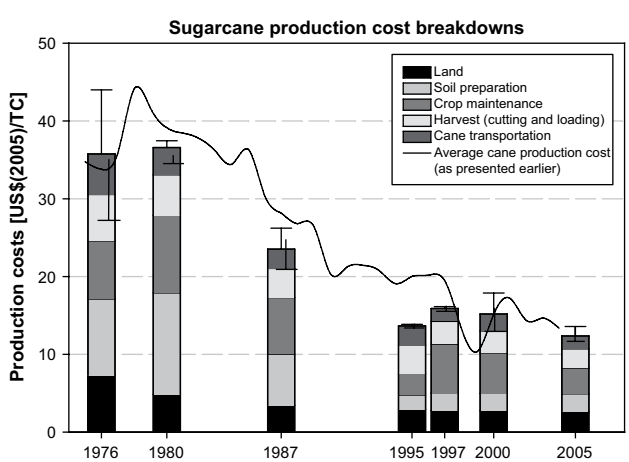

Fig. 9 – Examples of various sugarcane cost breakdowns in Sao Paulo between 1976 and 2005. Note that these studies were not carried out under the same conditions and some assumptions had to be made to provide complete breakdowns during time (see main text).

6. Analysis of future cost reduction potentials for sugarcane and ethanol

In the previous sections we have analyzed sugarcane and ethanol cost reductions in the past and discussed underlying factors. One of the main applications of experience curves is their extrapolation for future cost reduction potential analysis. In this section we first discuss why future cost reductions can be expected. We then make an estimate on how production costs may develop until 2020.

Feedstock production costs predominantly depend on agricultural yields (TC/ha; kg TRS/ha). National average is around 140 kg TRS/TC, but since sucrose yields are continuously increasing, further cost reductions are expected. Introduction of genetically modified cane varieties underlines the potential of increasing agricultural yields. Average harvesting and transportation costs are expected to decline further because best case technologies are not yet applied by the whole industry. Furthermore, larger scales in transportation and more optimal logistic systems reduce average costs. It is estimated that even if the introduction of genetically modified cane will not occur, the remaining factors could bring down the production costs of sugarcane by 20–40% within 15 years from now [10].

Scale effects played an important role in the observed cost reductions. The trend of upscaling is expected to continue up to a maximum of 4 million tonnes cane milled at a single plant, equaling an ethanol output of up to 1500 m^3/day [41]. Applying the scale factor of $R = 0.67$, investment costs and O&M costs are likely to decrease another 30% compared with the average installed capacities nowadays. This is likely an overestimation, as not all components of the plant can be scaled up continuously. Also, with increasing scales, feedstock transportation costs tend to go up. Still, it is expected that further upscaling will yield significant cost reductions.

Given all these expected future developments, further cost reductions are likely (see Table 6). Extrapolation of the experience curves (Figs. 6 and 7) shows us that continuously learning during production will bring down the costs of the various stages of production further down.

As a starting point, we assumed the prices of sugarcane and ethanol averaged over the period 2000–2004, and used the standard deviation as bandwidth for possible fluctuations (see Table 6). Furthermore, we assumed a constant annual growth rate of 8% for sugarcane and ethanol production (continued growth scenario). This is based on plans announced for future ethanol production. In 2005, production was about 17 million cubic meter, this is expected to increase to 26 million cubic meter in 2010 and 34.7 million cubic meter in 2015 [62]. Historically, the annual ethanol production growth rate has been even higher; about 12% per year averaged between 1975 and 2004 [37,49]. Applying the calculated PR's (and the uncertainty in the PR), and assuming of cane and ethanol production we extrapolated the experience curves up to 2020. Fig. 11 shows the results of this scenario. To evaluate the effects of a lower annual growth rate, we have also performed the same exercise assuming a pessimistic growth rate of 5%. This resulted in only marginally higher costs for sugarcane and ethanol (see Table 7).

Table 2 – Agricultural efficiency indicators [3,12,48].

