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An Assessment of Biomass Supply Chain: A DEA Application

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Renewable energy generation reduces carbon emissions and responds to the targets for renewable energy sources of most EU countries; it also enhances infrastructure resilience and creates flexibility of the energy matrix. However, the availability of biomass may drastically differ from country to country within the EU. In most cases, the most challenged countries to achieve high targets for sustainability are not those with a sufficiently large supply of biomass. Because of this, it is necessary to design new biomass supply chain networks and improve the existing networks. This paper aims to assess the efficiency of biomass alternative pathways of the supply network from South America to Europe. In this particular work, three scenarios of biomass using two transportation systems were investigated, i.e., transportation of wood logs, *pellets and torrefied biomass in the country of origin by truck and train transportation.* Efficiency was measured using a data envelopment analysis (DEA) model derived *from CCR. The results present the most efficient supply chain alternatives and highlight* the feasibility of establishing closer cooperation between Brazil and countries in Europe for green energy generation. This information can assist in the process of planning and decision-making to determine the practicability of the implementation of torrefaction facilities using the most efficient logistical pathways.

Keywords: Bio-based economy, Biomass, Brazil, Data Envelopment Analysis, Supply Chain Efficiency.

Introduction

In an uncertain economic environment, a development of strong energy supply chain networks is crucial. Most of the European countries have been pressed to reduce carbon emissions for generating power (European Comission, 2017). Among alternatives, there is electricity production through biomass consumption. In most of the cases, European countries, like the United Kingdom, do not have a sufficiently large stock of biomass for attending demand. On the

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other hand, Brazil has the second largest forest in the world, corresponding to 54.4% of its territory (MMA, 2013).

In this context of international trade, DelfimNetto and Ikeda (2007) describe the process of economic development like a combination of thermodynamics and economics: it captures the available energy in the environment and dissipates it again in the productive process. For this reason, the first limiting factor of growth in a country is the availability of energy and the second is the ability to import it, considering: (i) the physical volume of its export; (ii) the relative price of its export measured in terms of its import price.

To evaluate the process described in this article, we used the Data Envelopment Data (DEA), a popular tool for measuring productivity in complex production systems. Charnes et al. (1978) developed DEA based on the frontier production concept of Debreu (1951) and Farrell (1957). It permits the analysis of a group of Decision Making Units (DMUs), according to chosen parameters (inputs and outputs) returning a ranking of the efficiency of DMUs. The DEA may also be used as a multi-criteria decision-making (MCDM) tool, where each alternative is a DMU, the inputs are usually “less-the-better” of performance type and outputs are “more-the-better” type (Cook et al., 2014).

Since 1978, scientific research has expanded DEA applications, using and developing several models. Castro and Frazzon (2017) concluded that there two clusters in academic research about the benchmark of units: one that collectively utilizes several benchmark methods and another that utilizes DEA models. Melo et al. (2017) applied DEA for benchmarking grain supply chain alternatives in Brazil and in the United States.

The literature review was a structured focus on applications of DEA in supply chains. We searched in May 2017, in Scopus database of the following words ‘data envelopment analysis’ and ‘supply chain’, limited by articles. We found 256 papers, 50.39% of them were published from 2013 on, indicating the increasing relevance of the theme in recent years. Gridgoroudis et al. (2014) applied Recursive Data Envelopment Analysis (RDEA) for the development of an optimal supply chain network of biomass for energy generation from Asia to Europe. But this paper considers multi-echelons of supply chain and not horizontal supply chains as ours.

Besides DEA applications as Gridgoroudis et al. (2014), among the most relevant regarding biomass supply chain modelling, exploring other alternative solutions it is relevant to mention: Forsberg (2000) applied life cycle inventory (LCI) to select bioenergy long-distance transportation chains, considering options of bales, pellets, solid biofuels, and electricity via international grid. Hamelinck et al. (2005) analyzed bioenergy supply chains from Europe and Latin America delivered in Western Europe, considering generic data such as distance, timing and scale of performance. Kanzian et al. (2013) used the weighted sum scalarization approach to optimize the solution of biomass supply network in Mid-Europe. Rentizelas and Li (2016) analyzed the feasibility of long-distance bio-energy supply chains.

