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Exergy analysis: A tool to study the sustainability of food supply chains

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Abstract

This paper explores the potential of using exergy analysis to study and compare the environmental impact of food supply chains. The method identifies the links where exergy destruction takes place and shows where improvements are possible to minimize this destruction. The supply chains of three products were investigated: pork mincemeat, novel protein food (NPF) made from dry peas and pea soup. Exergy content and requirements of the various streams, products and processes were calculated for the three chains. As exergy is expressed in one unit, the Joule, the inputs and outputs of each chain are easily comparable. The contributions of the links to the total exergy loss are different in each chain. In the NPF chain, greatest input is required in the processing link whereas for the pork chain, primary processing and transportation require the highest inputs. The NPF chain is only slightly more efficient (1.2 times) than the pork meat chain. Such analyses are also useful in the design and redesign of supply chains.

Keywords: Exergy; Food supply chain; Environmental impact; Novel protein food

1. Introduction

At the turn of the 19th century, the earth's population was one billion. Over the next 100 years this number almost doubled and today it is more than 6.4 billion (US Bureau of the Census). It is only obvious that these growing numbers of people require increasingly larger amounts of food and fuel to meet their needs. However, there is an increasing awareness in the industrialised world that the present food production and consumption patterns were far from sustainable and had a heavy environmental burden (Pimentel et al., 1999; Tilman et al., 2001). To reduce the negative effects caused by these trends and to avoid sub-optimisations, systems analysis studies are needed; starting with simple products and as knowledge is gained and the methods are improved, shifting to more complex products and whole diets (Andersson & Ohlsson, 1999).

The World Commission on environment and development defined sustainable development as meeting the [human] needs of the present without compromising the ability of future generations to meet their own needs''. The relationship between sustainable development and the use of resources, fuel, food, land, water is very significant (Dincer & Rosen, 2004). It became obvious that using resources more efficiently would reduce the environmental impact of emissions. This was called 'energy conservation' (Rosen & Dincer, 2001). However, an examination of thermodynamic principles

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reveals that the focus on energy conservation as a strategy is at best incomplete and at worst wholly incorrect. As energy is converted from one form to another, it is neither lost nor destroyed. It does, however, "lose a certain quality which can be described as its ability to do work" (Torrie, 1981). For example, the heat in exhaust air and warm water has low quality, while electric energy has high quality. As conventional energy analysis fails to recognize this distinction, wasteful policies are often implemented. The amount of work that can be extracted from a fuel source in principle is actually larger than the amount of work that is actually produced from the fuel (Simpson & Kay, 1989).

This available energy or available work or quality of energy is called exergy. It measures the ability of a source to produce useful work. Exergy is therefore a thermodynamic unit that gives a numerical value to energy quality. It can also be defined as a physical concept that quantifies the usefulness or value of energy and material (Wall, 1977, 1986). Exergy is thus the maximum amount of work that can be extracted from a system (any specified collection of matter under study).

The concept of exergy is based on the First and Second Law of Thermodynamics (Szargut, Morris, & Steward, 1988). In contrast to energy, exergy is exempt from the law of conservation. In real processes, exergy input always exceeds exergy output. This is due to exergy destruction, also called irreversibility or lost work. Every real process has exergy losses leading to the reduction of the useful effects of the process or to an increased consumption of inputs from where the product was derived. The difference between exergy destruction or irreversibility and exergy waste or exergy flow to the environment is important.

Simpson and Kay (1989) illustrate the concept with the following example. The water at the top of a waterfall has gravitational potential energy due to its height above a gorge. This energy is transformed into kinetic energy as the water drops over the falls. The kinetic energy of the falling water can be used to produce work. The original gravitational potential energy that the water possessed at the top of the falls is converted to heat energy and also into sound energy – the roar of the falls. The water at the bottom of the falls is one eighth of a Celsius degree warmer than the water at the top per 100 m difference in height. This heat energy is caused by the friction of the water molecules colliding against one another and against the rocks. The total amount of sound and heat energy at the bottom of the falls is exactly equal to the total amount of gravitational potential energy at the top of the falls. The essential difference between the two forms of energy is that the high quality concentrated gravitational potential energy at the top of the falls can be harnessed to perform work – to run an electric generator for example – whereas the low quality sound energy and heat energy at the bottom is too dispersed to be of use.

Exergy analysis is a relatively new technique based on the above concept. An exergy balance when applied to a process or a whole plant shows how much of the available work potential supplied as the input to the system under consideration has been consumed (irretrievably lost) by the process (Kotas, 1986). It enables the determination of the location, types and magnitudes of wastes (streams that still contain exergy) and losses (exergy is irreversibly lost).

Life cycle assessment (LCA), which is a method for analysis and assessment of the environmental impacts caused by production systems, is commonly used for such analyses (Andersson, 2001; Guinee, 2002). The components of exergy analysis are more or less the same as in LCA. A drawback of LCA is that incomparable factors like global warming, acidification and ecotoxicity are taken together to generate one final figure for environmental impact. The major difference between the methods however, is that exergy analysis takes all energy forms (food/fuel) into account with respect to their ability to do work in a physical sense (Dincer & Rosen, 2004). Thus conversion factors between electricity, natural gas, diesel, etc. are not needed.