	1975–1980	1980–1985	1985–1990	1990–1995	1995–2000	>2000
Length of ratoon system [years]	3–4	3–4	4–5	4–5	5–7	5–7
Agricultural yield [TC/ha/year]	65–72	66–76	69–76	74–80	77–79	75–82
Agricultural yield [kg TRS/TC]	124–128	127–136	137–139	139–141	139–142	144–148

Finally, we calculate the total costs of ethanol in 2020 adding the feedstock and industrial costs, finding a total cost range in 2020 of about 220–260 US$/m^3 for the continued growth scenario (see Table 7). When assuming the industrial yield to increase up to 86 lit$_{hyd}$/TC, then about 3% lower costs are calculated.

Conversion efficiencies, [lit/TC] and [lit/kg TRS], have increased [61]. The industrial maximum is defined by a method described by Copersucar in 1990 [14] and is respectively 0.686 [lit$_{hyd}$/kg TRS] and 0.710 [lit$_{anh}$/kg TRS].[28] With common industrial yields of approximately 0.55 [lit$_{anh}$/kg TRS], and 0.58 [lit$_{hyd}$/kg TRS] and 148 [kg TRS/tonne], one can state that industrial efficiencies are still far from the theoretical maximum.

Alternatively, we calculated the total production costs of ethanol using the experience curve for overall ethanol costs (see Fig. 6) and the corresponding PR of 0.80 ± 0.02 (see Table 8). Assuming the 8% annual growth rate, total ethanol costs (including feedstock), would be within the range of 223–276 US$/m^3 in 2020, i.e. about 7–12% higher production costs compared to the results obtained from the previous approach. The difference in outcomes and underlying assumptions is discussed in the next Section 7.

7. Discussion and conclusions

7.1. *Sensitivity analysis – the influence of the initial cumulative production*

In a first publication on experience curves and ethanol production costs, Goldemberg [26] reported a PR of 0.70 for the period of 1980–1990, and a PR of 0.90 between 1990 and 1995. The change in slope is interpreted by a large expansion of the ethanol sector, with rapidly declining production costs. These costs then declined more slowly from 1990 onwards. In a second publication eight years later, Goldemberg et al. [25] find the exact opposite trend: a PR of 0.93 between 1980 and 1985, and PR of 0.71 between 1985 and 2002. In the 2004 publication, this trend is explained by an initial mediocre price drop due to slow gains in agroindustrial yields, while the sharp decrease prices after 1985 is attributed to increasing economies of scale and political pressure to reduce prices.

No explanation is given for the opposite findings. In our work, ranging from 1975 to 2005, we find a constant PR of 0.80 over the entire period. However, we observe that both Goldemberg [26] and Goldemberg et al. [25] only assume a very modest initial cumulative ethanol production before 1980. Goldemberg [26] estimates 9.2 million m^3 for the year 1980, Goldemberg et al. [25] use approximately 3 million m^3. In our analysis, we took into account the cumulative ethanol production from 1941 onwards, and determine a cumulative ethanol production of 25 million m^3 in 1980.

To evaluate the effect of choosing a different initial cumulative ethanol production, we calculated the PR of overall total ethanol costs assuming no previous production. In this case, we find a PR of 90% (see Table 7), a significantly less positive value. Also for the feedstock and industrial production cost sub-systems, ignoring production before 1975 results in much less optimistic PRs.

Summarizing, we cannot explain the varying results from Goldemberg [26] and Goldemberg et al. [25], but expect that the choice of a very small initial value (and possibly different methods to convert Reais to US$) may cause the differences. We conclude that the choice of initial production volume has significant influence on the calculated experience index. By including (high) initial cumulative production volumes, we find a continuous slope and we feel that from a methodological point of view, this approach is correct.

7.2. *Possibilities and limitations of estimating future production costs*

Using the separate experience curves for feedstock and industrial production costs, we calculated an ethanol production cost range in 2020 of about 200–260 US$/m^3 for the continued growth scenario (see Table 7). Alternatively, we calculated the total production costs of ethanol using the experience curve for overall ethanol and found a range of

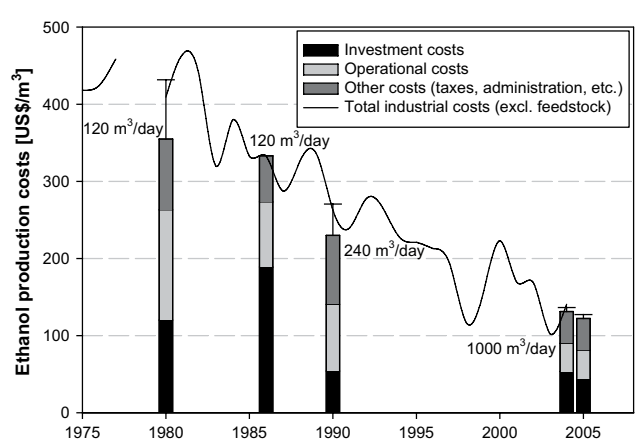

Fig. 10 – Cost breakdowns of the industrial ethanol production process excluding feedstock costs. Note that all studies were carried out under varying circumstances, and that several assumptions had to be made to make all studies comparable (see main text).