Guimarães and Piefer (2016) concluded that, despite the great potential of the partnership between Brazil and Europe, the first as a biomass supplier and the second as a biomass consumer and a technology supplier for alternative energy sources, this partnership is not developed due to several barriers. Among obstacles, there is a lack of information and public knowledge. Given the previous context, this paper aims to investigate and benchmark supply chain alternatives of wood-derived biomass from Brazil to the United Kingdom.

System Description

Eucalyptus plantations cover 5.6 million hectares of planted tree area of Brazil. Their forests are located primarily in the following states: Minas Gerais (MG) (24%), São Paulo (SP) (17%) and MatoGrosso do Sul (MS) (15%). Pine plantations cover 1.6 million hectares, concentrated in Paraná (PR) (42%) and Santa Catarina (SC) (34%) (IBA, 2016). We choose this origin states guided by: (i) the states with the current largest planted area, considering jointly eucalyptus and pines, i.e., Minas Gerais, São Paulo, MatoGrosso do Sul, Paraná and Santa Catarina (IBA, 2016); (ii) the states that are currently main wood exporters, Rio Grande do Sul and Amapá (MDIC, 2016).

The main ports that currently export wood were incorporated into the alternatives, i.e., Rio Grande (BR RIG), Santos (BR SSZ), São Francisco do Sul (BR SFS), Paranaguá (BR PNG), Itajaí (BR ITJ), Vitória (BR VIX) and Rio de Janeiro (BR RIO). The United Nations Code for Trade and Transportation Logistics (UN/LOCODE) is in brackets (MDIC, 2016). The routes and freight modes of transportation from principal state forests and exporting ports were drawn based on the National Infrastructure of Spatial Data (INDE, 2016). Table 1 summarizes the system description.

Table 1. Summary of the Brazilian System Description

Eucalyptus Producing States
Minas Gerais (MG)
São Paulo (SP)
Mato Grosso do Sul (MS)

Pine Producing States
Santa Catarina (SC)
Paraná (PR)

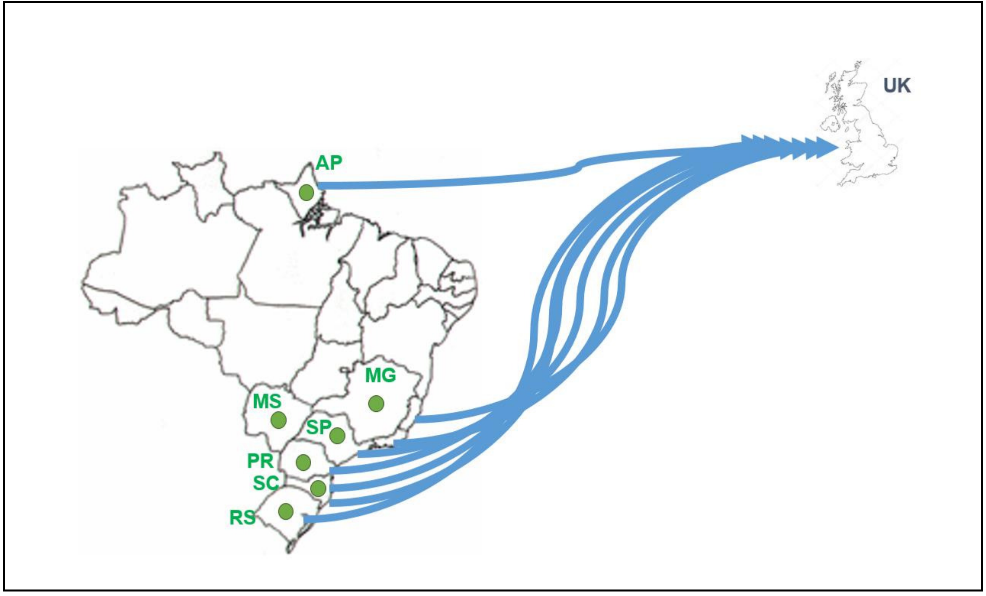
Wood Exporting States
Amapá (AP)
Rio Grande do Sul (RS)

Wood Exporting Ports	**UN/LOCODE**
Rio Grande	BR RIG
Santana	BR SAN
Santos	BR SSZ
São Francisco do Sul	BR SFS
Paranaguá	BR PNG
Itajaí	BR ITJ
Vitória	BR VIX
Rio de Janeiro	BR RIO

Source: The authors based on IBA (2016) and MDIC (2016).

Figure 1 represents the position of each analyzed state of origin (abbreviations in green) and maritime routes (without scale).

