Analysis of Dual-Choice Production Systems

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Abstract

A simple linear system consisting of one consumer, two power generators, two manufacturers and one disposal operation is described by using symbolic notation. The system characteristics concerning consumption of material and energy resources are studied. Constraints and dependencies are shown that influence decision-making by stakeholders involved in the system. 3D plotting techniques are used to illustrate multiple dependencies of different variables that determine the system's behaviour.

Key Words: system behaviour, symbolic notation, resource consumption, LCA

1. Intention

Numerous studies have been performed in the past that deal with questions of environmental impact caused by human consumption behaviour. Since this is an issue of high concern with regard to global environmental politics, the number of studies in this area will further increase. The majority of investigations performed so far have in common the handling of a large amount and variety of numerical data while focussing on specific products and services that provide a defined function and are of benefit to the user. By this means is tried to find the right solution for well defined problems related to the quest for sustainable development.

The present paper is intended to provide the student of life cycle assessment (LCA) techniques with concepts of analytical investigation that can help to better understand life cycle system's behaviour. Newcomers are often lured by the possibility to get newest, reliable and extensive data on processes and products from the spot that will allow them to give most appropriate advice how to deal with a specific situation of present environmental and societal concern. In fact, reality is relentless and beginners in the field of life cycle assessment suffer from being unable to see the wood for the trees. And, all too often there are not even enough trees.

The following example demands basic knowledge in calculus by using symbolic notation as introduced in our previous papers[1,2]. The target of the study is a simple straight-forward system specifically designed to see how the system behaves with respect to resource consumption according to the choices stakeholders involved in this system make.

2. System Description

2.1 Flowchart

As shown by Fig. 1 the system to be investigated consists of six modules. Modules E1 and E2 represent the supply of energy by independent power generating facilities. Both facilities are considered to be self-sustaining, that is to say they don't receive any material or energy input from other modules of the system. However, they use energy carrying natural resources R_{e1} and R_{e3} as input of course.

Modules M3 and M4 represent activities to provide the consumer with material products. Both modules need raw materials R_{m3} and R_{m4} respectively and get their energy from modules E1 and E2. The type of energy provided by both power generators is considered to be interchangeable. Therefore, the ratio of energy supply can vary from zero to hundred perceent. However, this is an exclusive rule. Increase of power supply by one generator decreases the purchase from the competitor. Module C5 is the centre of all activities and represents a group of consumers, which all behave similar. This group can choose products from M3 and/or M4 as well as energy from E1 and/or E2. The supply of energy and material can vary between zero and hundred percent respectively. The treatment of used products in the post-use phase is described by module D6. It is simply a single dumping operation without any recycling or energy recovery activities. The module is driven by energy provided by E1 and/or E2. Similar to the previous cases, the ratio of supply can vary from zero to hundred percent.

2.2 Fundamental Relations

A module is characterised by input of material m_e and energy E_e that *enters* the module and by output of usable material m_{aN} and E_{aN} that *appears* after an alteration inside the module. For description of the input/output relations characteristic figures are used expressed in Greek letters.

The Greek letter μ describes the ratio of material output to input as $\mu = m_{aN}/m_e$. The letter ε is used to link the input energy E_e needed to run an operation with respect to the material input m_e as $\varepsilon = E_e/m_e$. The letter η relates the energies that enter (E_e) and leave (E_{aN}) the system by the relationship $\eta = E_{an}/E_e$. These definitions are sufficient to describe the behaviour of the system to be investigated now.

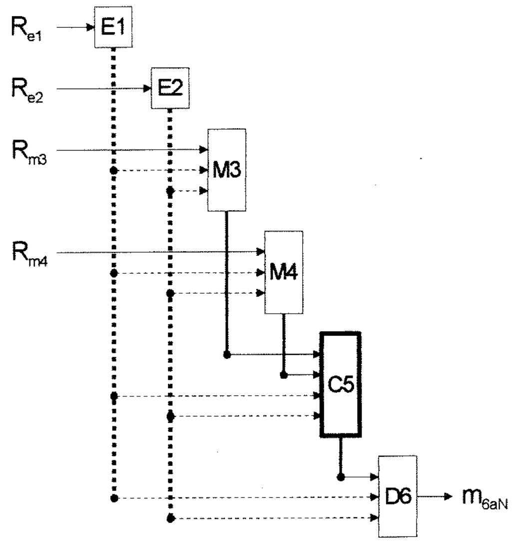


Fig. 1. Flow chart of the system to be studied.