A supply chain (SC) is an integrated process where raw materials are acquired, converted into products and then delivered to the consumer (Beamon, 1998). It is thus a possible pathway to manufacture and deliver a particular product to a consumer (Apaiah, Hendrix, Meerdink, G, & Linnemann, in press). The chain is characterised by a forward flow of goods and a backward flow of information. Food supply chains are made up of organisations that are involved in the production and distribution of plant and animal-based products (Zuurbier, Trienekens, & Ziggers, 1996). Such SCs can be divided into two main types (van der Vorst, 2000):

- SCs for fresh agricultural products: the intrinsic characteristics of the product remain virtually unchanged and,
- SCs for processed food products: agricultural products are used as raw materials to make processed products with a higher added value.

A food SC as defined in this paper consists of six links: primary production, ingredient preparation, product processing, distribution, retail and the consumer (Fig. 1).

Exergy analysis has been used successfully in the chemical industry (Cortez & Larson, 1997; Morris, 1991; Szargut et al., 1988). It has been applied in the food industry in many areas (Fang, Larson, & Fleischmen, 1995; Iibuchi, Yano, Kawashima, & Nakagawa, 1982; Midilli & Kucuk, 2003; Rostein, 1983; Tekin & Bayramoglu, 1998, 2001). However these studies are limited to exergy analysis and optimisation of a product/process in one factory. However a factory is just

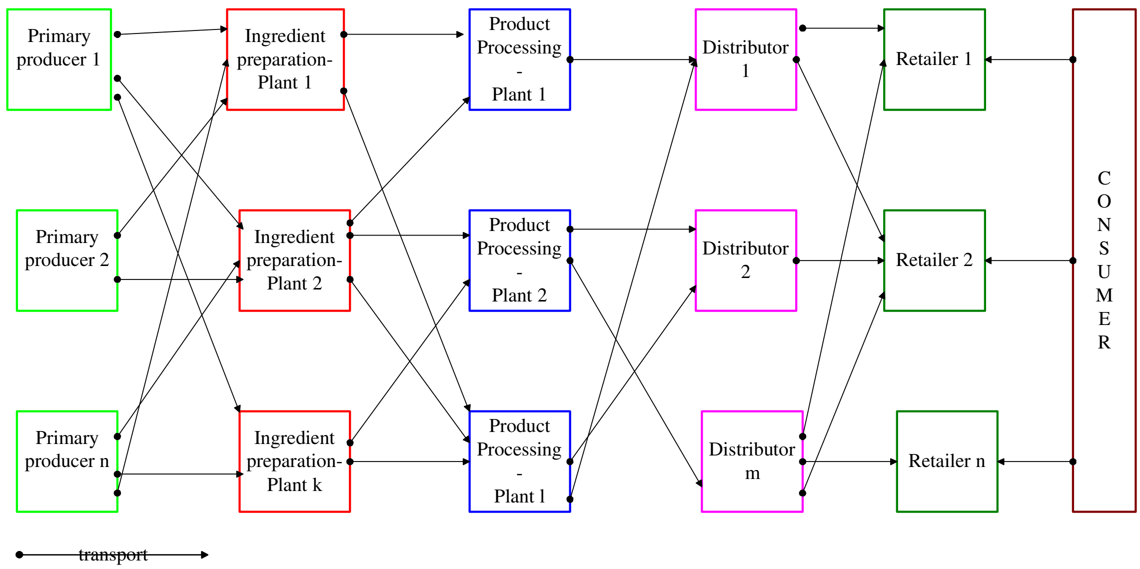

Fig. 1. Food supply chain (from Apaiah and Hendrix, in press).

one link in the supply chain of a product. The chain has to be studied in its entirety to avoid local and sub-optimizations.

This study was done within the framework of PROFETAS (www.profetas.nl), a multidisciplinary project in the Netherlands. It is based on the hypothesis that the current food production and consumption pattern is not sustainable. Meat production in particular is problematic because of the inefficient conversion of protein in the feed into protein in the slaughtered animal. As a result of this inefficiency, growing environmental impacts and the competitive element between food and feed crops, the possibilities to optimise the sustainability of the protein production and consumption chain are immense.

This paper explores the potential of using exergy analysis as a tool to study and compare the environmental sustainability of the entire supply chain of food products and identify opportunities to reduce their environmental impact. Three products were chosen: Novel Protein Foods (NPFs) – a pea-protein based product that is designed to replace meat-based ingredients in a consumer's diet; pork mince as the animal protein source because of the absence of secondary products like milk or eggs and its similarity to the NPF; and pea soup as it represents the simplest way of using peas as a food. Exergy inputs and outputs of the various streams, products and processes are calculated for the entire supply chain of a product. Exergy is measured in Mega Joules/unit of product and therefore a clear and objective overview is created. The evaluation of the product and its chain is therefore less disputable in exergy analysis. Resource intensive processes can be indicated easily and the improvement is a logical result. Engineers can optimize production processes to consume fewer resources like raw materials and fuel, and produce less emission and waste with the help of design tools like exergy analysis (Schijndel, Kasteren, & Janssen, 1998). Such analyses can be applied to the supply chain of existing and profitable products or can be applied to aid in the design of supply chains for new products. However in the latter case exergy analysis would have to be combined with some form of cost analysis to make the product cost competitive as well as environmentally friendly.