Figure 1. Sketch of States of Origin and Maritime Routes (without Scale)



Three main supply chain scenarios were investigated, as follows:

Scenario 1 (named W and AW): The biomass (logs) is taken from Brazilian forests and sent to the UK, where it is torrefied and utilized in power generation. Ten main transportation routes (named here 'cases') by truck exclusively (named W followed by a digit from 1 to 10) were identified. Ten cases with alternative modes of transportation were identified (named AW followed by a digit from 1 to 10).

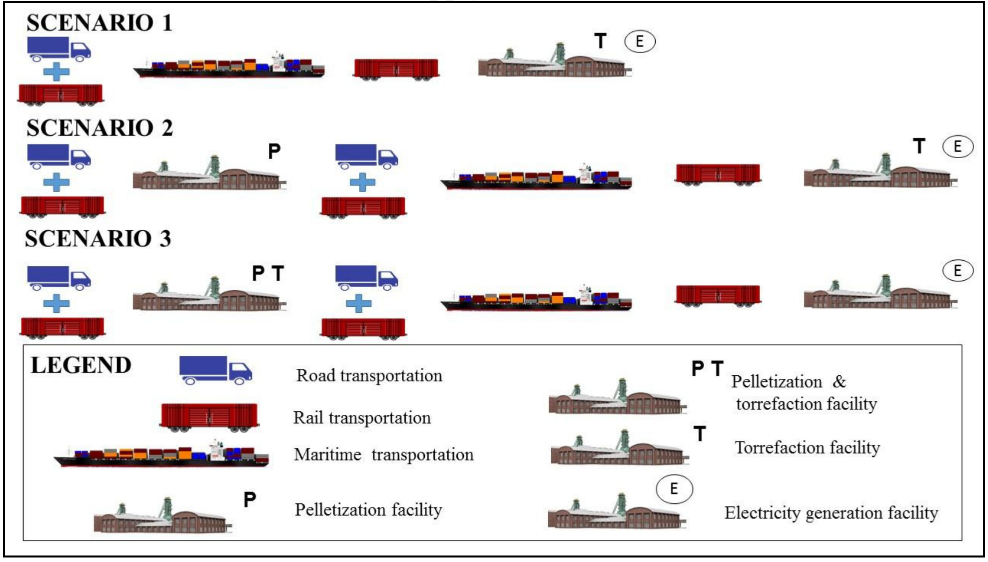
Scenario 2 (named P and AP): The logs are taken from the forest, pelletized in Brazil and exported. In the UK, pellets are torrefied and utilized for power generation. Ten cases of transportation by truck (named from P1 to P10) and two cases of alternative modes of freight transportation (named from AP1 and AP2).

Scenario 3 (named Q and AQ): The logs are taken from the forest, pelletized and torrefied in Brazil and exported. But the torrefaction plants do not presently exist in Brazil yet. This scenario considers a potential future solution that will require investment in torrefaction technology. Ten cases of transportation by truck (named from P1 to P10) and two cases of alternative modes of freight transportation (named from AP1 and AP2).

All scenarios consider unloading in the port of Immingham (GB IMM), which is one of the main ports handling biomass in the UK and rail transportation up to DRAX power plant, as a representative example of a large-scale biomass firing electricity generation facility.

Figure 2 is a schematic sketch of supply chain alternative scenarios. All cases are horizontal, i.e., only one unit (wood or facility) is considered for each case. The multiples echelons are not considered due to the limitations of the infrastructure of Brazil and the wide distances. It is considered that it is only possible to process the biomass in the geographically closest facility.

Figure 2. Schematic Sketch of Supply Chain Alternative Scenarios



Methodology

The choice of the most appropriate DEA model and variables for solving a specific question is not a trivial one. Golany and Roll (1989) guided the choice of models and variables existing until that year. Cook and Seiford (2009) broadened it, publishing a taxonomyof general of DEA models. Cook et al. (2014) reviewed procedures of choice. All papers emphasize the importance of viewing the whole 'process' for applying DEA, the use of reliable data and focus on the main objective. Hence, this paper focused on working with the minimal possible variables that could explain the 'process' and relied on trusted data: energy consumption, emissions, and costs. The specific input variables are also the ones of the primary interest for the decision makers.

For freight transportation, we calculated the emissions and the fuel consumption with software EcoTransIT (2016). The software default parameters are shown in Table 2. Logistics costs came from ESAQ-LOQ database, the official agricultural Brazilian logistics database (SIFRECA, 2016).