2.3 Describing Individual Modules

2.3.1 Module C5—Consumer behaviour

The material demand m_{5e} is fulfilled by supply of material from modules M3 and/or M4. The consumer group can arbitrarily decide on the ratio of supply from both sources. The supply ratio from source M3 is expressed by p under the condition $0 \leq p \leq 1$. Supply from source M4 is then determined by $(1-p)$. In addition, the consumer group can arbitrarily decide on the use ratio of energy supplied by E1 and E2. The supply ratio from energy source E1 is e_5 under the condition $0 \leq e_5 \leq 1$, and $(1-e_5)$ is therefore valid for the ratio of supply from source E2.

Mass relations — The output of modules M3 and/or M4 becomes the input of the consumer module M5, which is expressed by the following relations:

$$m_{3aN} = p \cdot m_{5e} \tag{1}$$

$$m_{4aN} = (1-p) \cdot m_{5e} \tag{2}$$

Energy relations — The energy supply for the consumer module, which is guaranteed by modules M1 and/or M2 is expressed by the energy supply ratio e_5 similar to the concept of material supply where instead of e_5 the product supply ratio p is used.

$$e_5 \cdot E_{5e} = e_5 \cdot \varepsilon_5 \cdot m_{5e} \tag{3}$$

$$(1-e_5)\cdot E_{5e}=(1-e_5)\cdot \varepsilon_5\cdot m_{5e} \tag{4}$$

2.3.2 Module D6 — Dumping of used material

Used material will not be recycled, but dumped. Garbage collection and dumping operations are described by module M6.

Mass relations — The input consists of the material output generated by the consumer module M5. In order to be consistent with the system's description concept, the amount of dumped material is defined as the output of "usable" product m_{6aN} from this operation.

$$m_{6aN}=\mu_6\cdot m_{5aN} \tag{5}$$

which can be rewritten as

$$m_{6aN}=\mu_6\cdot \mu_5\cdot m_{5e} \tag{6}$$

Energy relations — The energy that is needed for all downstream operations following the use phase is expressed by E_{6e}. This energy can be provided by power generator E1 and/or E2. The supply ratio is e_6 in case of E1 and $(1-e_6)$ in case of generator E2, which leads to the following expressions.

Energy delivered by module E1: $e_6\cdot E_{6e}=e_6\cdot \varepsilon_6\cdot m_{6e}=e_6\cdot \varepsilon_6\cdot \mu_5\cdot m_{5e}$ (7)

Energy delivered by module E2: $(1-e_6)\cdot E_{6e}=(1-e_6)\cdot \varepsilon_6\cdot m_{6e}=(1-e_6)\cdot \varepsilon_6\cdot \mu_5\cdot m_{5e}$ (8)

2.3.3 Module M3 — Supply of a material product

Module M3 is supplying material for the consumer module C5. The amount of material the consumer gets from this module is expressed by m_{3aN}. The value of this figure is determined by Eq. (1).

Mass relations — Since module M3 is an integrated module for provision of material product, all operation steps that are part of the production chain are encapsulated and expressed by a single module, which has the raw material R_{m3} as primary input.

$$R_{m3}=m_{3e}=\frac{m_{3aN}}{\mu_3} \tag{9}$$

Energy relations — Similar to the consumer module C5 and dumping module D6 the material producer can choose between energy supply from power generator E1 and E2. The amount of energy supplied depends on the producer, which is expressed by the supply ratios

e_3 and $(1-e_3)$ respectively, and from the decision of the consumer to order from this producer at ratio p. This relatonship leads to the following expressions.

Energy delivered by module E1: $e_3 \cdot E_{2d} = e_3 \cdot \varepsilon_3 \cdot m_{3e} = e_3 \cdot \varepsilon_3 \cdot \dfrac{m_{3aN}}{\mu_3}$ (10)

$$e_3 \cdot E_{3e} = e_3 \cdot \frac{\varepsilon_3}{\mu_3} p \cdot m_{5e} \tag{11}$$

Energy delivered by module E2: $(1-e_3) \cdot E_{3e} = (1-e_3) \cdot \varepsilon_3 \cdot m_{3e} = (1-e_3) \cdot \varepsilon_3 \dfrac{m_{3aN}}{\mu_3}$ (12)

$$(1-e_3) \cdot E_{3e} = (1-e_3) \cdot \frac{\varepsilon_3}{\mu_3} \cdot p \cdot m_{5e} \tag{13}$$

2.3.4 Module M4 — Supply of a different material product

Similar to module M3 this module is also supplying material to the final consumer. The amount of material is determined by Eq. (2). Both material products generate identical benefit for the consumer group. Since they are equally appreciated, they will also be regarded as interchangeable.