2. Methodology

2.1. System boundaries and assumptions

The system comprises the chain that is under study. Secondary chains e.g. the supply chain for the fertilizer production plants or the chains for the manufacture of a machine or transport vehicle are not included in the system. However, the cumulative exergy input necessary to produce a fertilizer and the exergy of the fuel used to run the machines are included as input in the relevant links.

The supply chains of the three products – pea-based novel protein food (NPF), pork meat and pea soup – were studied. The pork chain was chosen as it is a commonly utilised source of meat protein. It is well known and documented. The pea soup was included because it represents a chain where unprocessed peas are used almost directly for human consumption. The pea-based NPF is designed to resemble the vegetarian mincemeat currently available. NPFs based on peas do not exist yet. The supply chain and production schemes (Fig. 2) are based on similar products available in the market.

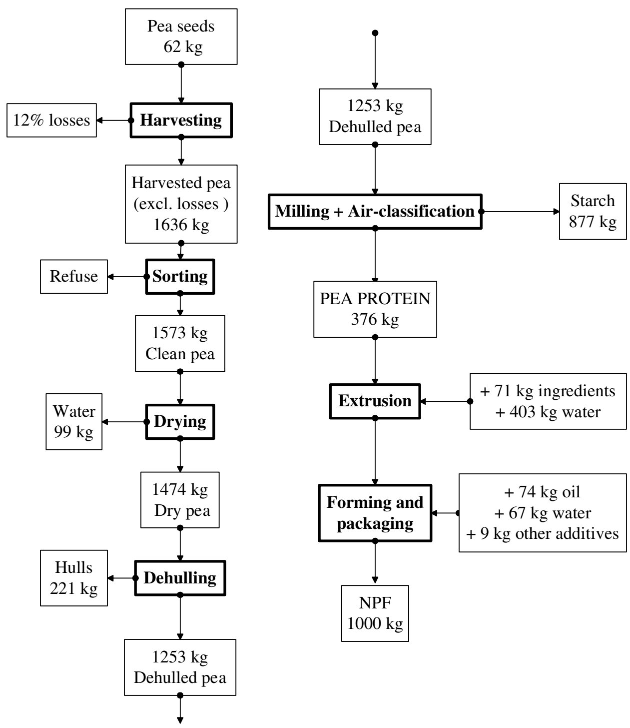

Fig. 2. Production scheme to make 1000 kg of NPF.

The supply chains for the products are described in detail (Figs. 3–5). Common inputs for the three chains are diesel, natural gas, electricity, fertilizers and pesticides (not shown in figures). All inputs to make the functional unit i.e. raw materials, fertilizers, and fuels are accounted for. All outputs and wastes at each link are also given in more detail in Appendix.

Chain 1: The pea-based NPF chain. The supply chain for NPF product is a theoretical one and is based on chains of similar meat substitutes on the market (Fig. 3). The actors/links for which most information is available were chosen to create the chain.

Chain 2: The minced pork meat production chain. The minced pork meat sector has a relatively simple supply chain in comparison with other more complex meat products. Like the NPF chain, this chain can be divided into links (Fig. 4).

Chain 3: The pea soup chain. This chain represents a simple use of the pea, in terms of both product processing and consumer processing (Fig. 5).

2.2. The functional unit

A comparable end product is necessary to genuinely contrast different food chains for their environmental impact. This is called the functional unit (FU), which in this case is 1000 kg of end product (NPF mince, pork meat, pea soup). The NPF and pork meat have similar nutritional compositions, but the pea soup is dissimilar. As mentioned earlier, the pea soup chain was included to demonstrate a simple use of the pea.

The exergy content and requirements of products and processes respectively were calculated as shown below.

The chemical exergy, at standard conditions, of substances containing several elements can be calculated by using the chemical exergy values of the elements together with known values of the Gibbs energy of formation at the same reference conditions. This method has been mainly used for the exergy calculation of fertilisers. The chemical exergy of complex chemicals that are not listed by Szargut et al. (1988) can be estimated by using group contribution methods based on information about their molecular structure to determine absolute entropy values and enthalpy of formation values at standard conditions and then to determine the Gibbs energy of formation values (Reid, Prausnitz, & Sherwood, 1977). The exergy value can also be calculated by using the Group Contribution Method of Szargut et al. (1988). This method has been mainly used for the exergy calculation of pesticides and packaging materials.