Table 2. Parameters Utilized for Freight Emissions and Energy Consumption

EcoTransIT Parameters	Road Freight	Rail Freight
Input mode	Extended	Extended
Amount	100	100
Unit	Bulk and Unit Loads (Tonnes)	Bulk and Unit Loads (Tonnes)
Type	Average goods	Average goods
t/TEU	10	10
Origin	City district	City district
Transport mode	Truck	Train
Vehicle type	26-40t	Average Train (1000t)
Emission standard	EURO5	Diesel
Load factor	100%	100%
Empty Trip Factor	50%	50%
Destination	UN/LOCODE	UN/LOCODE

Source: EcoTransIT 2016.

Table 3. Assumed Production Parameters

Torrefaction& Pelleting plant			Pelleting plant	
Both processes co-located - output: black pellets			**Output: white pellets**	
Parameters	**Assumptions**	**Sources**	**Assumptions**	**Sources**
Reference capacity	200,000 tons Dry substance/year (output)	Svanberg et al. (2013)	200,000 tons Dry Substance/year (Output)	Uslu et al. (2008)
Capital expenditure for reference capacity	45.5 Million Euros (2013 values)	Svanberg et al. (2013)	9.43 Million Euros (2014 values)	Uslu et al. (2008)
Maintenance cost for reference capacity	2% of capital expenditure per year	Svanberg et al. (2013)	5% of Capital expenditure per year	Uslu et al. (2008)
Personnel required for reference capacity	24	Svanberg et al. (2013)	Assumed the same as in torrefaction	
Scale factor	0.7	Svanberg et al. (2013)	0.7 – 0.8	Uslu et al. (2008)
Energy input in process	193 kWh electricity per produced ton	Batidzirai et al. (2014)	22 kWh electricity per produced ton	Batidzirai et al. (2014)

Source: Authors based on the identified references.

We assumed production parameters based on literature as summarized in Table 3. We considered all costs in US dollars, converting to the average dollar quotation in the last 12 months. All calculations were done considering that 1 ton of torrefied biomass will achieve its final destination, the power plant and that there is a material loss of 1% for each stage of transportation.

Table 6 under Appendix presents the utilized calculated data. Golany and Roll (1989) suggested the following process for differentiating inputs and outputs: to perform the linear regression for each variable “one at once”. A variable believed as input that presents a weak relationship with other variables (believed to also inputs) and a strong relationship with other variables believed to outputs may be, indeed, an input. The opposite is also true. The authors accentuated that this may not be considered a reliable rule, only an indication for carefully examining variables. Table 4 presents the results of correlation among variables proposed as inputs.

Table 4. The Linear Regression Results

Correlations				
		Cost (USD/ton)	**Energy (MJ/ ton)**	**Emissions (kg of CO_2eq/ton)**
Cost (USD/ton)	Pearson Correlation	1	0.364^{**}	0.255^{*}
	Sig. (1-tailed)		0.008	0.047
	N	44	44	44
Energy (MJ/ ton)	Pearson Correlation	-0.364^{**}	1	0.273^{*}
	Sig. (1-tailed)	0.008		0.036
	N	44	44	44
Emissions (kg of CO2eq/ton)	Pearson Correlation	0.255^{*}	0.273^{*}	1
	Sig. (1-tailed)	0.047	0.036	
	N	44	44	44

* Correlation is significant at 0.01 level (1-tailed).
** Correlation is significant at 0.05 level (1-tailed).

As can be seen in Table 4, all variables present a correlation at the confidence level of 0.01% (emissions - cost, emissions – energy) or 0.05% (energy – cost). As expected they also present a weak correlation, respectively, 0.255, 0.273, and -0.364. The negative signal between energy and cost is expected, once more requested energy normally implies into a higher freight cost.