Mass relations — This module also is an integrated one, similar to module M3, and all explanations concerning module M3 apply for this module also, whereas R_{m4} is the required amount of raw material taken from the natural environment.

$$R_{m4} = m_{4e} = \frac{m_{4aN}}{\mu_4} \tag{14}$$

Energy relations — What is said about the energy supply for module M3 applies in the same manner to module M4. The energy supply ratios are e_4 and $(1-e_4)$.

Energy delivered by module E1: $e_4 \cdot E_{4e} = e_4 \cdot \varepsilon_4 \cdot m_{4e} = e_4 \cdot \varepsilon_4 \cdot \dfrac{m_{4aN}}{\mu_4}$ (15)

$$e_4 \cdot E_{4e} = e_4 \cdot \frac{\varepsilon_4}{\mu_4} \cdot (1-p) \cdot m_{5e} \tag{16}$$

Energy delivered by module E2: $(1-e_4) \cdot E_{4e} = (1-e_4) \cdot \varepsilon_4 \cdot m_{4e} = (1-e_4) \cdot \varepsilon_4 \cdot \dfrac{m_{4aN}}{\mu_4}$ (17)

$$(1-e_4) \cdot E_{4e} = (1-e_4) \cdot \frac{\varepsilon_4}{\mu_4} \cdot (1-p) \cdot m_{5e} \tag{18}$$

2.3.5 Module E1 — Supply of energy

Module E1 is representing a power generation plant using an energy carrier based on fossil fuels or regenerative energies like waterpower, wind or solar energy. The amount of natural resources R_{e1} needed to provide the required energy E_{1aN} is expressed as follows.

$$R_{e1}=\frac{1}{\eta_1}\cdot E_{1aN}=\frac{1}{\eta_1}\cdot(e_3\cdot E_{3e}+e_4\cdot E_{4e}+e_5\cdot E_{5e}+e_6\cdot E_{6e}) \tag{19}$$

$$R_{e1}=\frac{1}{\eta_1}\cdot\left[e_3\cdot\frac{\varepsilon_3}{\mu_3}\cdot p\cdot m_{5e}+e_4\cdot\frac{\varepsilon_4}{\mu_4}\cdot(1-p)\cdot m_{5e}+e_5\cdot\varepsilon_5\cdot m_{5e}+e_6\cdot\varepsilon_6\cdot\mu_5\cdot m_{5e}\right] \tag{20}$$

2.3.6 Module E2 — Supply of a different type of energy

Module E2 has the same function as module E1 with the premise to generate and provide the power E_{2aN} under different circumstances using the natural resource R_{e2}.

$$R_{e2}=\frac{1}{\eta_2}\cdot E_{2aN}=\frac{1}{\eta_2}\cdot[(1-e_3)\cdot E_{3e}+(1-e_4)\cdot E_{4e}+(1-e_5)\cdot E_{5e}+(1-e_6)\cdot E_{6e}] \tag{21}$$

$$R_{e2}=\frac{1}{\eta_2}\cdot\left[(1-e_3)\cdot\frac{\varepsilon_3}{\mu_3}\cdot p\cdot m_{5e}+(1-e_4)\cdot\frac{\varepsilon_4}{\mu_4}\cdot(1-p)\cdot m_{5e}+(1-e_5)\cdot\varepsilon_5\cdot m_{5e}\right.$$
$$\left.+(1-e_6)\cdot\varepsilon_6\cdot\mu_5\cdot m_{5e}\right] \tag{22}$$

2.4 Expressing the Total System

The total system is driven by the demand of material and energy of all consumers represented by module C5. For our study it will be helpful to distinguish between the demand of material and that of energy.

