ANALYSIS AND SIMULATION OF STRAW FUEL LOGISTICS

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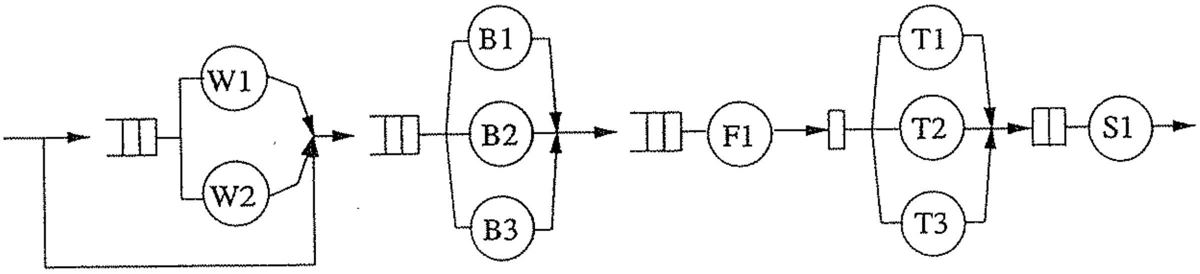

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ABSTRACT

Straw is a renewable biomass that has a considerable potential to be used as fuel in rural districts. This bulky fuel is, however, produced over large areas and must be collected during a limited amount of days and taken to the storages before being ultimately transported to heating plants. Thus, a well thought-out and cost-effective harvesting and handling system is necessary to provide a satisfactory fuel at competitive costs. Moreover, high-quality non-renewable fuels are used in these operations. To be sustainable, the energy content of these fuels should not exceed the energy extracted from the straw.

The objective of this study is to analyze straw as fuel in district heating plants with respect to environmental and energy aspects, and to improve the performance and reduce the costs of straw handling.

Energy, exergy and emergy analyses were used to assess straw as fuel from an energy point of view. The energy analysis showed that the energy balance is 12:1 when direct and indirect energy requirements are considered. The exergy analysis demonstrated that the conversion step is ineffective, whereas the emergy analysis indicated that large amounts of energy have been used in the past to form the straw fuel (the net emergy yield ratio is 1.1).

A dynamic simulation model, called SHAM (Straw HAndling Model), has also been developed to investigate handling of straw from the fields to the plant. The primary aim is to analyze the performance of various machinery chains and management strategies in order to reduce the handling costs and energy needs. The model, which is based on discrete event simulation, takes both weather and geographical conditions into account.

The model has been applied to three regions in Sweden (Svalöv, Vara and Enköping) in order to investigate the prerequisites for straw harvest at these locations. The simulations showed that straw has the best chances to become a competitive fuel in south Sweden. It was also demonstrated that costs can be reduced by adopting appropriate management strategies. Moreover, SHAM has also been used to determine the number of machines that result in the lowest total fuel costs. It was shown that straw can be delivered to a plant at Svalöv at a cost of 29.6 SEK GJ^{-1}.

Two new technologies were evaluated by using SHAM: systems based on compact rolls and systems based on chopped straw stored outdoors. The costs were about 5-20% higher with these methods compared with systems based on high-density balers, but their prospects of becoming competitive alternatives in the future are good.

CONTENTS

LIST OF INCLUDED PAPERS

This thesis for the degree of *Agronomie Licentiat* is based on the following papers. In the text, they are referred to by their Roman numerals.

I. Nilsson, D. Transportation Work and Energy Requirements for Haulage of Straw Fuels. A Comparison between the Plants at Såtenäs and Svalöv. *Swed. J. agric. Res.* 1995(25), pp 137-141.

II. Nilsson, D. Energy, Exergy and Emergy Analysis of Using Straw as Fuel in District Heating Plants. *Biomass and Bioenergy*, 1997(13), pp 63-73.

III. Nilsson, D. SHAM - A Simulation Model for Designing Straw Fuel Delivery Systems. Part I. Model description. Manuscript.

IV. Nilsson, D. SHAM - A Simulation Model for Designing Straw Fuel Delivery Systems. Part II. Model Applications. Manuscript.

Paper I and paper II are published with the permission of the journals. Paper III and IV might be subjected to changes to fulfil the requirements of the journal in which they will be published.

INTRODUCTION

Background

The estimated potentials for production of straw for energy purposes are 1 100 PJ year^{-1} in Europe (excl. former USSR) and 600 PJ year^{-1} in former USSR (NUTEK, 1993). In Sweden, the potential for straw energy is estimated to 7 PJ year^{-1} (Axenbom et al., 1992), taking soil condition, livestock bedding, weather restrictions etc., into account. The total energy use in Sweden during 1996 was about 1 500 PJ (NUTEK, 1997). There are three straw-fired district heating plants in Sweden with totally about 13 MW installed power (at Svalöv, Kvänum and Såtenäs). In addition, there are a few hundred straw-fired farm boilers.

Although the potentials are noteworthy, it is obvious that straw is far from being the solution to the world's energy problems. Besides the limited supply, there are still serious problems associated with handling and power production. Other uncertain supply factors for the future are, for instance, competitive straw utilization, the tendency to shorten straw in plant breeding, the prevention of soil erosion, the decrease of humus content, the decrease in grain acreage, etc. Therefore, it is important to consider straw as a by-product integrated with food production, rather than a prime energy source.

Nevertheless, the search for alternative fuels which do not contribute to the so-called greenhouse effect is one reason for promoting the utilization of straw as a fuel. Furthermore, increased straw utilization would stimulate regional economies, increase employment in rural areas and render an income to the farmers.

Straw is a renewable energy resource which annually passes through the environment as a "free" flow, provided that cereals are cultivated. The energy stored in this by-product originates from the energy flux of the sun during a few months. This is one reason why the fuel is dispersed and expensive to concentrate. The energy value per square measure is, at a rough estimate 56 GJ ha^{-1} year^{-1} (0.014 GJ kg^{-1} straw (18 % m.c., wet basis) x 4 000 kg ha^{-1} year^{-1}), with a solar capture efficiency of about 0.15 % (56 GJ ha^{-1} year^{-1} / (3.6 GJ m^{-2} year^{-1} x 10 000 m^{2} ha^{-1})) (south Swedish conditions, kernels not considered). On the other hand, previous work shows that the energy balance for fuel straw is favourable (Nilsson, 1991). Upgrading, long-distance transports, etc., could, of course, change these conditions.

Straw burning has had a fairly bad reputation in Sweden since the unsuccessful trials in the seventies. The handling systems, combustion technologies and knowledge of fuel characteristics have improved since then. The production costs are 420 - 450 SEK tonnes^{-1} for high-density bales stored indoors, which is nearly competitive with wood chips (however, the conversion process is more expensive because there are still many complications with straw combustion). If straw is to become a fuel for the future, it is important to further reduce the costs and to find out new reliable handling methods. Numerous studies of straw handling have been carried during recent decades. This work will make a systems analysis approach which emanates from modern straw handling and combustion technologies.

A global perspective on straw fuels*

The main agricultural resources for energy at present are residues from crop and animal production. Their total energy value in Europe is estimated at 7 300 PJ per year, of which 58 % is from animal waste and 42 % from crop residues. All the residues are not available for energy because considerable quantities cannot be removed from the field due to soil constraints,

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* This section is based on Nilsson & de Toro (1993), Hadders & Nilsson (1993), Nilsson (1992) and Nilsson (1993)

and other amounts have alternative uses; for instance, straw is also utilised for livestock bedding. Some residues are difficult to collect at reasonable costs, as in the cases of scattered fields or animal wastes which can only be collected if animals are confined. Taking into account all these limitations, the total amount of residues that might be available for energy must, as a rule be reduced by more than 70 % in the estimations. However, the actual residue amounts that are collectable strongly depend on the residue price. The higher the prices, the higher will be the percentage of collectable residues. Until now, collection and conversion costs of agricultural residues have been competitive with fossil fuels only in some cases and at a local level. Hence, few agricultural wastes are utilised for energy in Europe.

However, significant amounts of straw fuels are used in Denmark. Since 1973 it has been an important aim for the Danish government to increase the use of straw for energy purposes. Today, straw fuels are used in approximately 12 000 boilers on farms, and in 60 district heating plants with a total installed power of 220 MW. Furthermore, there are six, wholly or partially, straw-fired combined heat and power plants with a total power production of about 69 MW. The total consumption of straw fuels in Denmark is more than 800 000 tonnes per year (12 PJ), corresponding to more than 1.5 % of Denmark's gross energy use. The average price for straw delivered at the plant is about 440 DKK per tonne (ranging from 350 to 530 DKK tonne^{-1}), and the consumer heat price is about 150 DKK GJ^{-1} (excl VAT).

The use of straw fuels is negligible in the rest of Western Europe. There are occasional straw-fired plants in Germany and Italy. The straw is instead used for animal breeding, soil conditioning, mushroom production, etc. In Italy (Foggia), Hungary (Dunjavaros) and Spain (Zaragoza) straw is used as a raw material in the paper industry. As a result of high processing costs and a downward trend for wood pulp prices, the demand for straw pulp is not expected to increase in the immediate future. There are also small rice growing areas in Southern Europe. Rice husks from rice mills and rice straw are possible fuels, but negligible quantities have been used for production of heat and electricity. Also from Eastern Europe, where the potential is considerable, no straw-fired plants have been reported.

In USA, where the production of straw residues exceeds 100 million tonnes per year, straw fuels can not compete with fossil fuels. Thus, there are no commercial straw-fired plants. The same also applies to Canada. The production of cereal and rice residues in Asia is remarkable (about 800 million tonnes per year), but no straw is used for large-scale production of heat or electricity. Finally, interest for straw heating in Africa, Oceania and Latin America is, not surprisingly, cool.

1.3 Problems related to handling and combustion of straw

The handling of straw consists of a series of operations which aim to concentrate the fuel and, in the conversion step, release the stored energy (figure 1). The operations and some operational problems are discussed in greater detail below.