The DEA models differ in orientation, they may minimize inputs, maximize outputs or do both simultaneously. The DEA also can be constant or variable in scale (Mariano and Rebelatto, 2014). In this case, we considered the use model with a constant scale, because all alternatives consider a constant and equal production. As all variables were calculated considering the delivery of 1 ton of torrefied biomass at the final destination and they present a weak relationship between each other, it was assumed a model where the variable where all inputs to be minimized with a unitary output. This case is similar to the index known as Benefit of Doubt (BoD) (OECD, 2008) and it can be mathematically represented as follows:

$$\mathrm{Max} = \sum_{i=1}^{m} u_i \cdot y_{i0}$$

Subject to:

$$\sum_{j=1}^{n} v_j . x_{j0} = 1$$

$$\sum_{i=1}^{m} u_i \cdot y_{ik} - \sum_{j=1}^{n} v_j . x_{jk} \leq 0,\ k = 1,2,\ldots, z \qquad (1)$$

Where:

u_i = calculated weight to the product i

v_j = calculated weight to the product j

x_{jk} = quantity of input j to unit k

y_{ik} = quantity of output i to unit k

x_{j0} = quantity of input j to analyzed unit

y_{i0} = quantity of output i to analyzed unit

z = number of analyzed units

m = number of products types

n = number of inputs types

u_i and $v_j \geq 0$

Results

Through the evaluation of the proposed method, we measured the efficiency of the biomass supply chain alternatives from Brazil to the UK. We used the MATLAB software to calculate the efficiencies through DEA – CCR model with input orientation and Excel to tabulate the results. Table 5 presents the results of efficiency for the 44 analyzed DMUs.

Table 5. Results of the DEA Model

Code	Origin	Mode	Destination	Efficiency
AQ2	Lages (SC)	Rail	São Francisco do Sul (SC)	1
W3	Amapari (AP)	Road	Santana (AP)	1
AW7	Guarapuava (SC)	Rail	São Francisco do Sul (SC)	1
Q9	Telêmaco Borba (PR)	Road	Paranaguá (PR)	1
AW10	Cataguases (MG)	Rail	Vitória (ES)	1
AW4	Vespasiano (MG)	Rail	Vitória (ES)	0.999671213
AW3	Três Lagoas (MS)	Rail	Paranaguá (PR)	0.990185519
AW2	Três Lagoas (MS)	Rail	São Francisco do Sul (SC)	0.989929028
P9	Telêmaco Borba (PR)	Road	Paranaguá (PR)	0.962718822
P8	Amapari (AP)	Road	Santana (AP)	0.937295693
AW6	Apucarana (PR)	Road + Rail	Paranaguá (PR)	0.936260377
Q8	Oiapoque (AP)	Road	Santana (AP)	0.90896032
Q4	Canoinhas (SC)	Road	São Francisco do Sul (SC)	0.905362054
Q5	Lages (SC)	Road	Itajaí (SC)	0.901977036
P4	Canoinhas (SC)	Road	São Francisco do Sul (SC)	0.89982068
P5	Lages (SC)	Road	Itajaí (SC)	0.885481336
W9	Canoinhas (SC)	Road	Itajaí (SC)	0.869859994
AW5	Telêmaco Borba (PR)	Road + Rail	Paranaguá (PR)	0.847521405
W10	Lages (SC)	Road	São Francisco do Sul (SC)	0.840384236
W8	Telêmaco Borba (PR)	Road	Paranaguá (PR)	0.82503575
W1	Encruzilhada do Sul (RS)	Road	Rio Grande (RS)	0.824924192
AW1	Encruzilhada do Sul (RS)	Road + Rail	Rio Grande (RS)	0.819762178
W7	Conceição da Barra (MG)	Road	Rio de Janeiro (RJ)	0.809988121
Q6	Conceição da Barra (MG)	Road	Rio de Janeiro (RJ)	0.786761933
AW9	Lages (SC)	Road + Rail	São Francisco do Sul (SC)	0.77179443
AW8	Lages (SC)	Road + Rail	Rio Grande (RS)	0.767323628
Q10	Telêmaco Borba (PR)	Road	Paranaguá (PR)	0.75872525
W4	Bauru (SP)	Road	Santos (SP)	0.757671913
Q1	Bauru (SP)	Road	Santos (SP)	0.738886529
P10	Telêmaco Borba (PR)	Road	Paranaguá (PR)	0.732920655
AP2	Lages (SC)	Rail	São Francisco do Sul (SC)	0.730892085
Q3	Encruzilhada do Sul (RS)	Road	Rio Grande (RS)	0.730006651
Q2	Bauru (SP)	Road	São Francisco do Sul (SC)	0.72449231
P6	Conceição da Barra (MG)	Road	Rio de Janeiro (RJ)	0.718733021
AQ1	Encruzilhada do Sul (RS)	Road + Rail	Rio Grande (RS)	0.693147126
W5	Bauru (SP)	Road	São Francisco do Sul (SC)	0.684363535
P1	Bauru (SP)	Road	Santos (SP)	0.680087659
W2	São Jorge do Oiapoque (AP)	Road	Santana (AP)	0.67798574
P3	Encruzilhada do Sul (RS)	Road	Rio Grande (RS)	0.653977178
P2	Bauru (SP)	Road	São Francisco do Sul (SC)	0.652917189
AP1	Encruzilhada do Sul (RS)	Road + Rail	Rio Grande (RS)	0.644293407
Q7	Três Lagoas (MS)	Road	São Francisco do Sul (SC)	0.587773673
W6	Três Lagoas (MS)	Road	São Francisco do Sul (SC)	0.576082562
P7	Três Lagoas (MS)	Road	São Francisco do Sul (SC)	0.535065029