[28] The maximum ethanol yield per kilogram sucrose is based on the conversion factor 1.467 [kg sucrose/lit 100% ethanol], which is based on energy basis. The conversion factor for anhydrous ethanol is 0.993 lit/lit and hydrated ethanol 0.96.

Table 3 – Estimated relation between capacity and turn-key investment costs (Various editions of BA; Ref. [11]).

	<1970	1970–1980	1980–1990	1990–2000	>2000
Average capacity of new plants [m^3/day]	≤90	90–120	120–240	240–500	≥500
Average investment cost range of new plants [million US$(2005)]	Not available	22–26	26–30	30–35	55

Table 4 – Development of mill capacities and extraction efficiency [45].

	<1970	1970–1980	1980–1990	1990–2000	>2000
Capacity 54″ (TCH)	130	180	190	210	280
Capacity 78″ (TCH)	270	375	400	440	580
(RPM)	5.5 (turbine)			8.5	
Extraction ($\%_{vol}$)	91–93	93–95.0	94.5–96.0	96.0–97.0	97.0–97.5

223–276 US$/$m^3$ in 2020, i.e. about 7–12% higher production costs compared to the results from the first approach.

A couple of aspects of these scenarios have to be discussed. First of all these production costs may seem rather low compared to the present situation. However, production costs of ethanol described in this report are based on average national production costs. Best cases in Sao Paulo in 2005 already reach production costs as low as 200 US$/$m^3$ [62], which shows that the projected further reduction in production cost are not unrealistic.

Second, from a methodological point of view, we argue that the approach of using two separate experience curves will yield more accurate results, and allows for more detailed assumptions regarding the sugarcane and ethanol growth rates. In addition, the detailed cost breakdowns and qualitative analysis of further cost reduction opportunities provide essential arguments for the extrapolation of the experience curves. The fact that the combined approach also yields lower production costs than the overall approach implies that use of the overall experience curve could lead to a slightly underestimated future cost ranges.

Third, from a practical point of view, we emphasize that production costs are not the same as prices. Since 1999, the ethanol market has been completely deregulated. Thus, prices nowadays are much more influenced by market forces than in the period of 1975–1998. The demand for ethanol is rising national and international. Thus, while production costs will most likely go down further in the future, this does not automatically mean that prices will follow. This implies that the future use of prices as proxy for production costs in Brazil will be far more problematic.

Fourth, besides higher scales, increased yields and load factors, there are more technological breakthroughs leading to further cost reductions to be expected (see Section 6). Major cost reducing potential is expected to be the use of the cellulosic material contributing to approximately 30% of the total energy content of sugarcane [42]. The industry is seriously discussing the several options of collection and transportation of tops and leaves. There are several possible ways to produce additional power, e.g. through combustion or (allowing even higher yields) through gasification and co-firing with natural gas [53]. These routes are not (yet) economical attractive. In time however, it is expected that it would generate an income equivalent of approximately 30% of the cost of sugar and ethanol [37]. Economical feasible collection and transportation methods of sugarcane tops and leaves are expected to become available on a short term [42].

Alternatively to electricity production, increasing the ethanol output through fermentation of cellulose materials in the future could also be an attractive option when oil prices stay high (see e.g. Ref. [29] for further reading).

7.3. *Summary, conclusions and recommendations for further research*

The analysis has shown that the overall costs of bio-ethanol in Brazil have decreased significantly with cumulative production. We have shown that the experience curve approach can also be used to describe the development of the feedstock costs and industrial processing costs. We conclude that the methodological approach of analyzing the feedstock cost and industrial processing costs separately has revealed more

Table 5 – Main fermentation performance indicators, results of a benchmark study by CTC [21].