In the harvesting operation, the straw is compacted into discrete units, e.g by pressing it to bales, briquettes, etc., or comminuted and loaded into transportation units, e.g. chopping. Principally, the compression process can be done by normal- (e.g. balers for rectangular bales) or radial pressure methods (e.g. round- and compact roller balers). The roller compression method seems to be more energy efficient and may result in higher material densities (Harms, 1992). Chopping usually requires machines designed for handling of "fluids" rather than packages. Thus, the transportation density may be low. Important limiting factors for the harvesting are weather restrictions, risks of delaying the following autumn-sown crops and other timeliness-related costs, peak demand of labour, etc. The costs can be lowered if the machines are to be used not only for straw harvesting during a few weeks per year but also for other farming operations.

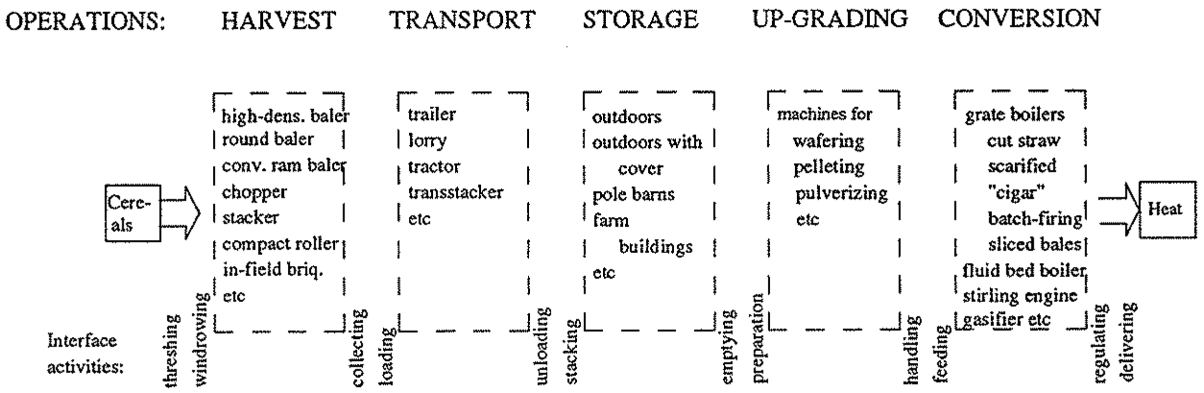

Figure 1. *Mass-flow outline for handling of straw from threshing to delivery of heat.*

The transportation operation means that the fuel is concentrated to intermediate storages and then to conversion plants. The first stages of the transports are usually carried out with high capacity during a short period, whereas the later are carried out during the firing season with lower intensity. The transport capacity (and costs) depends on type of vehicle, geography (distances), infrastructure, material density, traffic restrictions (freight space and maximum speed), loading/unloading time, etc. There must also be security for delivering the straw on time, because the storage capacities at the heating plants usually are very limited.

Storage is necessary because the harvesting period does not coincide with the utilization period. The fuel should be protected against quality deterioration during storage. Biological and chemical processes, e.g. fungal growth and self-heating, can be avoided by low initial moisture contents (< 20 %, w.b.) and maintaining an appropriate storage environment (humidity, temperature, etc.). Too high harvesting moisture contents will lead to fungal growth, dry matter losses and cause hygienic problems, whereas wetting during the storage period can lead to putrefaction and result in a fuel with strongly varying quality. Therefore, storage costs are associated with both quantitative and qualitative losses.

Straw is a voluminous and hygroscopic material. "Loose" dry straw contains just a few per cent organic matter on a volume basis; thus the air content is predominant. Even if the straw is compacted by high-density balers (0.3-0.5 MPa), the density usually is not more than 150 kg m^{-3}, corresponding to about 90 % air. Hence, space is a limiting factor when transporting and storing straw, rather than weight. Due to the hygroscopicity and biodegradable properties of the material, and the fact that it is harvestable during a short period once a year, a well thought-out harvesting and handling system is required to provide a satisfactory fuel.

Upgrading increases the density and fluidity of the material, which results in reduced handling costs and opens new markets for the fuel. Briquetting, pelletization or pulverization are possible methods, which also are used for fuel wood. The upgrading process often requires two different distribution chains, one for the raw material and one for the upgraded product.

When the bales arrive at the district heating plants, the moisture content is measured and the bales are visually inspected. The straw is stored not more than a few days at the plant. Then, the bales are automatically picked up, scarified and fed into the furnace. There are, however, numerous alternative types of receiving, feeding and burning equipment, e.g. systems based on cutters, "cigar firing" and batch firing of whole bales. There is a relationship between the handling system and the conversion system, because the fuel must be prepared to fit the needs of the furnace/boiler and feeding equipment to prevent shut-downs. The cumbersome

3.2.2 Results and discussion

By using the process analysis method and the system boundaries presented in paper II, it is obvious that straw is quite a profitable fuel in this respect. The total energy ratio from field to hot water is 12:1. For delivering the straw to the plant, the direct energy ratio is 60:1 and the total energy ratio 43:1 (nitrogen replacement not considered). The latter figure can be compared with other agricultural biofuels; *Salix* for heat production: 19, *Salix* for ethanol production: 1.8, rape methyl ester (RME): 2.7, winter wheat for heat production: 3.8 and winter wheat for ethanol production: 1.3 (Sonesson, 1993).

The possibilities to reduce the direct energy use for straw handling seem to be limited, at least in the short term. It is unlikely that the fuel efficiency of existing machines will be dramatically improved, and emerging methods will probably render moderate improvements (paper II and IV). The easiest way to reduce energy requirements for straw transportation at a given site might be larger loads (paper I), but this potential is also limited for technical/economic reasons.

The indirect energy use for replacement of nutrients (i.e. nitrogen) constitutes a large part (21 %) of the total energy requirements (990+260 MJ tonne^{-1}). However, this figure should be seen as a "worst case", because it is difficult to estimate the additional amount of nitrogen available for the plants when the straw is left in the fields. Straw has a very high C/N-ratio and requires mineral nitrogen in the decomposition process, and in this "worst case" scenario the field is seen as a closed system with no losses in the long run.

3.3 Exergy analysis

3.3.1 Introduction

In energy analyses, it is not only interesting to quantify the energy requirements but also informative to estimate the energy quality losses in the transformation steps. In all real finite-time processes, the energy transformations are irreversible, i.e. the energy can only be converted into other forms by consumption of its quality. This means that the change of entropy (or "disorder") is always positive for these transformations ($dS>0$). The driving force for all processes is the contrast to the environment, or the tendency to increase the entropy. This contrast can be described by the concept of exergy, which was mainly developed and introduced in the middle of this century. The following general definition was suggested by Baehr (1965): "Exergy is that part of energy that is convertible into all other forms of energy". Wall (1986) says that "energy is motion or ability to produce motion", whereas "exergy is work or ability to produce work".

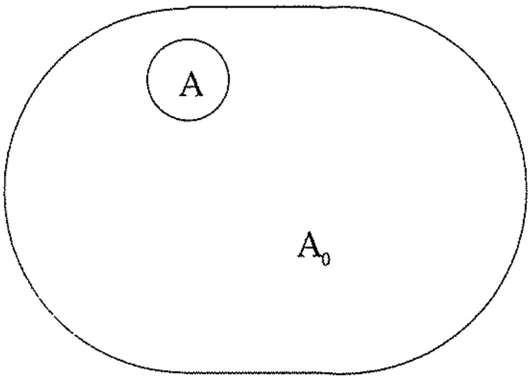

Figure 3. *System A in the environment A_0.*

Consider a system A_0 (figure 3) described by the intensive (i.e. independent of the size of the system) parameters T_0 (temperature), p_0 (pressure), $\mu_{i,0}$ (chemical potentials) and the extensive (i.e. dependent on the size of the system) parameters U_0 (energy), V_0 (volume), S_0 (entropy), $n_{i,0}$ (number of moles of different elements) as

$$A_0 = \{T_0, p_0, \mu_{i,0}, U_0, V_0, S_0, n_{i,0}\}$$

System A_0 is assumed to be in internal thermodynamic equilibrium. Within this system, there is a much smaller system A, which is described by the seven-tuple

$$A = \{T, p, \mu_i, U, V, S, n_i\}$$

where

$$U \ll U_0$$
$$V \ll V_0$$
$$n_i \ll n_{i,0}$$

It can be shown that the exergy of system A in the environment A_0 is (Wall, 1986)

$$E = U + p_0 V - T_0 S - \sum_i \mu_{i,0} n_i$$

or equivalently

$$E = S(T - T_0) - V(p - p_0) + \sum_i n_i(\mu_i - \mu_{i,0})$$

When system A reaches equilibrium with A_0, we can also express the exergy or amount of extractable work from this process as (Wall, 1986)

$$E = U - U_{eq} + p_0(V - V_{eq}) - T_0(S - S_{eq}) - \sum_i \mu_{i,0}(n_i - n_{i,eq})$$

If $\Delta n_i = 0$, $p = p_0$ and $T = T_0$ we can, for instance, derive Gibbs free energy as a special case;

$$G = U + pV - TS$$

and, when $\Delta n_i = 0$, $\Delta S = 0$ and $p = p_0$, enthalpy as

$$H = U + pV$$

The following conclusions can be derived from these equations

- exergy is a phenomenological concept and can be measured ("directly" or indirectly) in experiments
- exergy always refers to a reference state which is in internal thermodynamic equilibrium
- exergy describes contrasts and is therefore not conserved
- exergy includes both energy and material resources
- exergy can be applied to specific processes as well as to macro-systems (such as ecological and human systems), but the latter often require hypothetical reference states.