Discussion

Cases with alternative modes of transportation were more efficient than those with exclusively road transportation. Considering the 11 most efficient DMUs (25%), seven of them presented alternative modes of transportation. On the other hand, considering the 11 least efficient DMUs (25%), only two of them presented alternative modes of transportation, suggesting that rail freight may be a factor that contributes for increasing efficiency.

Both cases that count on rail transportation are originated in Southern State Rio Grande do Sul (RS) and the destination port of Rio Grande, one of them belongs to Scenario 2 (AP1) and another to Scenario 3 (AQ1). This fact may that the current rail infrastructure (rail web) in the region is not the most adequate for flowing wood production. Although RS is the greatest wood exporting Brazilian state, the closest terminals from the woods do not operate with wood products. The results suggest that decision makers should focus investments in rail infrastructure of Rio Grande do Sul (RS).

The most efficient cases are concentrated in a specific scenario? Figure 3 presents the cases of Scenario 1 that are among the most and the least efficient quarters. Scenario 1 considers direct exportation of wood logs. There are seven cases among the most efficient and only three among the least, suggesting that direct exportation of logs tend to be more efficient in the current conditions.

Figure 3. Summary of the Cases of Scenario 1

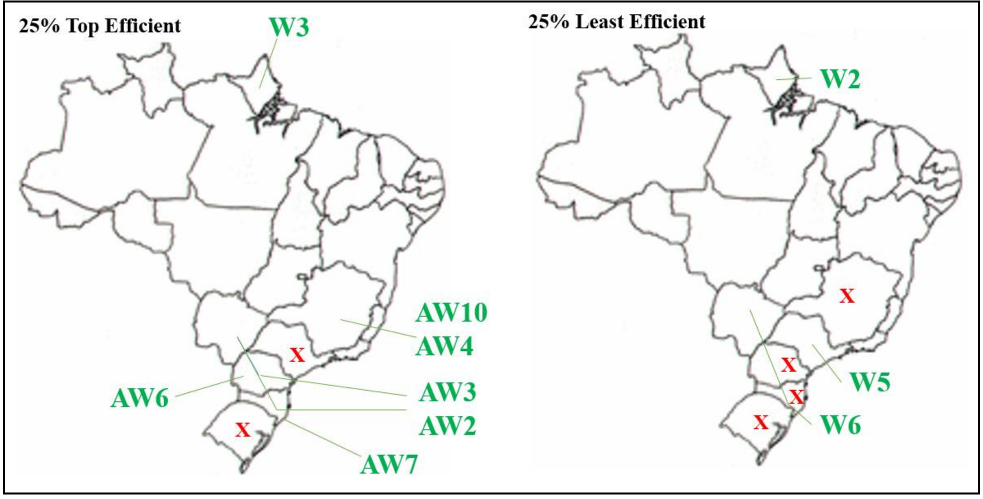


Figure 3 points that cases originated from São Paulo (SP) and Rio Grande do Sul (RS) are not among the most efficient. In contrast, there are neither cases originated from RS among the least efficient, suggesting RS is at an intermediary condition of efficiency. Six of the seven cases of the efficiency of Scenario 1 count on rail transportation.