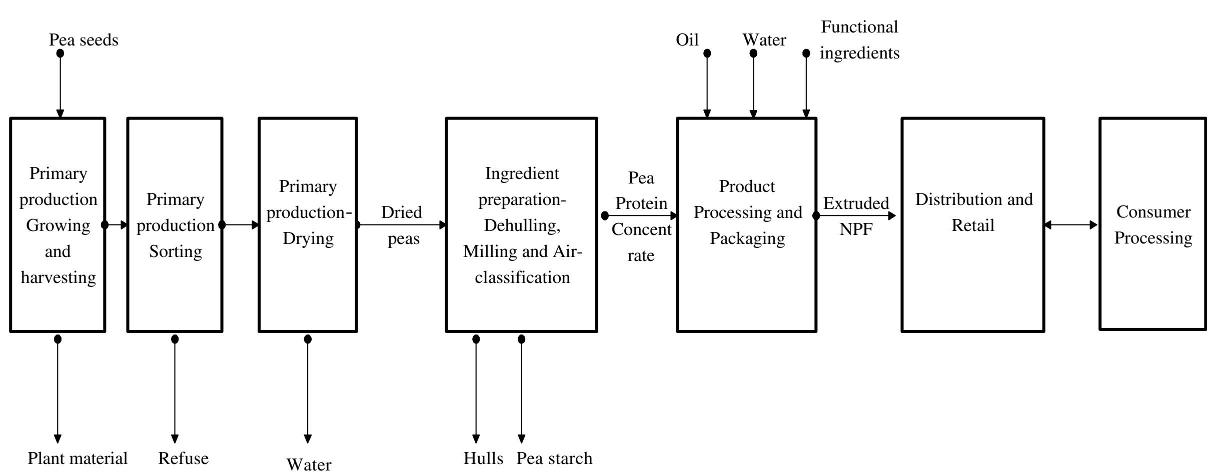

Fig. 3. NPF supply chain.

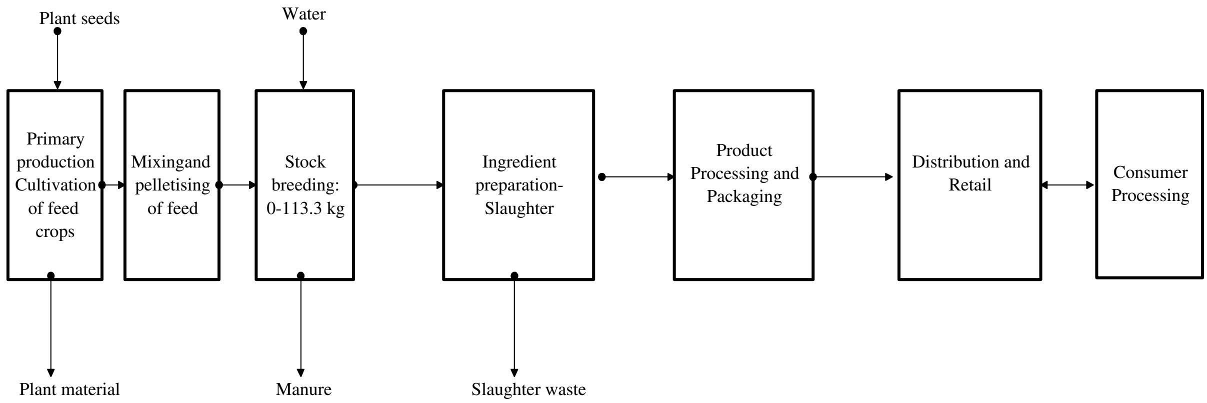

Fig. 4. Pork meat supply chain.

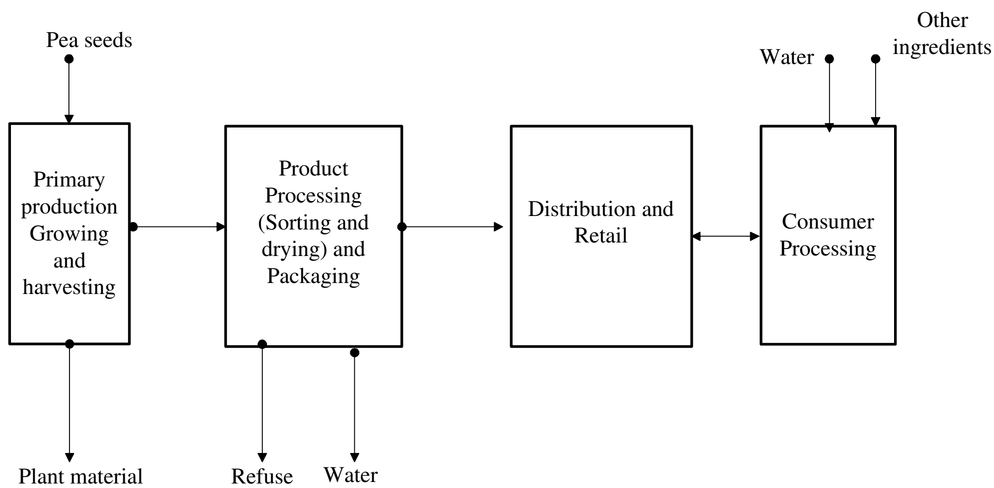

Fig. 5. Pea soup supply chain.

Schenk (2001) gives a detailed description of the methods and their formulas. Sample calculations have been included in Appendix. The Gibbs energy of formation can also be estimated directly for organic compounds, gases and liquids with the method developed by Krevelen and Chermin (1952). The chemical exergy can then be calculated by using the sum of the products of the stoichiometric coefficients of the elements in the formation reaction and the exergy value of the elements, and the Gibbs energy of formation value at the same standard temperature and pressure, this can be called the Element Method.