3.3.2 Results and discussion

An example of the applicability of exergy analysis is demonstrated in paper II, where a conversion process (straw combustion) and a macroscopic system (straw handling) are investigated. By assuming the system boundaries shown in paper II for a district heating boiler, the exergy efficiency will be about 15 % (note that the boundaries imply that the exergy of the electricity input is of thermomechanical nature, not chemical). This is a much lower figure than the energy efficiency. These quality losses depend on the irreversible combustion process and the large temperature difference between the flame and the water, as pointed out by McGovern (1990). The exergy efficiency could be improved considerably by including power generation facilities. However, technical/economic problems have so far limited the use of straw in CHP plants.

If we follow the production trajectory of goods or services by means of the process analysis network, we can calculate the cumulative exergy consumption (CExC) (Szargut et al., 1988). The CExC can, in principal, take all natural resources into account (energy and materials), usually in the form of chemical exergy. The reference state is specified at a pressure of 101.3 MPa and at a temperature of 25°C. The calculations in paper II for straw handling indicate that about 9/10 of the exergy in the resources required to "extract" the fuel from the environment still remains at the boiler (note that straw is considered as a by-product). This can, for example, be compared with furnace oil, which has a value of about 4/5 (Szargut et al., 1988).

3.4 Emergy analysis

3.4.1 Introduction

The emergy (abbreviation of *energy memory* or *embodied energy*) analysis emanates from systems ecology and its cornerstones are based on the maximum power principle, pulsing, self-organization and transformity. The maximum power principle, originally presented by Lotka (1922), was adopted by H. T. Odum, who is the founder of the emergy analysis, to explain the behaviour in nature. All natural systems are said to be hierarchial and strive to reinforce the resource use in order to maximize the use of emergy. Emergy is measured in *sej* (solar emergy joules), which express the amount of solar equivalent energy that has been used in the past to form or construct the studied item or system. Thus, emergy describes the historical production costs in terms of energy, whereas exergy describes the energy potential that a system possess at the moment. Transformity is a basic concept in emergy analysis and is defined as the emergy required per unit product or service (figure 4). The application of emergy analysis has widened in recent years into economy, history, sociology etc (see e.g. Ulgiati et al. (1994) and Sundberg et al. (1995)). For more information about the fundamentals of emergy analysis, see for instance Odum (1984, 1987, 1988a, 1988b and 1996).

According to figure 5, two essential emergy indices can be derived. The net emergy yield ratio (NEYR) describes the emergy output of a process compared with the inputs from the economy;

$$NEYR = Y/F$$

The process is not profitable (in emergy terms) for the economy if the ratio equals one. The ratio must be higher than two if the environmental inputs would exceed the inputs from the economy. For practical use, the ratio should not be lower than the alternatives of primary energy sources if it is to be competitive. The emergy investment ratio (EIR);

$$EIR = F/I$$

expresses the degree to which inputs from the economy are used to exploit environmental sources. If the ratio is low, the cost of the process is usually low, and it will be competitive on the market.

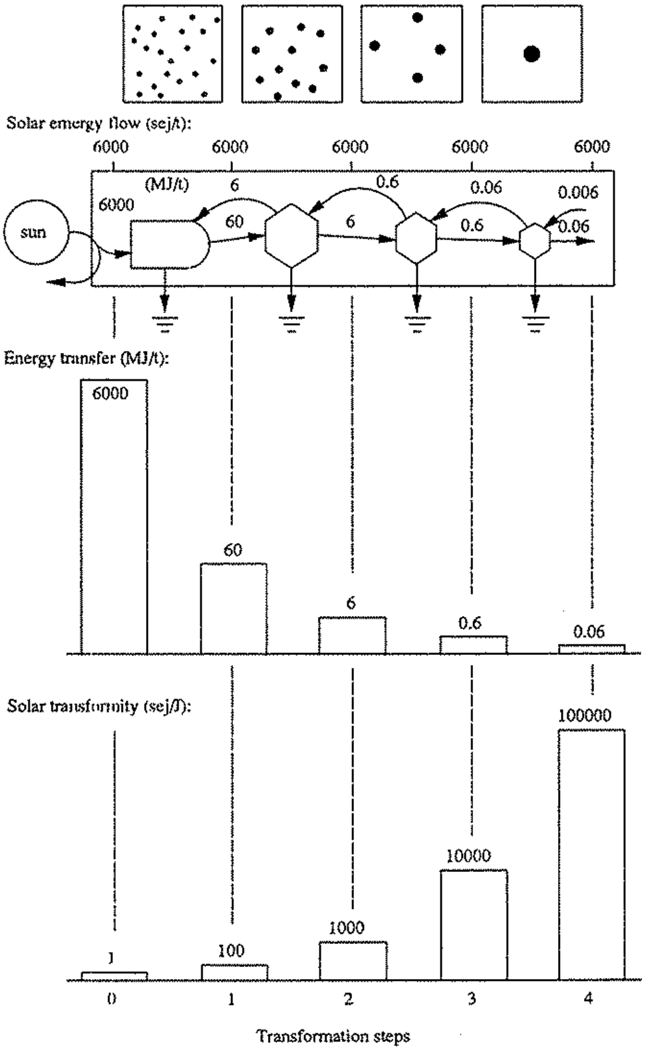

Figure 4. *Sketch showing how to calculate transformities. Here, a food web is followed from the production of grass - herbivores - carnivores - to e.g. a man. The solar emergy flow is the same for all transformation steps, but some energy is lost to the heat sink at each stage. At the same time, the transformities increase correspondingly at each hierarchial level (Odum, 1988a).*

In emergy analysis, the human economy is seen as a sub-system to the ecosystem. The annual use of emergy by a nation is assumed to measure its wealth. Describing wealth in terms of money or gross national product (GNP) is not correct according to Odum's theories, because the environmental work is not considered. In most cases, environmental inputs are seen as free inputs to the economy, and their intrinsic worth is ignored. Dividing a nation's emergy use by its GNP will give an indication of the amount of real wealth that is bought by money.

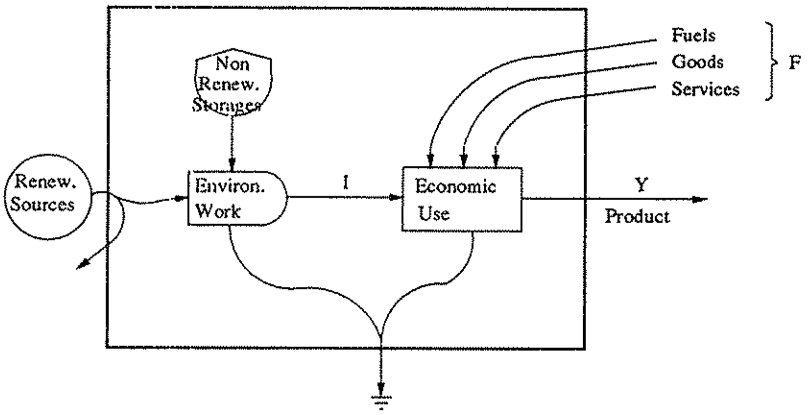

Figure 5. *Diagram showing the principles of emergy accountings. Note that emergy is not lost to the sink, just energy. It follows that Y=I+F (Ulgiati et al., 1994).*

3.4.2 Results and discussion

The emergy calculations in paper II show that the transformity, NEYR and EIR for heat from straw will be 100 ksej J^{-1}, 1.1 and 11, respectively. These figures can be compared with calculations for chunk-wood and oil (Swartström, 1991): 30 ksej J^{-1}, 1.5, 1.9 and 110 ksej J^{-1}, 2.6, 0.6. The calculations show that the environmental contribution arises from the chemical potential in rain, and the main economic contributions arise, as expected, via "goods and services".

These results are, however, as in all kinds of energy analysis, strongly dependent on how the analyst perceives and defines the system. For example, if the impact of organic matter losses were considered, the transformity would be higher. Similarly, if the straw is not treated as a by-product but rather as a main product or a split (figure 6), the transformity would be halved and the ratios more "favourable". According to Odum (1996) and figure 6, however, it is reasonable to treat straw as a by-product, because there is an energy transformation (e.g. threshing) in the branching between the flows.

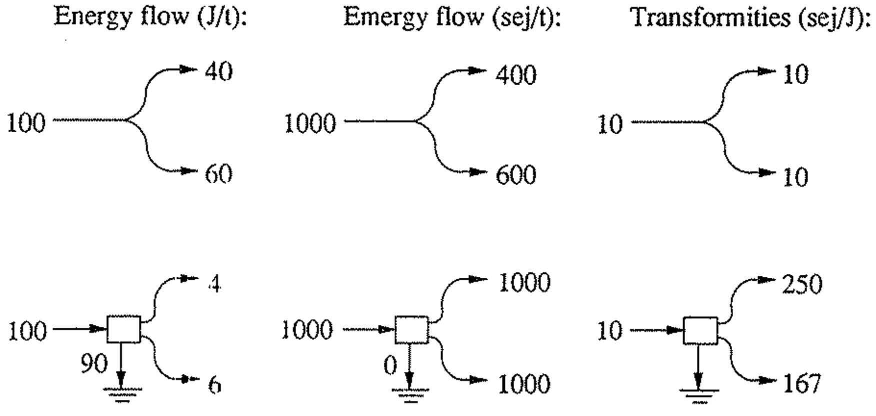

Figure 6. *Illustration of a split of emergy into two flows (uppermost) and a by-product branching (lowest). Co-products of different types branch from energy transformations (Odum, 1996).*

In emergy analysis, the system delimitations more or less are established as soon as it is decided which product or organization is to be studied. For example, the rear system delimitations to a certain degree are optional in conventional energy analysis and in cumulative exergy analysis, but not in emergy analysis. Production of grain and the corresponding emergy flows can not be ignored in an emergy analysis for straw harvesting, because emergy analysis by definition accounts for all previous energy transformations. Principally, a product has only one "true" emergy value, but may have several in energy and exergy analysis depending on system boundaries, reference states, etc. We do not have, however, complete knowledge about the studied system, especially about the emergy flows via the economic system. In the straw fuel system, more than 90 % of the emergy flow comes from the economic system. In such human-related technical systems, based on microeconomic activities, it is difficult to interpret and implement the results from the emergy calculations. The strength of the emergy analysis primarily lies in its clarification of system structure and in its description of the ecological-economic interactions. If it is to be a practicable decision tool, however, more research about the method's applicability is necessary.