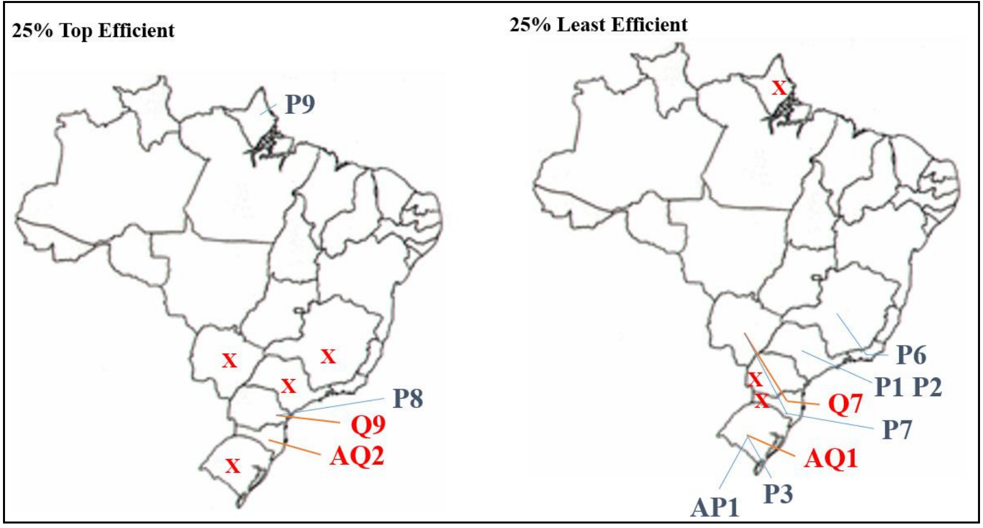
The only exception, i.e. an efficient case without rail freight, is W3, originated in the Amazon State of Amapá (AP). This is a short-distance case because the wood is close to the exporting port of Santana. The W2 is a case from the same state that is among the least efficient, because, in this case, the analyzed wood was more distant from the port, reinforcing that road transportation may be efficient only for short-distance routes. MatoGrosso do Sul (MS) simultaneously present cases among the most efficient (AW2 and AW3) and the least (W6). For this state, the same wood was considered as the point of origin, the distance is the same and the difference is the use of trains for increasing the efficiency. It is remarkable to remember that the biggest cellulose plants of Brazil are in MS.

Another observation is that only cases from Minas Gerais (MG) through the port of Vitória (AW10 and AW4) were considered efficient. The cases originated from the same State, but exported through the port of Rio de Janeiro were not among the efficient, suggesting the longer distances and port fees may be factors that reduce efficiency. But the port of Vitória is focused on ore exportation, if the ore demand is high, port fees may become prohibitive for wood exportations.

For decision makers, it means the most efficient cases that should be the focus of deeper investment studies are those that involve exporting logs by road from Amapá (W3) and logs by rail from Paraná (AW6) and Santa Catarina (AW7).

To keep the investigation whether the most efficient cases are concentrated in a specific scenario, Figure 4 presents the cases of Scenario 2 and 3 that are among the most and the least efficient quarters. The Scenario 2 considers the existing pellet facilities and the exportation of biomass in pellet format. The Scenario 3 considers the cost construction and operation of torrefaction facilities jointly to the existing pellet facilities and the exportation of terrified biomass.

Figure 4. Summary of the Cases of Scenario 2 and Scenario 3



Among the most efficient, there are two from Scenario 2, one from Paraná (P8) and one from Amapá (P9). There are two cases from Scenario 3, one from Paraná (Q9) and one from Santa Catarina (AQ2). The last present alternative mode of transportation. They are all short-distance routes. That suggests decision makers may deeper investment prospects in these States.

Among the least efficient quarter, there are six cases of the Scenario 2 and two of the Scenario 3. Two cases are originated in Rio Grande do Sul and considers an alternative mode of transportation (AQ1 and AP1), reinforcing the use of rail in this State is not adequately distributed for wood transportation. There are no cases originated from Amapá, Paraná and Santa Catarina among the least efficient. The inefficient case from Minas Gerais utilizes the port of Rio de Janeiro for exporting.

For decision makers, this represents that using biomass from Amapá (logs or pellets) transported by road (there is no operating rail infrastructure yet in the State) may be the focus of investment analysis. It equally points that the use of biomass (logs and torrefied biomass) from Paraná and Santa Catarina transported by rail may be interesting, as well as pellets from Paraná.

The decision to build a torrefaction facility may be focused on these two States. Investments in rail infrastructure should be focused on Amapá and Rio Grande do Sul. The DEA results pointed out the priority may not be on MatoGrosso do Sul, Minas Gerais, and São Paulo.