2.3. Exergy balance for a process

$$\mathrm{Ex_{in}\,total} = \mathrm{Ex_{out}\,product} + \mathrm{Ex_{out}\,waste} + \mathrm{Ex_{out}\,losses} \tag{1}$$

where $\mathrm{Ex_{out}}$ product, Exergy value of the desired end product (MJ); $\mathrm{Ex_{in}}$ total, total of all exergy inputs in the process (MJ); $\mathrm{Ex_{out}}$ waste, Exergy value of outputs other than the desired product; $\mathrm{Ex_{out}}$ losses; exergy losses due to the irreversibility of the real process.

Eq. (1) gives the exergy balance for a process. This is applied to each link of the chain to determine how much of the input exergy is used to produce the desired end product and how much is lost as wastes and losses. Tables 1a and 1b present a sample calculation of the exergy balance for the ingredient preparation link in the manufacture of NPFs.

3. Results and discussion

3.1. Comparison of chains – inputs and outputs

Figs. 6–8 describe the chains in different ways. What goes into the chain, where it enters the chain and what the output is becomes very clear when all outputs and inputs are converted into exergy values (measured in MJ/1000 kg of product). Problem areas can easily be recognised and the potential for optimisation can be identified.

Table 1a
Input data for the ingredient preparation link in the NPF chain for one FU

Process name/product	Mass kg	MJ	Exergy_chem (MJ/kg)	Total Exergy_chem (MJ)
Harvested peas	1635.68		18.19	34334.69
Sorting				4.42
Drying				3934.95
Dehulling				159.16
Milling				197.92
Air classification				9.02
Total input				38640.15
Details				
Sorting				
Electricity		4.42	1.00	4.42
Total input				4.42
Drying				
Electricity		70.66	1.00	70.66
Natural gas		3680.28	1.05	3864.29
Total input				3934.95
Dehulling				
Electricity		159.16	1.00	159.16
Milling				
Electricity		197.92	1.00	197.92
Air classification				
Electricity		9.02	1.00	9.02

Table 1b
Output data for ingredient preparation link in the NPF chain for one FU

Process name/product	Mass kg	MJ	Exergy_chem (MJ/kg)	Total Exergy_chem (MJ)
Pea concentrate	376		20.90	7854.12
Intermediates				
Refuse peas	62.91		18.19	1144.49
product	1572.77		18.19	28612.24
Drying				
water	99		0.53	52.250435
product	1473.68		19.47	28689.023
Dehulling				
hulls	221		18.19	4021.45
product	1252.63		19.47	24385.67
Milling				
product	1252.63		19.47	24385.67
Air classification				
coarse fraction	876.84		18.32	16064.60
product	376		20.90	7854.12

Fig. 6 shows the exergy input per link for the three chains. The exergy required for primary production in the pork chain is very high when compared to the other chains. This is due to the inefficient conversion of plant protein from the feed to animal protein in the pig. Ingredient preparation is an exergy intensive process in the NPF chain as the peas have to be sorted, dried to reduce moisture, dehulled, and milled. The protein in the pea flour has then to be concentrated. In comparison, slaughtering is the only process in the corresponding link of the pork chain and therefore requires less exergy. The link of ingredient preparation is absent in the pea soup chain. Product processing is an important link in the NPF chain as the concentrated protein from the preceding link is made into an edible form. The process considered here is extrusion. The exergy input for this and packaging the product is considerably more than what is required to form the product in the pork meat chain (mincing and packing the mince). In the pea soup chain this link involves only sorting and packaging the peas.

Distribution and retail for both the NPF and the pork mince are similar. The products have about 50% moisture and therefore have to be transported and stored under refrigerated conditions and therefore require more exergy input than the dry peas.

Consumer processing is the last link considered here. This includes shopping, storage and cooking. This results in an exergy input 453 MJ/1000 kg functional unit (Table A.3, Appendix) (Velthuizen, 1996). The exergy input for the pork meat is similar. Both the NPF and pork mince need to be refrigerated as they have a moisture content of about 50%. It is assumed that the consumer handles the NPF the same way as pork meat, so 80% is frozen before consumption (Velthuizen, 1996). This results in an exergy input of 1475 MJ/1000 kg functional unit.

Cooking the product is the last step. Natural gas provides the required energy. The consumer can cook the NPF and pork mince in different ways. It was assumed that the product is pan-fried; figures are based on this method of cooking. This results in an exergy input of 4.2 MJ/kg product that is cooked for 30 min on a 2 kWh burner (Velthuizen, 1996). The pea soup chain again differs from the others at this link. The exergy input for storage is less as the peas can be stored under ambient conditions. However, it is important to remember that the exergy consumption in this link is very variable and difficult to control as it depends on individual consumers.

The exergy input for transportation is highest in the pork chain. It is assumed that 50% of the crops used in pig feed are transported over 10,000 km by barge (ocean) and 50% by truck over 100 km (Berg, Huppes, & Ven, 1995) to the Dutch pig feed factories whereas the peas required for the NPF and pea soup are assumed to be transported on average over 100 km only.