3.5 Environmental impacts

3.5.1 Nutrient value and organic matter content

Removal of straw implies removal of nutrients and reduced replenishment of organic matter to the soil. Straw is a lignocellulosic material, and is comprised of about 35-40 % cellulose, 35 % hemicellulose, 17 % lignin, 3-5 % proteins and 1-2 % fats (% of dry weight) (Nielsen, 1987). The inorganic fraction (ash) usually comprises 5-10 % of the dry matter content, and the volatile compounds about 70-80 %. From the literature, however, it is obvious that the composition of straw is highly variable. According to Axenbom et al. (1991), the composition is affected to a varying degree by

- type of crop (cereals, oil seed, etc)
- variety of crop
- type of soil
- weather conditions during the crop growth season
- weather conditions during the harvest season
- types of fertilizers and pesticides used in the crop cultivation
- ripeness when threshing
- contamination (e.g. soil)
- storage conditions

It is therefore difficult to define a "standard" composition of nutrients in straw. Among the numerous elemental analyses of straw (e.g. Ebeling & Jenkins, 1985; Ghaly & Al-Taweel, 1990), a Swedish investigation is shown in table 1.

The high C/N-ratio ($\approx$90) may lead to additional requirements of nitrogen supply to the following crop, because the microbes will bind mineral nitrogen in the decomposition process. Hence, it seems that incorporation of straw has a slight positive effect on crop yield, primarily due to the extra nitrogen supply and also the return of potash (White, 1984). Comparisons between straw removal and straw incorporation indicate, however, that the long-term impacts on crop yield are generally small (Persson, 1982). It should be noted that the content of organic matter in root systems are considerable, and that chaff, leaves and stubble, which not are removed in the straw harvesting, constitute 1/3 to 1/2 of the amount of total organic matter above ground.

Table 1. *Elemental composition of straw in percent of dry matter content (Ivarsson & Nilsson, 1988)*

Element	Cereal straw Average (%)	Ranging (%)	Rape straw Average (%)	Ranging (%)
C	46	45-47	46	45-47
H	5.9	5.8-6.0	5.7	5.4-5.8
N	0.5	0.4-0.6	0.8	0.6-0.9
O	40	39-41	39	38-40
S	0.08	0.01-0.13	0.17	0.14-0.22
Na	0.11	0.01-0.60	0.14	0.04-0.24
Mg	0.11	0.06-0.14	0.10	0.07-0.14
Si	1.7	0.6-4.0	2.0	0.4-7.6
P	0.07	0.04-0.10	0.08	0.07-0.12
Cl	0.31	0.14-0.97	0.22	0.15-0.31
K	0.99	0.69-1.3	1.00	0.58-1.50
Ca	0.4	0.26-0.66	1.34	0.92-1.60
Al	0.02	0-0.09	0.22	0.05-0.70
Fe	0.02	0-0.11	0.16	0.04-0.56

Soil-incorporated straw prevents erosion, which does not seem to be major problem in Sweden, improves the porosity and structural stability in soils, and increases the humus content (Persson, 1982; Schjønning, 1986; Christensen, 1986). But it seems to be difficult to quantify the long-term effects on soil properties due to straw removal. There are also studies, e.g referred by Butterworth (1985), that show no significant differences in soil properties between straw removal and straw incorporation. To conclude, the soil is a very complex system which changes slowly through the years and includes a vast amount of factors.

Although it may be troublesome to establish a correct compensation for the nutritional and biological effects of straw removal, the farmers in Sweden are paid about 70 SEK per tonne of straw. This compensation is primarily based on the long-term replacement of nitrogen and potassium. There are no differentiations between so-called grey and yellow straw. Grey straw has a lower content of alkali metals (which cause slagging, agglomeration and fouling in the conversion process) and chlorine due to leaching.

3.5.2 Ash

As the straw composition regarding nutrients and heavy metals varies, the ash composition varies as well. There may be fairly large differences between ash fractions (bottom or fly ash), types of straw (e.g. wheat, barley, rye, rape), soil types and combustion techniques. The liming effect for rape straw ash is, for instance, threefold compared with wheat straw ash (Sander & Andrén, 1995). The dominating components in ash are SiO_2, K_2O and CaO. Average concentrations of nutrients and heavy metals from a Swedish investigation are shown in table 2. The ash samples are taken from 7 heating plants ranging from 25 kW to 5 MW. Note that the values for mixed ash are not comparable with those for bottom and fly ash, because the samples are taken from different furnaces.

As can be seen, the concentrations of Zn, Pb and Cd are almost 10, 15 and 40 times higher in fly ash than in bottom ash, respectively. Fly ash constitutes, at a rough estimate, 10-20 % of the total amount of ash in grate boilers (Green, pers. comm.). On the other hand, the concentrations of Cr and Ni seem to be higher in bottom ash than in fly ash. The Cd/P ratio is 22 mg kg^{-1} in the bottom ash, whereas it is 620 mg kg^{-1} in the fly ash.

Table 2. *Average concentration of nutrients and metals in bottom, fly and mixed ash from four straw types (wheat, barley, rye and rape). LOI = loss on ignition, i.e. unburned matter. Percentages of DM (mass-%) and g tonne^{-1} (ppm). (Sander & Andrén, 1995)*

Type of ash	P (%)	K (%)	CaO (%)	Cr (ppm)	Ni (ppm)	Cu (ppm)	Zn (ppm)	Pb (ppm)	Cd (ppm)	Cd/P (mg kg^{-1})	LOI (%)
Bottom	1.5	15.6	22.8	48.0	19.5	54.4	127.8	11.6	0.33	22	11.3
Fly	1.5	20.9	12.5	13.8	8.1	99.4	917.3	133.4	9.3	620	17.7
Mixed	1.4	10.3	14.4	19.1	11.6	44.4	117.3	17.4	1.1	79	19.5

About 80 % of the district heating plants in Denmark return the ash to the farmers to be used as a fertilizer (The Centre of Biomass Technology, 1992). Most of the ash from the Swedish plants is also returned. There are no regulations in Sweden concerning disposal of straw ashes. The Swedish Environmental Protection Agency has, however, a general policy that ashes from combustion of biofuels should be regarded as a resource and be re-cycled to their place of origin (Naturvårdsverket, 1994). Generally, straw ashes are valuable as P-, K- and micronutrient fertilizers, as well as a liming agent. The main problem is the content of heavy metals. Due to technical and economic reasons, the ash is spread in much higher doses in the fields than the corresponding yearly removal of nutrients in straw. Thus, there is a risk of accumulation of heavy metals. One way to overcome this problem might be to avoid in-field spreading of fly ashes from grate boilers.

3.5.3 Air emissions

The handling and combustion of straw generate pollutants to the air. According to paper II, approximately 7 litres of diesel fuel (250 MJ) are required to deliver one tonne of straw to the heating plant. If we assume that the emissions per MJ diesel fuel are 0.15 g SO_2, 1.3 g NO_x, 0.30 g CO, 0.21 g HC, 79 g CO_2 and 0.10 g particulates (Tillman et al., 1991), the emissions will be 38 g SO_2, 320 g NO_x, 75 g CO, 52 g HC, 20 kg CO_2 and 25 g particulates per tonne straw (the emission factors arise from diesel use in engines and include crude oil extraction, transportation and refining of the fuel). Apart from emissions caused by direct energy use, there will also be emissions from the production of machines, buildings, etc. However, based on a life-cycle approach, they will be small and can be neglected.

The emissions from straw burning are strongly dependent on the type of boiler and type of equipment for flue gas cleaning. Today, most district heating plants have installed a multi-cyclone followed by a bag filter, because it seems to be the cheapest method to fulfil the emission legislations. However, some bigger Danish plants have installed electrostatic precipitators or gas scrubbers (The Centre for Biomass Technology, 1992).

Typical emission values for district heating plants are listed in table 3 (the figures are from Denmark (Forsyningskataloget 1988), quoted by The Centre of Biomass Technology (1992)). The sulphur dioxide emissions are lower than from burning of fuel oil, but are at the same level compared with wood fuels. No straw-fired district heating plants have installed desulphurization equipment (The Centre of Biomass Technology, 1992). The amount of emitted NO_x, which is influenced by the design of the furnace, is at the same level for all fuels in table 3. As straw is a renewable biomass, it is considered to be CO_2-neutral.

Table 3. *Emmission values for district heating plants (Forsyningskataloget 1988, referred by The Centre of Biomass Technology, 1992). In the column for particles, the first figure is valid before cleaning, and the following for the filters C = cyclone and B = bag*

Fuel	SO_x as SO_2 (g GJ^{-1})	NO_x as NO_2 (g GJ^{-1})	CO_2 (kg GJ^{-1})	Particles (g GJ^{-1})
Fuel oil (1.0 % S)	495	150	74	60/-
Natural gas	0	150	57	0/-
Straw	130	130	0	1100/800C/20B
Wood	130	130	0	500/300C/20B

Flue gases may also contain harmful pollutants such as carbon monoxide (CO), poly-aromatic hydrocarbons (PAH), dioxins and hydrogen chloride (HCl). CO and PAH are poisonous, and some PAHs are even carcinogenic. They are both a result of incomplete combustion. The relatively high content of chloride in straw contributes to the formation of dioxins and HCl. An investigation by Nielsen & Pedersen (1987) indicated that the dioxin formation is at a magnitude of 100 ng per tonne fired straw. However, ordinary waste incineration plants emit 500-5 000 times more dioxins per tonne of fuel (The Centre of Biomass Technology, 1992). The formation of acids, principally HCl (and later on sulphuric acids), contributes to the acidification and corrosion of materials.