MatoGrosso do Sul is the Brazilian state with largest forest planted area, but it is in a central position, simultaneously far from Atlantic and Pacific Oceans and it counts with the biggest cellulose factories of the continent. The exclusion of São Paulo and Minas Gerais from the top performer alternatives may be due to the expensive logistics costs, mainly port fees. It is important to remember that a significant percentage of the wood produced in Minas Geraisis already used for steel production and in São Paulo for cellulose.

Conclusions

This paper utilized the data envelopment analysis (DEA) to analyze alternatives of biomass supply chain from Brazil to the United Kingdom (UK). The pool pointed that exporting it without refined processes, i.e., in logs, may the most efficient solution; exporting it in pellet format may be efficient only considering Northern State of Amapá and Southern State of Paraná; and installing a torrefaction plant in Brazil may create an efficient supply chain depending on the region, but further investment analysis may be performed. It is important to mention that, although alternatives were compared and the best performers identified, this does not mean they are profitable, once this was not the focus of the study.

In this context, according to the Central European Biomass Conference (2014) in Graz, Austria, several torrefaction technology companies can invest in plants at full scale. These plants, due available biomass resources, can be most likely be situated in Brazil, Asia, Eastern Africa, etc.

Considering the biomass Borges et al. (2016) found that torrefaction is feasible for the energy conditioning of Eucalyptus biomass (5.6 million hectares of planted tree area of Brazil.) and improves the biomass to a higher quality biofuel. Therefore, the logistics aspects are improved due to torrefaction. The process causes significant changes in Eucalyptus properties, reducing water and increasing energy density, in this way, permitting the transportation of more energy with less consumption and emissions. Our paper pointed out that, although torrefied biomass reduces volume and increase energy storage, the installation of new torrefaction facilities may be economically interesting only in some Brazilian States, such as Paraná and Santa Catarina, due to mainly logistics obstacles for flowing biomass from plants to exporting ports (distance and costs). Due to this, Brazil can be an interesting place to future investments in torrefaction industry. A final decision demands further studies on investments, given that several aspects of the decision making regarding investments are beyond the scope of this paper.

The DEA model proved to be useful once it excluded low performer options. It also pointed to Paraná, Santa Catarina, and Amapá as the most efficient alternatives, while highlighted the condition in which intermediary may improve (Rio Grande do Sul with rail transportation). DEA is a useful tool for decision-makers in any condition where it is important to determine which alternative present the best performance. Furthermore, it determines the alternatives in which investments should focus on, and provides several suggestions on how to improve the performance average of analyzed alternatives. The application of DEA for supply chain performance is relatively new but promising.

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Appendix

Table 6. Calculated Data

Code	Cost (USD/ton)	Energy (MJ/ ton)	Emissions (kg of CO_2eq/ton)
W1	128.55	12269.851	397
W2	140.68	15524.931	642
W3	94.32	10565.798	270
W4	142.49	13263.121	472
W5	141.53	15298.39	624
W6	168.34	18166.013	840
W7	123.94	12760.522	433
W8	119.64	12605.041	401
W9	114.12	11931.062	371
W10	115.05	12465.925	411
AW1	143.59	11808.067	364
AW2	179.91	9477.541	188
AW3	177.76	9475.086	188
AW4	141.42	9389.786	180
AW5	147.40	11119.273	313
AW6	137.13	10020.816	228
AW7	123.72	9452.137	185
AW8	187.79	12227.035	394
AW9	167.45	12156.207	389
AW10	126.70	9382.093	180
P1	118.47	31477.913	478
P2	123.40	33080.041	601
P3	123.20	32201.176	531
P4	89.54	29458.748	330
P5	90.99	29393.471	322
P6	112.10	31530.561	482
P7	153.04	36251.223	839
P8	85.96	29247.754	308
P9	83.69	28658.214	266
P10	109.93	31464.807	477
AP1	125.91	30946.996	440
AP2	140.45	27005.143	145
Q1	114.83	23406.085	361
Q2	116.52	24291.188	430
Q3	116.21	23702.734	382
Q4	90.35	21492.484	220
Q5	90.92	21409.128	212
Q6	106.43	22984.991	329
Q7	146.99	27550.046	674
Q8	89.82	21529.803	218
Q9	80.57	20331.702	130
Q10	110.75	23559.36	372
AQ1	124.91	23173.145	346
AQ2	145.03	19265.754	53