Fig. 7 shows the various streams that enter each chain. The inputs of electricity, diesel (fuel) and natural gas are for the entire chain. The seed input is largest in the pork chain; a large amount of feed is required to get one FU pork meat because of the inefficient conversion of plant to animal protein. The NPF chain has the largest input of extra ingredients, while the pork meat chain has the highest drinking water input.

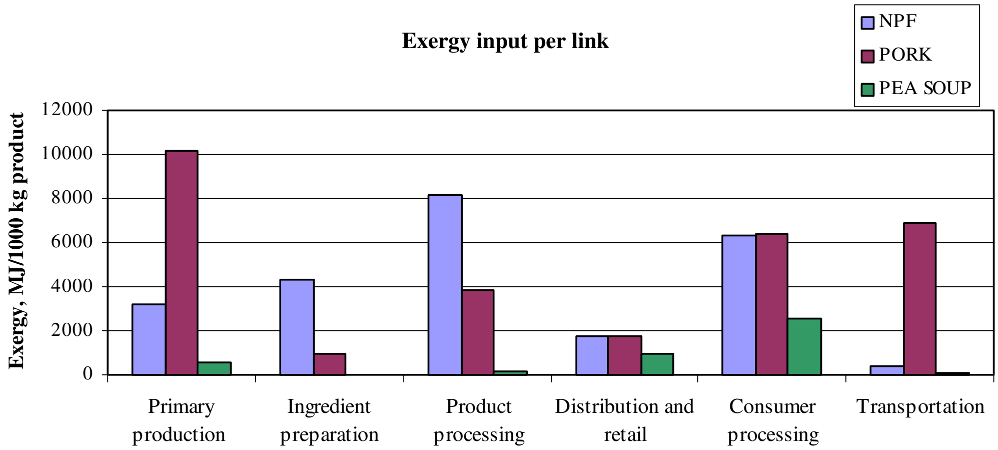

Fig. 6. Comparison of exergy input between the three chains.

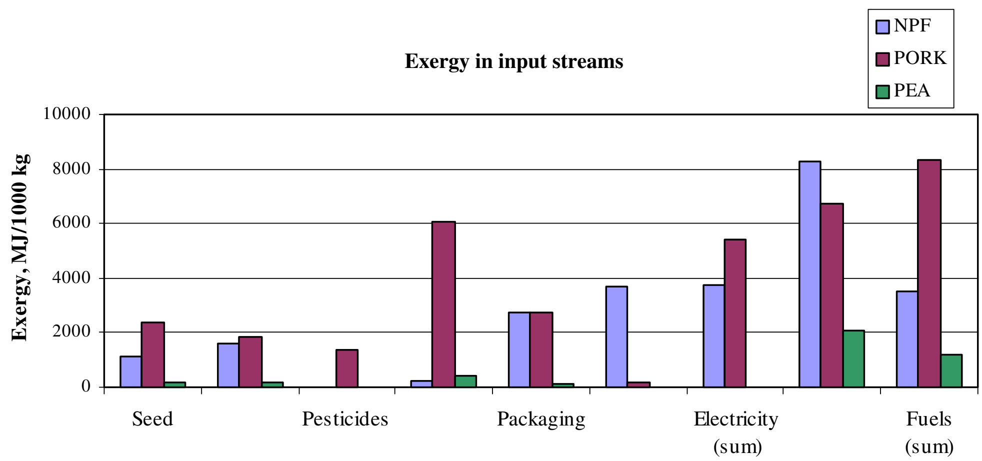

Fig. 7. Exergy input per stream.

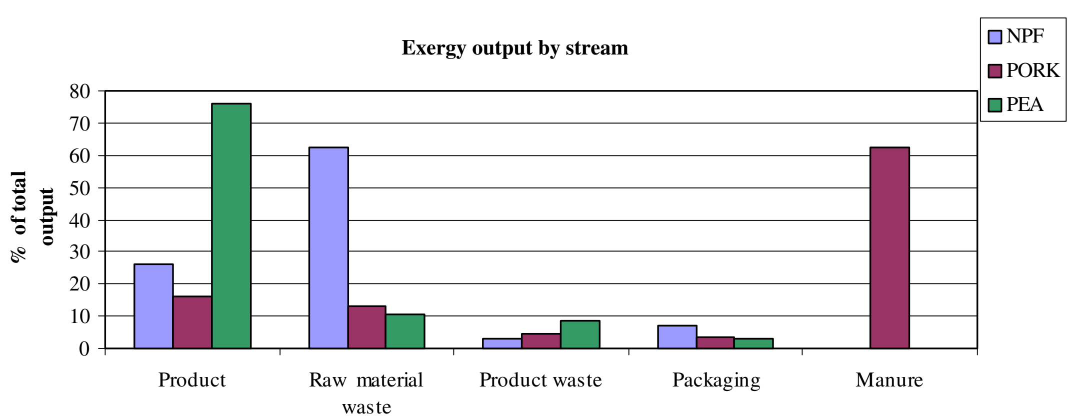

Fig. 8. Exergy output per stream.