	Fermentation time	Ethanol % after fermentation	Overall efficiency
1977	14.5	6.2	83
1982	13	7.5	86
1990	8	12	91
2000	8.68	12.73	91.43

Table 6 – Estimated future production costs of ethanol and sugarcane in US$ in 2020. The industrial yield are assumed constant at 82 lit_{hyd}/TC.

	Present cost range (2000–2004)	Estimated future costs (2020)
Sugarcane [US$/TC]	14.9 ± 0.7	9–12
Industrial costs [US$/$m^3$]	161 ± 22	113
Total production costs (as sum of feedstock and industrial costs) [US$/$m^3$]	342 ± 30	223–260

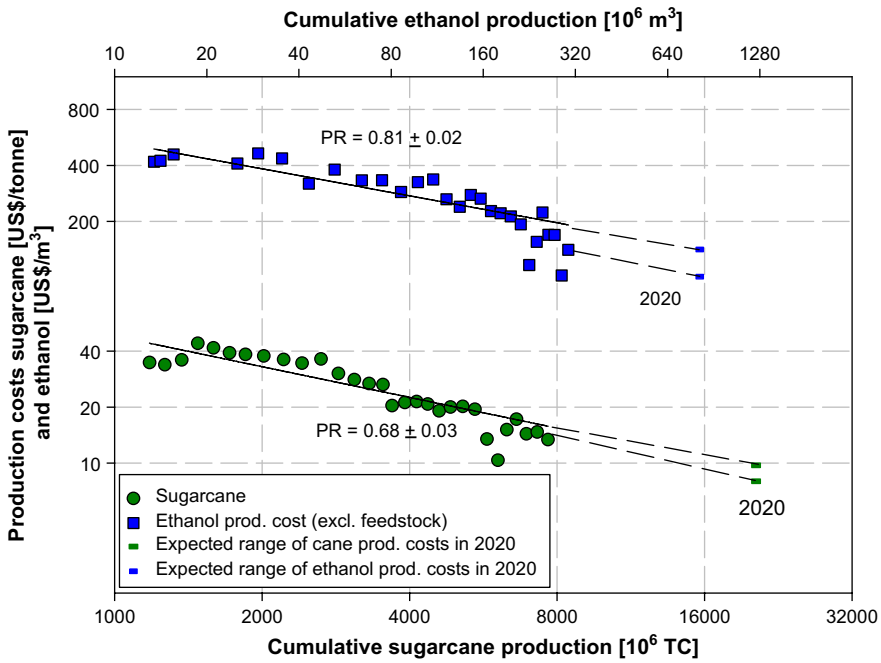

Fig. 11 – Estimated future costs of sugarcane and ethanol production (excluding feedstock costs) assuming 8% annual growth of sugarcane and ethanol production.

Table 7 – Expected production costs[a] of ethanol and sugarcane in US$ in 2020. The industrial yield are assumed constant at 82 lit_{hyd}/TC.

	Present cost range (2000–2004)	Low growth rate scenario (5% growth/year)		Continued growth scenario (8% growth/year)	
		Mean	Range	Mean	Range
Sugarcane [US$/TC]	14.9 ± 0.7	9.6	8.8–10.5	8.8	8.0–9.7
Industrial costs [US$/m^3]	161 ± 22	126	106–147	120	101–141
Total production costs (as sum of feedstock and industrial costs) [US$/m^3]	342 ± 30	243	213–275	227	199–259
Total production costs (from overall experience curve) [US$/m^3]	342 ± 30	262	236–289	249	223–276

a When an alternative exchange rate of US$ = R$3,6 (average for the year 2004) is used the total production costs in 2000–2004 would be around US$218, and in the 8% growth rate scenario costs would be as low as US$160, indicating the sensitiveness of the exchange rate. Comparison of production costs in Brazil and the United States are therefore very difficult.

Table 8 – Effects of applied initial cumulative production values on calculated PR's.