4 SIMULATION OF STRAW HANDLING

4.1 Logistics and the systems approach

Initially, the term logistics ensued from military operations during the World War II, meaning the planning of movement and maintenance of forces. Today, the concept has broadened considerably, and includes business logistics or industrial logistics and, in recent years, also the total system life cycle cost (Blanchard, 1992). The Council of Logistics Management (CLM) in USA defines business logistics as (Blanchard, 1992): "the process of planning, implementing and controlling the efficient, cost-effective flow and storage of raw materials, in-process inventory, finished goods and related information from point of origin to point of consumption for the purpose of conforming to customer requirements". From the literature it is clear, however, that logistics is an ambiguous concept.

In this study, logistics is concerned with moving straw from the production fields to the consumer plants. In other words, the aim of straw handling is to supply the right product in the right condition to the right place at the right time at the least cost. This logistic view (Attwood & Attwood, 1992), sometimes called distribution logistics, describes the physical flow of the product, often by means of operations research. Logistics is closely linked to the systems concept. The intention here is to treat the straw handling system in a holistic/logistic point of view.

The systems approach provides us a method to observe and explain the courses of events in reality as a number of components that are connected between themselves and act together. Blanchard (1992) states that "A *system* may be considered to be a nucleus of elements structured in such a manner as to accomplish a function to satisfy an identified need. The elements of a system include a combination of resources in the form of materials, equipment, software, facilities, data, services, and personnel integrated in such a manner as to meet a specified requirement: that is, a self-sufficient entity operating in a satisfactory manner, in a defined user environment, throughout its planned life cycle. A system may vary in form, fit, and function." A *model* is an abstraction of reality, or in other words, a system we have chosen to depict essential properties of another system (Gustafsson et al., 1982).

The straw fuel system is complex, including human, technological, biological, climatic, environmental and economic factors. In order to analyze and optimize such systems, it is convenient to use computer models, on which experiments are conducted.

4.2 Models related to straw handling - a literature review

Numerous models that are related to straw handling have been constructed. A selection from them is presented below. Note that the following classification is somewhat rough. The modelling approach is mainly determined from the *objective* of the study and the *boundaries* of the system.

4.2.1 Static models for cost calculations

Static models have stationary properties, i.e. the properties are not dependent on time.

Brundin (1986) presents a model for cost calculations of energy grass and straw handling. The model has been constructed in Symphony, which is a spread-sheet programme. The model includes a data base, a section for handling and input options, and a calculation and output section. The model assumes fully divisable machines, buildings and men. The impact of weather during the harvesting season is taken into consideration by an analytical formula which expresses the accessibility of harvesting days as a function of the number of years out of ten in which all the straw is to be harvested dry. If it is anticipated that all the straw will be harvested dry in eight years out of ten, the capacity can, for example, be 50 % lower than corresponding capacity for ten years out of ten. The formula is based on statistical weather data for certain places in Sweden. The model describes a large number of handling alternatives for harvesting, storing and transportation of energy grass and straw. The results of the calculations are presented by Brundin (1988).

Flodén (1994) developed a spread-sheet model for the harvesting and handling of high-density bales. He compares, for instance, new handling equipment such as bale-chasers, transstackers, bale accumulators, etc. His model is similar to that developed by Brundin (1986).

Parsby & Gylling (1991) constructed a spread-sheet model for the cost assessment of biomass-fired CHP-plants. The model consists of four modules; technical and economic basic data, energy and mass balance, energy demand and energy profile for a place, and an economy module. The model is not a model for straw handling, but rather a model to adapt the mass-energy-flow of biomass to the energy demand of a village. In the report, for instance, they simulate and make sensitivity analyses for a 6 MW CHP-plant based on straw gasification.

A computer program in FORTRAN was developed by Noble & Clegg (1984) to calculate the costs of some straw handling chains. The results are presented in Clegg & Noble (1987). The model was used to compare different systems based on conventional bales, round bales, large rectangular bales and chopped straw. Among the large quantities of cost calculations, it may be worth noting that Astrupgaard & Stenholm (1993) discuss handling costs for chopped straw, which is stored outdoors, and that Nilsson (1991) calculated the costs for in-field wafering of straw.

4.2.2 Machinery optimization based on linear and mathematical programming

Both linear programming (LP) and mathematical programming (e.g. network analysis, dynamic programming, etc.) are techniques to find the optimal solution among competing activities when the resources are limited. These methods have also been used for machinery selection in agriculture.

Nilsson (1976) describes a model for machinery selection, e.g. from a given cropping plan, with mixed binary integer programming. This method has advantages according to data handling and has no fractional solutions. In connection with the model, a data base is established, and a sensitivity model constructed, in which some stochastic variables and timeliness effects can be studied. A similar optimization model for farms in North Dakota and Minnesota is reviewed by Pfeiffer and Peterson (1980). The timeliness function is an important factor in many machinery selection models. Timeliness in relation to machine size is discussed by Von Bargen (1980). The last example of using LP-models is reported by Audsley (1989). He investigated the economy of whole crop harvesting of cereals, and concluded that the profit is doubtful on cereal-growing farms.

Jenkins & Arthur (1983) used networks of handling operations and dynamic programming to determine the optimal system. Networks can be described by arcs and nodes (figure 7), and are powerful tools to select the optimum alternative among hundreds of possible alternatives. The objective function can, for instance, contain one (e.g. minimizing cost) or multiple criteria (minimizing cost and e.g. maximizing reliability, safety, etc.). Langille & Ghaly (1990) constructed a network model for multiple criteria, with a view to determine the optimum system for straw handling. The criteria were weighted with a decision matrix, where each criterion had a factor from 0 to 1.0, depending on its relative importance. Then, the alternatives were rated against the criteria. A review of multiple criteria decision-making (MCDM) techniques in agriculture is reported by Rehman & Romero (1993).

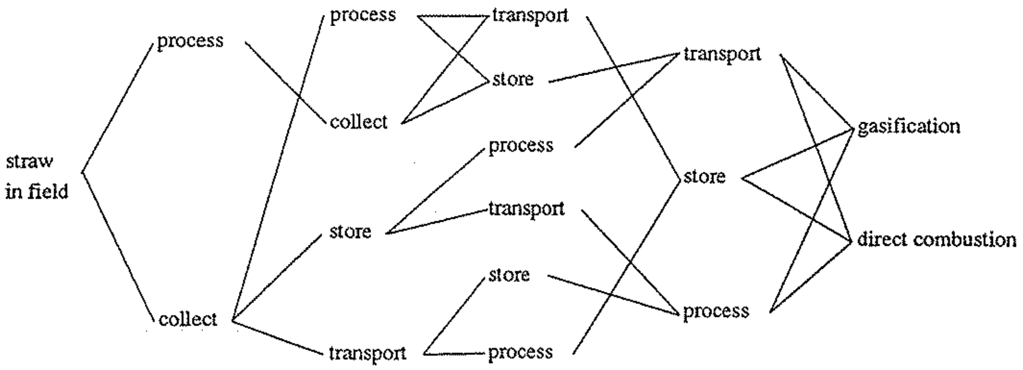

Figure 7. *Principles of a network for straw handling (Jenkins & Arthur, 1983).*

Jenkins et al. (1984) compared handling systems for straw, cotton stalks, prunings and other biofuels by means of networks and least cost functions. Network analysis for optimizing machine capacities was also performed by Ademosun (1986).

Comparisons between a simulation model with a heuristic procedure and an LP-model, both for scheduling farm operations, are discussed by van Elderen (1980).

4.2.3 Integrated simulation models

In this context, the term "integrated" alludes to many of the models presented here consisting of sub-models describing plant growth, field drying, harvesting, weather conditions, etc. Simulation techniques and definitions are described in many textbooks, and for instance by Loewer et al. (1980).

A combined simulation model for handling of maize stalks, low-quality hay and wood chips is described by Mantovani & Gibson (1992). The model includes harvesting, transport and storage, taking geographical aspects into account. The plant is able to switch from one fuel to another throughout the year, and the most appropriate fuel is chosen from weather and supply conditions, as well as fuel costs.

The model was written in SLAM II. This language has the ability to simulate the system in a continuous, discrete event or network point of view, or any combination of these. The authors have chosen to view their biomass handling system from a combined network-discrete event perspective. The operations are seen as process-oriented, where each process contains queues, servers (e.g. balers) and decision points (is the weather good enough?). Land areas are chosen as entities, which flow through the network. The characteristics of each entity are stored as "attributes".

Many of the inputs to the model are read from matrices; for instance "days not suitable for field work", "amount of precipitation", "maize and hay yields", "fraction of each region planted with corn, hay or commercial forest" and "percent of hay diverted to plant". The matrices are based on data from three regions in Indiana, USA, during the years 71/72 - 80/81. Furthermore, cost data, type of operations and data belonging to them are added. Areas of each feedstock round the plant, the amount of feedstock consumed per day by the plant, average radius for transportation, etc. are calculated by auxiliary programs and also read as inputs to the model. Outputs include costs, machine utilization, etc.

An additional SLAM-model, which is proposed to be general-purpose for agricultural operations, is referred by Buck et al. (1988). In the article, the authors apply the model on a forage harvesting system.

A model, called DAFOSYM, was constructed to compare technologies and management strategies for dairy farms (Rotz et al., 1989). Important submodels are crop growth, harvest, storage, feed utilization and economic analysis. Information about the model development and adjacent topics is presented by Savoie et al. (1985), Savoie et al. (1982) and Savoie et al. (1981). An additional extensive simulation model for hay-making systems is described by Gupta et al. (1990). Furthermore, a Fortran-based model for machinery selection on dairy farms is presented by Russel et al. (1983), and a model in the C language, which simulates equipment and manpower levels against climatic variability, is reviewed by Papy et al. (1988).