Fig. 8 compares the outputs of the three chains. As mentioned earlier, high exergy sources like fuel, raw material etc are used to create a desired product. However only part of the input exergy goes into the desired product – part of it goes into waste streams (the environment) and the rest is irreversibly lost. The largest output in the pea chain is the desired product whereas in the NPF chain it is the raw material waste with the desired product a far second. The largest output in the pork meat chain is manure with meat only 15% of the total output.

3.2. Comparison of chains: Efficiency analysis

The chains can also be compared on the basis of their efficiency. There are many ways to calculate exergetic efficiencies. The chosen efficiency parameter (Eq. (2)) focuses on the conversion of energy in the process. A process is most sustainable when it uses the exergy of its inputs efficiently, since production can be carried out with a minimum input of exergy and material resources (Lems, van der Kooi, & Swaan Arons, 2002).

$$\mathrm{Eff} = \frac{\mathrm{Ex_{out}\,product}}{\mathrm{Ex_{in}\,total}}, \tag{2}$$

with $\mathrm{Ex_{out}}$ product, exergy value of the desired end product (MJ); $\mathrm{Ex_{in}}$ total, the total of all exergy inputs in the production chain (MJ).

Exergy from a process can be lost in two ways – losses due to the irreversibility of real processes and losses due to waste streams. Both these exergy losses contribute to the inefficiency of a process. The exergy of waste streams can be considered useful when the products are used in other processes/chains. In this analysis, waste steams are not recycled or used in other processes or products. Emissions to the environment were not included in this study as the aim here is to show the efficiency of the chain on the basis of the desired product only. Eq. (2) thus calculates exergetic efficiency on the basis of the desired product.

An important issue that was encountered was whether to include renewable natural resources like sunlight and rainfall in the inputs. The amount of solar energy is based on the land requirement for the feed crops and pea crop. The land required to grow feed crops for 1000 kg of pork meat is 2.4 times the land needed to grow peas to make 1000 kg NPF. The calculated efficiencies are very different with the two approaches. When the renewable resources are included

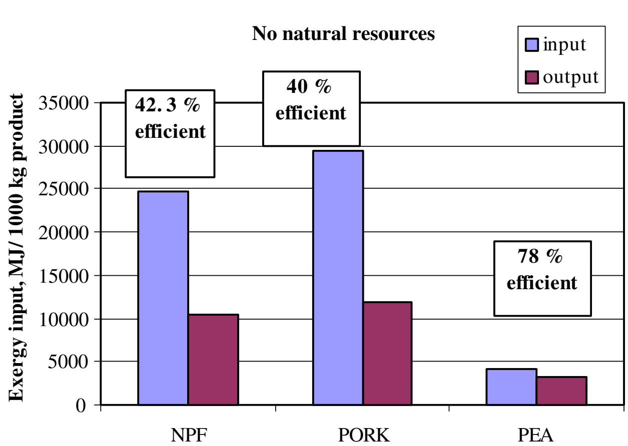

Fig. 9. Total exergy inputs and product outputs.

the efficiencies of the NPF, pork and pea chains are 0.2%, 0.09% and 0.48%, respectively. Fig. 9 shows the total exergy input/output of the three chains when natural resources are not included. Now, the efficiencies are respectively 42.3%, 40% and 78%. The NPF chain is 1.2 times more efficient than the pork meat chain when only controllable inputs are included but is twice as efficient when natural resources are incorporated. Similarly the pea chain is 1.8 times better than the NPF chain when controllable inputs are included but 2.3 times better otherwise.

These results are interesting as it was expected that the NPF chain would be much more efficient than the pork meat chain. The large amount of processing required to convert the dry pea into the final product is partially responsible for this. Also, the existing pork meat chain is optimal and the NPF chain is a hypothetical one with room for improvement.

3.3. Problem areas in the chains

Exergy analysis can help identify problem areas in chains and aids in identifying losses and inefficient uses of natural resources.

NPF chain:

- Ingredient preparation and product processing were identified as exergy intensive links in this chain.
- Exergy consumption in the consumer processing link can be very variable.
- Ingredient input into this chain is high.
- Electricity, natural gas and diesel use is high because of the intensive processing required.
- Only 42% of the input exergy goes into the desired product, raw material waste is high.

Pork chain:

- Primary production and transportation are exergy intensive links.
- Exergy consumption in the consumer processing link can be very variable.
- Seed input is high because of the inefficient conversion of plant to animal protein.
- Drinking water input is high.
- The largest output is manure with the pork mince being only 15% of the total output of this chain.

4. Conclusions

Exergy analysis is a useful method to study the impact of supply chains of food products on the environment. The analysis requires an in-depth input–output analysis of the links of a chain. This involves some investment of time but once this is done, results are visible and conclusions can easily be drawn, as was shown in the present paper. Efficiencies based on exergy, unlike those based on energy, are always measures of the approach to ideality, and therefore provide more meaningful information when assessing the performance of food chains. All inputs and outputs are measured in one covering unit, the Joule, making the method simpler to use.

This method pinpoints the links where the exergy destruction takes place. It is therefore possible to investigate these links in detail and perform an improvement analysis to minimise this destruction.