	Cane production cost		Ethanol production cost (excl. feedstock)		Total ethanol production cost	
Initial cumulative production (*CUM*)	*CUM* 1975 (CUM=0)	*CUM* 1941–1974	*CUM* 1975 (CUM=0)	*CUM* 1931–1974	*CUM* 1975 (CUM=0)	*CUM* 1931–1975
Progress ratio ± standard error	0.87 ± 0.02	0.68 ± 0.03	0.91 ± 0.01	0.90 ± 0.02	0.81 ± 0.02	0.80 ± 0.02

detailed insights in the factors behind the cost reductions achieved. It revealed that cost reductions in the sugarcane production actually follow a steeper experience curve (PR of 0.68), thus making ''cane the key'' factor behind the overall cost reductions, especially through achieving increasing yields per hectare. For the industrial processing sub-system, increasing efficiencies and system optimization were found to be the most important factors driving down production costs.

Regarding the estimation of future production costs, the compound system approach, in combination with detailed

cost breakdowns and qualitative analysis of further cost reduction opportunities, allows for a more accurate estimation of further production cost developments. The determined achievable further cost reductions of 200–260 US$/m^3 are impressive compared to current average costs of about 340 US$/m^3, but not unrealistic, as already these low costs can already be achieved nowadays by the best cases in the Sao Paulo ethanol industry.

Another aspect remains to be investigated: Brazilian ethanol is famous as one of the most efficient biofuels in terms of energy balance and greenhouse gas emissions [34]. It is likely that the energy balance also improved over time given the observed increases in amongst other higher yields per hectare, more efficient transportation and higher conversion efficiencies. However, it is unclear how and when the energy balance improved, and whether the experience curve approach would also be suitable to quantify improvements with cumulative production.

Based on the successful analysis of the feedstock and industrial processing costs for the Brazilian case, we recommend further case studies for other successful biofuels. Studies investigating the production of ethanol from corn in the USA and biodiesel from rapeseed in Germany are currently being carried out.

Finally, taking a broader perspective, the Brazilian ethanol case illustrates how early and continued governmental support (so-called ''learning investments'') have led to significant production cost decreases, enabling ethanol from sugarcane as one of the few biofuels to compete directly with gasoline without subsidies. Given the expected further cost reductions and possible high oil prices, it can be expected that the Brazilian ethanol will continue to reap the benefits of this effort. It is also recommended to investigate how the Brazilian experience can be exported to other countries. Many other countries in Latin American, Africa and Asia have significant potentials for sugarcane. Because of the success of the learning in ethanol production in Brazil it is now the challenge to export the Brazilian knowledge and enable these countries to join ''riding down'' the ethanol experience curve.