Van Elderen (1987) presents a systems analysis and a model in Simula for simulating the scheduling of farm operations. He defines scheduling as "the allocation of operations in time". The model is a detailed model for most farm operations in the field. Hence, storing and transportation is not considered. The scheduling system is divided into subsystems; the biological subsystem (materials, e.g. crops, and weather), the man-machinery subsystem (men and machinery which form gangs) and the decision subsystem (operations and decision). The term "operation" can be seen as a link between the biological and man-machinery systems, whereas "decision" implies the ranking of operations. Van Elderen (1977) has developed a heuristic decision strategy in which the operations are ranked depending on their urgency. The most important factor affecting the urgency is the timeliness function. It expresses the "relationship between recoverable value (depending on quantity, quality and price) and the time when the operation is performed" (van Elderen, 1987).

An integrated simulation model for hay harvesting was constructed by Axenbom (1990). The model consists of the following submodels: growth, field operations, management, field drying, barn drying, field losses and conservation losses. The field operations and management models constitute the "base" model, which is a discrete event simulation model in Simula (using the package DEMOS). The remaining models are continuous and dynamic and describe biological processes. The "base" model emphasizes the behaviour of the man-machinery system. The entire model is primarily designed for research, and in particular for "analyzing problems related to planning of hay machinery systems and management".

Both van Elderen and Axenbom simulated in Simula, which is a general-purpose and object-oriented language. Objects (or actors) are defined by classes, whose data, characteristics and functions can be referred to in the program, and that make hierarchial structures possible. It is also possible to simulate combined systems, i.e. systems with both continuous processes and discrete events.

Chen et al. (1976) developed a discrete event simulation model in SIMSCRIPT II.5 for evaluating the interactions between plant growth, weather, machinery and labour for harvesting of pickling cucumbers. Eventually, a model for manure logistics was developed by de Mol & Koning (1992).

4.2.4 Decision support systems (DSS), AI and expert systems

In recent years, decision support systems (DSS) based on artificial intelligence (AI) and expert systems has come into use in agriculture. Initially, the researchers expected great things from these techniques, but the enthusiasm is more temperate today. Although the use of these methods for investigating straw handling systems can be questionable, some reports on farm machinery management are briefly reviewed here.

A general discussion on applications of expert systems in agriculture is conducted by Doluschitz & Schmisseur (1988) and Jones (1989). A DSS for machinery management at farm level is FARMSYS, which is constructed in PROLOG (Lal et al., 1992). PROLOG is a logic programming language and provides an object-oriented environment. FARMSYS consists of the following components; Info Manager, Operations Simulator (Lal et al., 1988), Expert Results Analyzer (Lal et al., 1991) and Yield Estimation System. FARMSYS evaluates daily operations by means of "weather data, machinery capacities, labor availability, and information on permissible and prioritized operators, tractors and implements" (Lal et al., 1992).

An attempt to make LP-models for machinery selection more user-friendly by using expert systems is reported by Kline et al. (1988). Another strategy for expert systems is to let heuristic rules govern procedures described by algorithms (Spugnoli & Vieri (1992).

4.2.5 Modelling of transportation and allocation

So far, most models act on harvesting, either for tactical (on the short view) or strategical (on the long view) planning, and can be classified into models for field-scale or whole-farm management. Some of the following models, however, also consider postharvest aspects. An example is a discrete event model written in SIMAN for postharvest operations of peaches (Thai & Wilson, 1988).

Kindler et al. (1981) present a model for transportation in agriculture. They perceive the systems as typical discrete dynamic systems, and recommend Simula for these purposes. Their model is applicable to harvesting systems, manure transport systems, container transport, transport into factories, etc.

Transportation distances, costs and optimal plant size are discussed by Kristensson & Axenbom (1991). They present cost calculations for transport of straw and salix chips with tractor and lorry. Furthermore, the relationships between market price, gathering area and straw supply is discussed.

A model for optimizing collection and transport of manure from feedlots was developed by Egg et al. (1981). They use queueing theory with a single server to minimize fuel consumptions in the operations. Another transportation model is reported by Jenkins et al. (1983). The model is intended for "determining the best mix of biomass resources to provide minimum total delivered cost at a site and any size utilization facility at the site". The model takes region-specific prerequisites, such as area of biomass cultivation, regional centres and distances into account. The output of the model ranks the regions and biomass types to minimize the delivering costs. The model is said to be "useful in comparing alternative sites, selecting the optimum size of a utilization facility, or determining which mix of biomass is best used at a site." Csáki (1985), Asikainen (1995) and Gallis (1996) also present models or approaches applicable to handling of biofuels.

4.3 Model specifications and system boundaries

Because the primary aim of the project is to reduce the straw handling costs from the heat plant's perspective, it is necessary to follow the whole handling chain from threshing to delivery at the plant. However, internal material flows in the plant are not considered. The model should also calculate the costs on a yearly basis, considering both harvest and post-harvest operations.

Harvest of straw includes measures that are not directly valued in monetary quantities, for example, the time the fields are occupied with un-baled straw. If the fields are occupied for too long a time, there is risk of delayed autumn farming. This may lead to farmers becoming unwilling to sell the straw. Therefore, the model must be able to analyze the performance of the studied system. Thus, a dynamic model should be used.

The model should also consider the energy requirements for straw handling, which will facilitate accounting of energy balances and environmental assessments.

The weather and geographical aspects have a great impact on straw harvesting and should also be included in the model. After the straw has been loaded into the storage, however, the weather has a minor impact (unless the straw is stored outdoors). Consequently, the harvest season should be modelled dynamically, whereas a static model could be used for the post-harvest operations.

From a logistic point of view, it is convenient to consider the material handling as a discrete event system (DES). Compared with continuous dynamic systems, most DES are man-made and describe the timing of essential discrete events. These events can be caused by arrivals and departures of "jobs" (e.g. bales) to resources (e.g. machines), which serve the "jobs". Whereas a trajectory for continuous dynamic systems is constantly changing, a DES trajectory describes states and holding times. What is happening before, during and after a "service" is less interesting in this context. Haphazard external disturbances, for example, machinery breakdowns and rainfall, confirm the DES approach. Simulation of discrete event systems is discussed further in the next chapter.

The simulation language should be powerful and flexible, having a graphical user interface and animation capabilities to facilitate its use and to improve its acceptability.

None of the models in the literature study could be adapted to these requirements without major modifications. Therefore, a computer model has been developed, which is based on discrete event simulation.

4.4 Discrete event simulation

4.4.1 Discrete event systems

Consider a drop-in barbershop where customers arrive randomly. The barbershop has two hairdressers who serve the customers. One hairdresser is specialized on women, but also dresses men's hair. However, the second one dresses only men's hair. The service time is dependent on the type of job required. Occasionally, the queue grows considerably, and some customers leave the queue before they are serviced and go to a rival barber. Therefore, the owner of the barbershop is wondering if it would be more profitable to employ an additional hairdresser, or specialize his business on either men or women.

Furthermore, consider a large highly automated manufacturing plant where cars are made. Thousands of parts are delivered per day from different suppliers to the plant. When they arrive, they are stored at different places until they begin their "flow" through the plant. Then they will visit hundreds of stations within the plant where they are "served" by different resources. Finally, they have been put together into new cars. How should this plant be designed in order to make the production processes as efficient as possible?

Both these examples can be viewed as discrete event systems (DES). Usually, there are some kinds of "jobs" (e.g. customers, parts) with some properties (e.g. male or female) which demand and compete for service from resources (e.g. hairdressers, turners). Thus the "jobs" may spend a lot of time waiting in queues and waiting for completion of tasks. The systems dynamically change their states as time goes on, depending on the occurrences of so-called events, such as arrivals of "jobs", breakdowns, completion of tasks etc. These events may be stochastic and follow a probabilistic distribution. For instance, the arrivals of customers to the barbershop can be viewed as a random process.

DES can be investigated by discrete event simulation. The advantages of discrete event simulation, as well as modelling in general, are many. Fishman (1978) lists the most important:

- It enables an investigator to organize his theoretical beliefs and empirical observations about a system and to deduce the logical implications of this organization.
- It leads to improved system understanding and brings into perspective the need for detail and relevance.
- It expedites the speed with which an analysis can be accomplished.
- It provides a framework for testing the desirability of system modifications.
- It permits control over more sources of variation than direct study of a system would allow.
- It is generally easier and less costly to manipulate than the real system.

In particular, simulation is of advantage when the real-world systems are complex and have stochastic properties (Law & Kelton, 1991). In such cases, simulation may be the only possible way to investigate the systems, especially when they cannot be evaluated analytically by mathematical models. However, Pegden et al. (1995) remind us of some important drawbacks with simulation:

- Simulation results are sometimes difficult to interpret. Because the model is trying to capture the randomness of the real system, it is often hard to determine whether an observation made during a run is due to a significant relationship in the system or to the randomness built into the model.
- Model building requires specialized training. The quality of the analysis depends on the quality of the model and the skill of the modeler. Model building is an art, and the skill of the practitioners may vary widely.

- Simulation can be time-consuming and expensive; it may be difficult to collect data, the model may be more detailed than necessary or not well-balanced, it may be difficult to find and remove unintentional errors in the logic of the model, etc.

4.4.2 Discrete event simulation vs continuous simulation

It may be illustrative to compare the sample paths for DES and continuous-variable systems. The latter are described by differential equations of the form

$$\dot{x}(t) = f(x(t), u(t), t)$$

where $u(t)$ is the input. The state is constantly changing as the trajectory evolves (figure 8), and $x(t)$ can take any value in the state space $X = \mathbf{R}^n$. This behaviour can be found in all natural sciences, describing, e.g., the population of animal species, plant growth, motion of a mass-spring system etc.