The analysis also shows that supply chains of products that are relatively simple, minimally processed, derived from local ingredients and sold in domestic markets have a low exergy requirement. In reality, such products are few. Processed 'value added' products are more exergy intensive – these products are more profitable to the manufacturers and more popular with consumers and the real money in food business comes from these. The supply chains of such popular and profitable products can be redesigned to make the chain more sustainable from an environment perspective – making it possible to deliver a product that performs well and is environmentally friendly.

Exergy analysis is also useful while designing the supply chains for new products. However, in such cases, exergy analysis needs to be extended to include monetary costs. This will make the technique more acceptable to supply chain managers. A detailed study of the chain, as will result from the above analysis, can lead to increasingly environmentally sustainable and profitable products.

Acknowledgements

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Appendix A

Szargut et al. (1988) have proposed an idealised model of the environment with three reference states: gaseous and solid reference species in the environment and reference species dissolved in seawater. The exergy values of these reference substances are taken as zero. The solid species are treated as the components of an ideal solution. The standard chemical exergy of a pure reference species is then given by the Eq. (2.1) and listed in Szargut et al. (1988):

$$\mathrm{Ex}^0_{\mathrm{chem},i} = -RT_n \ln x_{i,n}, \tag{2.1}$$

with R as the gas constant (8.3145 J/mol K), T_n is the standard temperature, usually 298.15 K (K) and $x_{i,n}$ the conventional mole fraction of the solid and ideal gas reference species in the environment (mol/mol).

Szargut et al. (1988) developed an empirical method for the calculation of the chemical exergy of fuels. The method relates the net caloric value (NCV) to the chemical exergy. For each type of fuel a β-value can be calculated which is a function of the atomic fuel composition (see Table A.1).

$$\mathrm{Ex}^0_{\mathrm{chem},i} = \beta_i \cdot \mathrm{NCV}_i. \tag{2.2}$$

The β-value can be considered as a quality factor that relates energy to exergy content (see Tables A.1–A.3).

Table A.1

Substance	β-value	Reference
Natural gas	1.0500	Schenk (2001)
(Fuel) oil	1.0700	Szargut et al. (1988)
(Hard) coal	1.0485	Schenk (2001)
Naphtha	1.055	Szargut et al. (1988)
Electricity	1.0000	Szargut et al. (1988)

Chemical exergy packaging

Poly styrene packaging

Chemical formula	n∗[C_8H_8]
MW	105.088 g/mol

Group contribution method (Table III, Appendix, Szargut et al., 1988)

Group no.	Amount (#)	B_0 chem (KJ/mole)	Total
2	1	545.27	545.27
3	1	651.46	651.46
14	1	466.41	466.41
15	5	568.28	2841.40
Exergy Poly styrene			4504.54 kJ/mol
			42.86 MJ/kg

Exergy values of macronutrients

Protein

All proteins are assumed to be polymers of alanine (Berg et al., 1995)

Chemical formula –(N–CHR–CO)– with R = CH_3

MW 70 g/mol

Group contribution method (Table III, Appendix Szargut et al., 1988)

Group no.	Number (#)	B_0 chem (kJ/mol)	B_0 chem,total (kJ/mol)
2	1	545.27	545.27
4	1	752.03	752.03
29	1	281.36	281.36
38	1	195.56	195.56
Exergy protein			1774.22
			25.35 MJ/kg

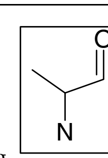

Table A.2
Exergy balance for the NPF chain

Process	Exergy in	Exergy out product	Exergy loss
Soil preparation	471.00	0.00	471.00
Sowing	1291.27	0.00	1291.27
Growing	5079801.72	37023.90	5042777.83
Growing no-natural resources	2218.60	37023.90	−34805.30
Harvesting	303.87	29756.73	7571.04
Transporting	136.74	29756.73	136.74
Sorting	4.42	28612.24	1148.91
Drying	3934.95	28689.02	3858.17
Dehulling	159.16	24385.67	4462.51
Milling	197.92	24385.67	197.92
Air classification	9.02	7854.12	16540.57
Extrusion	2075.79	9350.14	579.77
Cuttering	2417.27	11639.40	128.00
Shaping	57.14	11639.40	57.14
Packaging	3418.02	14371.70	685.71
Storage and distribution	746.50	14371.70	746.50
Retail	993.99	14371.70	993.99
Shopping	452.74	14371.70	452.74
Storage home	1474.99	14371.70	1474.99
Cooking	4410.00	10475.46	8306.24
Total (no natural resources)	24773.37	10475.46	14297.91
Total (with natural resources)	5102356	10475.46	5091881.04

Table A.3
Calculations for consumer processing of the NPF

1	Average family size in the Netherlands[a]	2.7
2	Food per person per day[a]	2708 g
3	Total consumption of food per week	51181.1 g
4	Meat per person per day	99 g (3.7% of 2)[a]
5	Meat share per week	1871.1 g[a]
6	Pork meat per week	471.5 g (25.2% of 5[b])
7	% NPF (of food consumed)	0.9
8	Exergy of fuel for shopping trip	12.9 MJ
9	Food share in groceries	66.7%
10	Average trips per week	2.69
11	NPF share in trips	0.6%
12	Exergy required	453 MJ per 1000 kg NPF

[a] (Voedingscentrum, 1998).
[b] (De Koning, personal communication, 2002).

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