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REFERENCES

[1] AgroAnalysis. Journal of the Getulio Vargas Foundation March 1995.
[2] Agrianual, various editions. Annual edition of FNP Consultancy; 1996–2005.
[3] Alcool and Açucar. Custo de producao de cana de açucar no Estado de São Paulo; 1985.
[4] Bevington PR. Data reduction and error analysis for the physical sciences. New York, USA: McGraw-Hill; 1969.
[5] Boston Consultancy Group. Perspectives on experience. Boston: Consultancy Group Inc; 1968.
[6] Brasil Açucareiro. Desenvolvimento economico, politica energetica e alcool; May 1980.
[7] Brasil Açucareiro. Colheita da Cana-de-Açucar; April 1977.
[8] Braunbeck O. Personal communication on 6-12-2005. Professor Faculty Engenheria Agrícola. Campinas, Brazil: UNICAMP; 2005.
[9] Braunbeck O, Bauen A, Rosillo-Calle F, Cortez L. Prospects for green cane harvesting and cane residue use in Brazil. Biomass and Bioenergy 1999;17(6):495–506.
[10] Burnquist W. Personal communication on agricultural yields and outlooks, 19-12-2005. Head of the department variety development. Piracicaba, Brazil: CTC; 2005.
[11] Chaves Consultancy. Internal report: indicadores de eficiência agroindustrial e seus impactos nos custos de produção de cana, açúcar e álcool; 2005.
[12] CTC. Internal benchmark report on 15 *usinas* in the state of São Paolo; 2004.
[13] CTC. Simposio de Avaliacao da Agroindustria da Cana-de-Açucar no Estado de Alagoas; 1988.
[14] Damen K. Future prospects for biofuel production in Brazil; A chain analysis comparison of ethanol from sugarcane and methanol from eucalyptus in Sao Paulo state, report NWS-E-2001-31, supervised by Dr. A. Faaij, Department of Science Technology and Society, Utrecht University, Utrecht, The Netherlands, 2001, 68 pp.
[15] Dedini. Internal report on equipment costs, from Olivério, head of Dedini; 2005.
[16] Delfini P. Personal communication on mill technologies, 19-12-2005. R&D Coordinator – CTC. Piracicaba, Brazil; 2005.
[17] Dornburg V, Faaij A. Efficiency and economy of wood-fired biomass energy systems in relation to scale regarding heat and power generation using combustion and gasification technologies. Biomass and Bioenergy 2001;21(2):91–108.
[18] Dutton JM, Thomas A. Treating progress functions as a managerial opportunity. Academy of Management Review 1984;1:235–47.
[19] Eid F. Progresso Tecnico na Industria Sucroalcooleira. In: Informações Economicas, vol. 26; 1996. São Paulo, Brazil.
[20] Finguerut J. Personal communication on fermentation, 19-12-2005. Fermentaçao – CTC. Piracicaba, Brazil; 2005.
[21] Finguerut J. Producao de Álcool: Pesquisa e Desenvolvimento. Piracicaba, SP, Brazil: CTC; 2004.
[22] Geller HS. Energy revolution – policies for a sustainable future. Washington, USA: Island Press; 2003.
[23] Geller HS. Ethanol fuel from sugarcane in Brazil. Annual Energy Review 1985:134–64.
[24] German Federal Ministry of Food, Agriculture and Consumer Protection (BMELV). Biofuels for transportation – Global potential and implications for sustainable agriculture and energy in the 21st century. Washington, D.C; 2006. p. 224–38.
[25] Goldemberg J, Coelho ST, Nastari PM, Lucon O. Ethanol learning curve – the Brazilian experience. Biomass and Bioenergy 2004;26(3):301–4.
[26] Goldemberg J. The evolution of ethanol costs in Brazil. Energy Policy 1996;24:1127–8.
[27] Goldemberg J, Monaco LC, Macedo IC. The Brazilian fuel-alcohol program. In: Johansson BJ, Kelly H., Reddy AKN, Williams RH, editors. Renewables for fuels and electricity, Washington, D.C: Island Press; 1992. p. 841–64.
[29] Hamelinck CN, van Hooijdonk G, Faaij APC. Ethanol from lignocellulosic biomass: techno-economic performance in