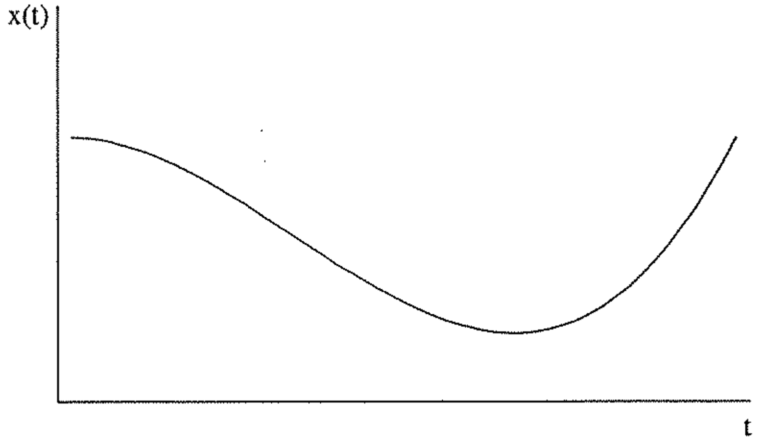

Figure 8. *A trajectory for a continuous-variable system.*

A trajectory for a DES is shown in figure 9. Here, the state jumps from one discrete value to another in the state space

$$X = \{s_0, s_1, s_2, s_3, s_4, s_5, s_6\}$$

A state transition can only take place when an event occurs, according to Cassandras' (1993) definition of DES as "a discrete-state event-driven system", where "its state evolution depends entirely on the occurrence of asynchronous discrete events over time". Furthermore, the trajectory is piece-wise constant during the simulation. DES are typically manmade and have become significant during recent decades. Typical DES are manufacturing plants, computer networks, transportation systems, logistics, service operations etc, all more or less including human beings in the modern world (Ho, 1991).

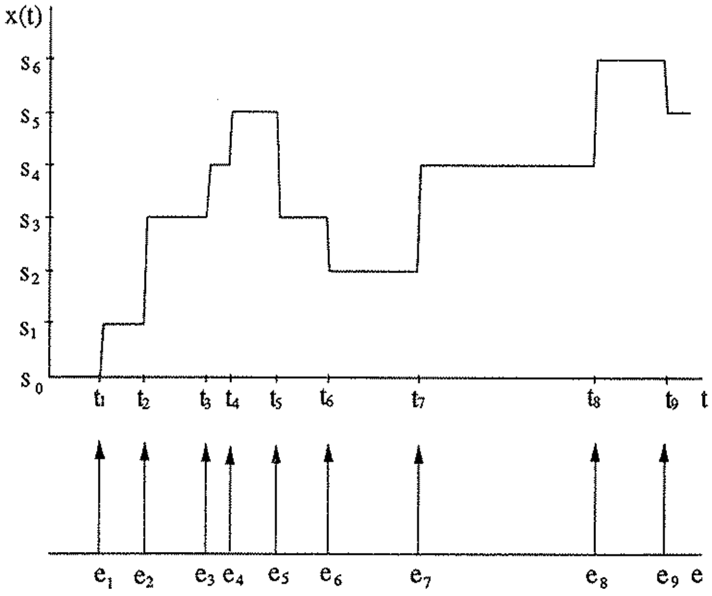

Figure 9. *An example of a trajectory in a discrete event system. For instance, it can be seen that the event* e_6 *at time* t_6 *changes the state of the system from* s_3 *to* s_2*.*

4.4.3 The process-oriented approach

Time and the scheduling of events can be treated in different ways in DES (Cassandras, 1993). The most common simulation schemes are the so-called event scheduling simulation scheme and the process-oriented simulation scheme. In the former, all feasible events are placed in a scheduled event list, where they are ordered in increasing occurrence times. The next event updates the state of the system and time, whereby some new events may become active and placed in the list. The process-oriented simulation scheme may be more "natural" for resource-competing systems, where entities (e.g. customers, bales) with some properties or attributes undergo different processes. A process can be described as a sequence of logical and time-delaying functions, which are triggered by the entities (Cassandras, 1993). The basic principles of the process-oriented scheme are shown in figure 10. The "activities" in the figure are associated with resources that serve the entities and thus cause time delays.

The simulations can be implemented in computer programming languages, general purpose simulation languages or in simulators (Sagert, 1995). The computer programming languages, such as FORTRAN, Pascal and C, have greater flexibility, but require more coding and may be time-consuming to learn and use. Therefore, general purpose languages have been developed in recent decades to make modelling of DES easier. GPSS was one of the first languages, followed by, for example, GASP, SLAM, SIMSCRIPT and SIMAN. There are also some object-oriented languages (e.g. SIMULA and MODSIM II). Most simulation languages have quite comprehensive capabilities of random variate generation, performance analysis and animation. The simulators, which are constructed for specific applications, are easy to use but their flexibility is limited.

ENTITIES
having ATTRIBUTES
interact with ACTIVITIES
under certain CONDITIONS
creating EVENTS
that change the STATE OF THE SYSTEM

Figure 10. *The process-oriented approach (Shannon, 1975).*

4.5 SHAM - simulation of straw handling

4.5.1 Model overview

A simulation model, called SHAM (Straw HAndling Model), has been developed for performance, cost and energy analysis of straw handling systems. The dynamic part of the model is written in the SIMAN language in the Arena environment (Pegden et al., 1995; Systems Modelling Corp., 1995). The model consists of four main submodels as described in figure 11: a location submodel, a weather and field drying submodel, a harvesting and handling submodel and a model for calculations of costs and energy requirements. SHAM is a combined continuous (weather and field drying) and discrete event (harvesting and handling) simulation model. The model is primarily intended for research and development. A description of SHAM is presented in paper III and some applications are presented in paper IV.

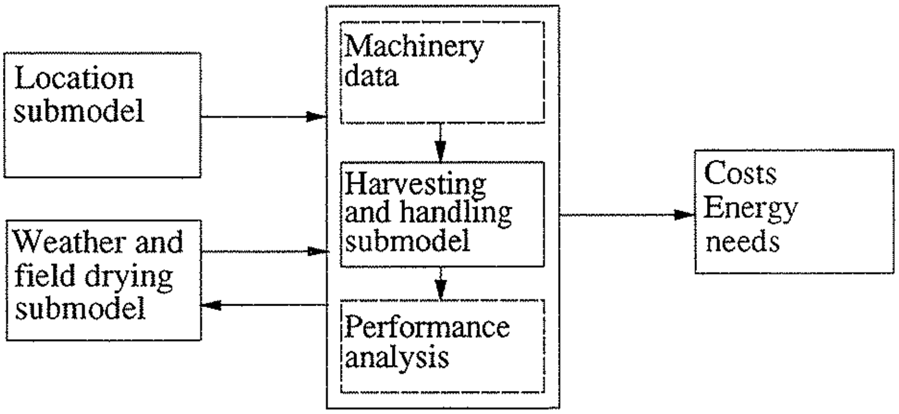

Figure 11. *General outline of SHAM.*

4.5.2 The location submodel

The geography and the infrastructural conditions have a great impact on the straw handling system, because they settle or influence the transportation distances, mode of transportation, field sizes and the spatial concentration of straw, location of storages, etc. The locations of the fields, storages and the plant are determined using a map and the model presented in paper III. A digital map is also used in the animations.

4.5.3 The weather and field drying submodel

In addition, the weather has a crucial impact on the straw harvesting system, at least in the Swedish climate. The amount of precipitation is at maximum in July, August and September, and the mean of the daily relative humidity exceeds 80 % already in the middle of August at many places (Taesler, 1972). The straw that is to be harvested must be dry enough to ensure a high heating value, and to avoid machinery stoppages and dry matter losses due to fungal growth. The fields must also be dry enough to make the field traffic easier and to avoid soil compaction. Because the straw moisture content dynamically changes as the weather changes, a model that predicts the straw moisture content at any time during both drying and rewetting was necessary. Such a model is developed and described in paper III. The model is based on empirical and semi-empirical relationships between drying/rewetting rates and weather parameters of significance.

The weather parameters that control the field drying model can be obtained from stochastic weather generators or from actual observations. A number of weather generators were found in the literature (Richardsson, 1981; Ndlovu et al., 1994; Carter et al., 1995). In principal, they all treat the occurrences of wet (i.e. days with precipitation) and dry days as an independent variable, which is determined from a first-order Markov chain. In other words, the probability of rain one day is conditioned on the status of the previous day. The amount of precipitation is determined from probability distributions, usually the exponential distribution. Other weather parameters, like maximum and minimum daily temperatures, solar radiation and cloudiness, are then correlated with the precipitation status of the day.

These weather generators use a time step of (minimum) one day and have a limited amount of weather parameters. Evapotranspiration and relative humidity, for example, are not included. Also, they have not been tested and validated for Swedish conditions. Therefore, historical weather data, from the years 1980-94, have been used in the simulations. The data are obtained from the Swedish Meteorological and Hydrological Institute (SMHI) for weather stations as close to the heating plants as possible.

No field drying models that could be directly applied on straw were found in the literature. The models developed by Stewart and Lievers (1978) and Hadders (1993) are indeed applicable on straw, but they do not consider the equilibrium moisture content. The equilibrium moisture content, which mostly is dependent on the relative humidity, strongly influences the straw moisture content, especially near the harvesting moisture contents. The straw drying model by Jenkins et al. (1985) considers the equilibrium moisture content, but requires hourly weather data, which is not available for most weather stations. Thus, it was necessary to develop a model which sufficiently accurately predicts the drying and rewetting of straw, using readily available weather variables.

There are a number of models for drying of hay; either based on energy- and mass balances (Brück & van Elderen, 1969; Thompson, 1981; Smith et al. 1988; Atzema, 1994), or empirical models based on diffusion equations (Kemp et al., 1972; Hayhoe & Jackson, 1974; Dyer & Brown, 1977; Savoie et al., 1982: Pitt, 1984). The former are complex and comprehensive and require weather data that are not available from standard weather stations. The latter approach was chosen to reduce model complexity and development effort.