short- middle- and long-term. Biomass and Bioenergy 2005; 28(4):384–410.
[30] Hemerly FX. Cadeia produtiva da cana-de-açucar: Alternativas para aumento de sua efficiencia, research for CCTA/UENF.IEA/OECD, 2004. Biofuels for transport – an international perspective. Paris, France: OECD; 2000.
[31] IEA/OECD. Experience curves for energy technology policy. Paris, France: OECD; 2000.
[32] IEA. Biofuels for transport – an international perspective. Paris, France: OECD; 2004.
[33] Joseph H. Usage of ethanol in passenger cars, Anfavea, presented at the workshop and Business forum on Sustainable biomass production for the world market, November 30–December 3, 2005, Campinas, Brazil. Available from: www.bioenergytrade.org; 2005.
[34] Hettinga WG, Junginger HM, Dekker SC, Hoogwijk M, McAloon AJ, Hicks KB, Understanding the reductions in U.S. Corn ethanol production costs: an experience curve approach. Energy Policy, in press, doi:10.1016/j.enpol.2008.08.002 [available online 30 September 2008].
[35] Junginger M, de Visser E, Hjort-Gregersen K, Koornneef J, Raven R, Faaij A, Turkenburg WC. Technological learning in bioenergy systems. Energy Policy 2006;34:4024–41.
[36] Junginger M, Faaij A, Björheden R, Turkenburg WC. Technological learning and cost reductions in woodfuel supply chains in Sweden. Biomass and Bioenergy 2005;29:399–418.
[37] de Carvalho Macedo I, et al. Sugar Cane's Energy – twelve studies on Brazilian sugar cane agribusiness and its sustainability. São Paulo, Brazil: Berlendis & Vertecchia; 2005.
[38] Macedo I, Cortez LAB. Industrial uses of biomass energy – the example of Brazil. London, England; 2000. p. 140–54.
[39] McDonald A, Schrattenholzer L. Learning rates for energy technologies. Energy Policy 2001;29:255–61.
[40] Moreira JR, Goldemberg J. The alcohol program. Energy Policy 1999;27:229–45.
[41] Nastari P. Personal communication on 20-12-2005. President Datagro Consultancy. São Paulo, Brazil; 2005.
[42] Nastari PM, Macedo I. Observations on the draft document: potential for biofuels for transport in development countries. World Bank; 2005.
[43] Neij L, Dannemand Andersen P, Durstewitz M, Helby P, Hoppe-Kilpper M, Morthorst PE. Final report of EXTOOL – experience curves: a tool for energy policy programs assessment. Lund, Sweden; 2003. p. 125.
[44] Neij L. Use of experience curves to analyze the prospects for diffusion and adoption of renewable energy technology. Energy Policy 1997;25:1099–107.
[45] Nunez Gago JS. Personal communication on mill technologies, 19-12-2005. Mill specialist. Piracicaba, Brazil: CTC; 2005.
[46] de Oliveira A. Reassessing the Brazilian alcohol program. Energy Policy 1991;19:47–55.
[47] Olivério JL. Various mail contacts, Vice President – Dedini. Piracicaba, Brazil; 2005.
[48] Orplana. Available form: www.orplana.com.br; 2005 [accessed 12.12.05].
[49] Piacente E. Perspectivas do Brasil no Mercado International de Etanol. Master thesis. University of Campinas; 2005.
[50] Puppim-de-Oliveira JA. The policy making process for creating competitive assets for the use of biomass energy – the Brazilian alcohol program. Renewable and Sustainable Energy Reviews 2002;6:129–40.
[51] Regis M. Personal communication on general trends, 20-09-2005. Campinas, Brazil: Fac. Engenharia Mecânica UNICAMP; 2005.
[52] Remer D, Chai L. Design cost factors for scaling-up engineering equipment. Chemical Engineering Progress 1990; 86:77–81.
[53] Rodriguez M, Faaij A, Walter A. Techno-economic analysis of co-fired biomass integrated gasification/combined cycle systems with inclusion of economies of scale. Energy: The International Journal 2003;28(12):1229–58.
[54] Rosillo-Calle F, Cortez LA. Towards PROALCOOL II – a review of the Brazilian bioethanol program. Biomass and Bioenergy 1998;14:115–24.
[55] Rubin ES, Yeh S, Antes M, Berkenpas M, Davison J. Use of experience curves to estimate the future cost of power plants with CO2 capture. International Journal of Greenhouse Gas Control 2007;1(2):188–97.
[56] van Sark WGJHM. Introducing errors in progress ratios determined from experience curves. Technological Forecasting and Social Change 2008;75(3):405–15.
[57] Snik A. Experience curves for Photovoltaic Energy Technology. Utrecht: Utrecht University; 2002. p. 44.
[58] Unica. Various editions of Informação Unica (internal magazine of Unica); 2000–2005.
[59] Usineiro. A evolucao do custo de producao de cana de açucar dos fronecedores; April 1987.
[60] Vegro CLR, Ferreira T. Comparativo entre evolucao dos precos recebidos e da productividade de culturas, Brasil 1970–1994. In: Informações economicas, vol. 26; 1996. São Paulo, Brazil.
[61] van den Wall Bake JD. Cane as key in Brazilian ethanol industry. Master thesis. Utrecht, The Netherlands, Copernicus Institute, Utrecht University, Available from: http://www.chem.uu.nl/nws/www/publica/publicaties2006/NWS-I-2006-14.pdf; 2006.
[62] Walter A, Rosillo-Calle F, Dolzan P, Piacente E, Cunha KB. Perspectives on fuel ethanol consumption and trade. Biomass and Bioenergy. 2008;32:730–48.
[63] ÁLCOOL ANIDRO NA GASOLINA (em %), National Association of Petroleum, Natural Gas, and Biofuels (ANP), 22 November 2005. Available from: <http://www.alcopar.org.br/estatisticas/Graf_anidroxgasol.pdf>.
[64] Grübler A, Nakicenovic N, Victor DG. Dynamics of energy technologies and global change. Energy policy 1999;27(5): 247–80.
[65] Oanda, 2008,.US$ / R$ average exchange rate over 2005, FXHistory®: historical currency exchange rates. Available at: <http://www.oanda.com/convert/fxhistory> [accessed November 2008].
[66] Ionta, R. Personal communication with Ricardo Ionta, manager maintenance at Cosan Group (sugar and ethanol producer), autumn 2005.