4.5.4 The harvesting and handling submodel

As described in figure 1, the handling of straw can be viewed as a mass flow from the field to the plant. The straw is delayed either in queues waiting for service or during processing by the different resources. The resources are, in turn, working according to schedules (e.g. time in the day), rules and conditions. In a general view, the harvesting and handling submodel has two main entity flows; a "physical" flow of straw from the fields to the storage, and an "information" flow to a simulated manager.

The "physical" flow is represented by the graphics exemplified in figure 12. The circles represent the resources and the preceding queues are represented by open boxes. The slots in the queue symbol indicate waiting individuals. The capacities of the queues may in some cases be limited, which is indicated by closed boxes. In such cases, there is risk of blockages, which may cause machinery standstills or jams backwards in the queueing network. All the queues have a special queueing discipline, which determines the next customer to be selected from the queue.

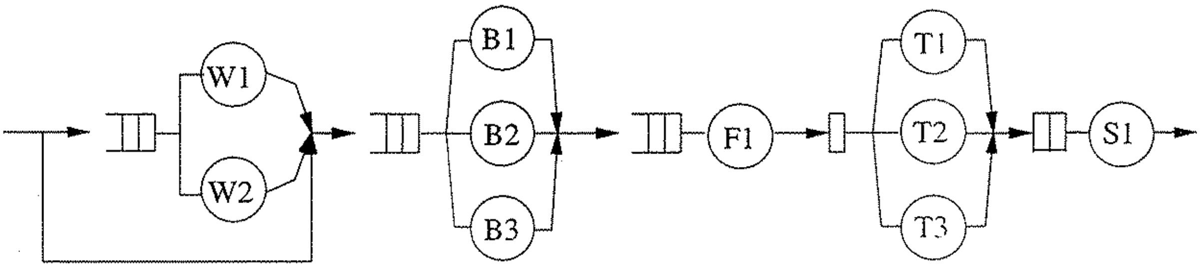

Figure 12. *The flow of straw from the fields to the storage. The straw is served by windrowers (W) (optional), balers (B), a field loader (F), transporters (T) and a storage loader (S).*

In the high-density baler systems, each tonne of straw is represented by a corresponding entity. After the baling operation, each entity represents one load of straw (13 tonnes if winter wheat). In figure 13, it is described in greater detail what happens when a baler man has been allocated to a field. The interactions with the "manager" are also shown.

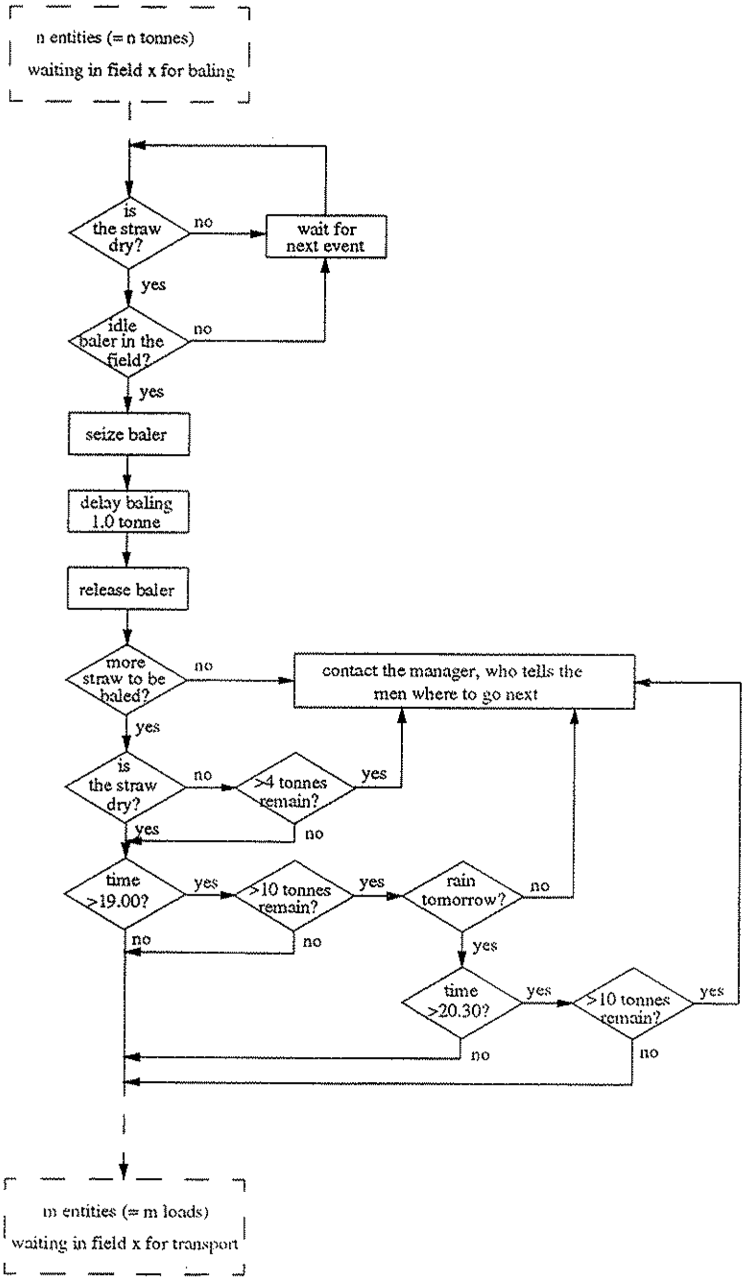

Figure 13. *An outline of the baling operation.*

4.5.5 Output analysis

A large number of system performance measures can be studied. For example, the waiting time in queues, utilization of resources and the amount of straw that the machines are able to harvest, can be evaluated for different machinery chains, weather sequences, straw yields, geographical conditions and management strategies.

In the applications in paper IV, the TBT (threshing-baling time), BST (baling-storing time), total amount of harvested straw, and the fraction of straw that was baled within 9 days in all replications, were chosen as the main system performance measures. TBT (in hours) expresses the time from threshing until the last bale has been baled in each field, whereas BST (in hours) expresses the time from this moment until the straw has been loaded into the storage.

The time the machines are working in the different states (e.g. baling, transporting, breakdown, idling) is also registered and used in the cost and energy submodel to calculate the costs and energy requirements.

4.6 The results of the simulations in brief

4.6.1 Systems based on high-density balers

Today, the high-density baler is the dominating machine for harvest of straw. It produces bales with a density of 130-150 kg m^{-3}, each weighing 480-550 kg and having the dimensions of 1.2 x 1.3 x 2.5 m^3. The results from simulations with systems based on high-density balers are presented in paper IV.

The prerequisites for harvest of straw were investigated for the municipalities at Svalöv, Vara and Enköping. The climate and geographical conditions differ between these locations, and the aim was to compare the costs, energy needs and system performance when using the same machinery equipment and management strategies. The simulations showed that the costs were lowest at Svalöv. By using appropriate management strategies, however, the costs can be further reduced and the system performance increased. Finally, optimizations were made in order to determine the number of machines that result in the lowest total fuel cost for the heating plant. With the assumptions presented in paper IV, it was shown that the straw can be delivered at a cost of 29.6 SEK GJ^{-1} to a plant at Svalöv.

4.6.2 Systems based on new technologies

Simulations with systems based on compact rolls and chopped straw stored outdoors are presented in paper IV. These technologies are not yet commercial, but seem to be interesting alternatives for the future. The compact roller machine was invented in Germany, whereas the idea about chopped straw stored outdoors for large-scale combustion originates from Denmark. Some trials with the latter method have been performed in Skåne in south Sweden.

The simulations showed that these technologies are almost competitive with systems based on high-density bales. It might, however, be possible to further reduce the costs by optimizing the systems and improving the capacity of the handling equipment.

5 GENERAL DISCUSSION

The discrete event simulation approach has proved to be a powerful tool to investigate and optimize handling of biofuels. Modern simulation software allows comprehensive studies to be made of such complex handling systems. The main part of the total costs for these fuels arises from harvesting and handling operations. For example, 80 % of the total straw production costs are related to these operations. The values for other agricultural biofuels, such as *Salix Viminalis* and *Phalaris Arundinacea*, are about 60 % and 70 %, respectively.

The energy analyses showed that straw is beneficial in many respects. When assessing macroscopic systems in general, however, it is necessary to clarify the underlying implication of the term "energy quality", thereby making interpretation of results from different energy evaluation methods meaningful.

The ideas of the emergy analysis may in many respects be attractive. However, the practical calculations are often difficult to interpret and implement. Therefore, it is necessary to describe the emergy analysis in a more formal mathematical way with established notations and incontestable definitions. The applicability of the method to human-related economic activities should also be elucidated.

Generally, the cost calculations in this study, as well as the energy analyses and the environmental assessments, have shown that straw is an interesting fuel for the future. For use in district heating plants, the simulations showed that the chances to become economically competitive are best in south Sweden (Götaland). On the present-day energy market, it will be economically difficult to establish straw-fired plants northwards, due to poorer weather conditions, lower yields, longer transportation distances and a higher supply of competing biofuels.

The new technologies investigated, compact rolls and chopped straw stored outdoors, are promising alternatives to the high-density baler system. They should, however, be seen as complements rather than adversaries to the high-density bales. The compact rolls may be competitive where the transportation distances are long and where the storage space is limited and/or costly, whereas chopped straw preferably should be used where the transportation distances are shorter and where it can be fed directly into the furnace without costly feeding equipment (e.g. scarifiers). The development of these technologies should be further followed and promoted.

The storage of straw makes up a considerable part of the total costs (15-20 %). More research and development efforts are necessary to reduce these costs. In particular, special attention should be paid to investigate and solve the problems associated with storage outdoors.

Straw is one of many biofuels that can be used in many ways. For example, it may be questioned whether straw should be used for heat production in district heating plants at all. It should perhaps be used for heat production solely in small-scale farm boilers, or for production of ethanol in large-scale plants. Perhaps it should be used in mixes of biofuels, together with wood chips? To investigate such alternatives, it is necessary to use a systems approach. Therefore, studies based on the systems approach are necessary to clarify the role of straw in future energy systems.

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