2.4.1 Required material resources

The total demand of raw materials needed to furnish all material that is required inside the system by the final consumer C5 is the sum of raw material input R_{m3} and R_{m4} by modules M3 and M4. The raw material consumption is a function of the final demand m_{5e} and can be expressed as follows.

$$R_m=R_{m3}+R_{m4}=\frac{m_{3aN}}{\mu_3}+\frac{m_{4aN}}{\mu_4}=\frac{1}{\mu_3}\cdot(p\cdot m_{5e})+\frac{1}{\mu_4}\cdot[(1-p)\cdot m_{5e}] \tag{23}$$

$$R_m=\left[\left(\frac{1}{\mu_3}-\frac{1}{\mu_4}\right)\cdot p+\frac{1}{\mu_4}\right]\cdot m_{5e} \tag{24}$$

2.4.2 Required energy resources

Primary energy carriers for power generation are needed by modules E1 and E2 only, because all other activities shall only use secondary energy carriers like electricity. The demand of these secondary energy is determined by the material manufacturers M3 and M4, the consumer group C5 and the collection/disposal activities D6 as defined already. Using these dependencies one gets the following expression to determine the consumption of primary energy resources.

$$R_E = R_{e1} + R_{e2} \tag{25}$$

$$R_E = \left\{ \begin{array}{l} \left[\frac{e_3}{\eta_1} + \frac{(1-e_3)}{\eta_2}\right] \cdot \left(\frac{\varepsilon_3}{\mu_3} \cdot p\right) + \left[\frac{e_4}{\eta_1} + \frac{(1-e_4)}{\eta_2}\right] \cdot \left[\frac{\varepsilon_4}{\mu_4} \cdot (1-p)\right] \\ + \left[\frac{e_5}{\eta_1} + \frac{(1-e_5)}{\eta_2}\right] \cdot \varepsilon_5 + \left[\frac{e_6}{\eta_1} + \frac{(1-e_6)}{\eta_2}\right] \cdot (\varepsilon_6 \cdot \mu_5) \end{array} \right\} \cdot m_{5e} \tag{26}$$

3. System Characteristics

We will now use the basic Eq.s (24) and (26), which describe the consumption of natural resources due to the decisions of stakeholders, which are involved in the total system to evaluate the impact of decision-making on natural resources and to look for constraints.

3.1 Consumption of material resources

The consumption of resources that are needed for manufacturing of material products can be expressed by the relatively simple relationship shown by Eq. (24).

$$R_m = \left[\left(\frac{1}{\mu_3} - \frac{1}{\mu_4}\right) \cdot p + \frac{1}{\mu_4}\right] \cdot m_{5e} \tag{27}$$

The consumption of natural resources R_m is directly proportional to the demand m_{5e} of the consumers. The consumption of resources is further influenced by the selection ratio p concerning the supplier of material products. This selection is linked to the respective productivity μ_5 and μ_4.

3.1.1 Boundary behaviour

Condition $p = 1$—Under the condition that only supplier M3 gets a look-in, Eq. (27) becomes very simple.

$$R_{m.p\_1} = \left[\left(\frac{1}{\mu_3} - \frac{1}{\mu_4}\right) \cdot 1 + \frac{1}{\mu_4}\right] \cdot m_{5e} = \frac{1}{\mu_3} \cdot m_{5e} \tag{28}$$

It is obvious that in this case the consumption of natural resources is determined by the productivity (resource efficiency) of manufacturer M3 only.

Condition $p=0$ — If manufacturer M4 is chosen as single supplier of material products, Eq. (27) reduces to the expression

$$R_{m.p\_0}=\left[\left(\frac{1}{\mu_3}-\frac{1}{\mu_4}\right)\cdot 0+\frac{1}{\mu_4}\right]\cdot m_{5e}=\frac{1}{\mu_4}\cdot m_{5e} \tag{29}$$

This expression is similar to the previous case, instead the resource efficiency μ_4 of manufacturer M4 is now the crucial factor.

How to select the proper material supply source — An environmental conscious consumer would like to chose a product that causes lowest environmental load with respect to consumption of raw materials. The two choices that can be made in our case are determined by the product selection factor p, which fulfils the boundary conditions $0 \leq p \leq 1$. The difference of material consumption Δ_{Rm} is then defined as

$$\Delta_{Rm}=R_{m.p\_1}-R_{m.p\_0}=\frac{1}{\mu_3}\cdot m_{5e}-\frac{1}{\mu_4}\cdot m_{5e}=\frac{(\mu_4-\mu_3)}{\mu_3\cdot\mu_4}\cdot m_{5e} \tag{30}$$

In principle, the higher the level of consumption m_{5e} is the more raw material can be saved (Δ_{Rm}). If the difference is positive, then $R_{m.p\_1} > R_{m.p\_0}$, which means $p=0$ leads to lower the consumption of raw materials, and supply by manufacturer M4 is the preferable choice. In case of $R_{m.p\_1} < R_{m.p\_0}$ vice versa, supply by manufacturer M3 leads to lower

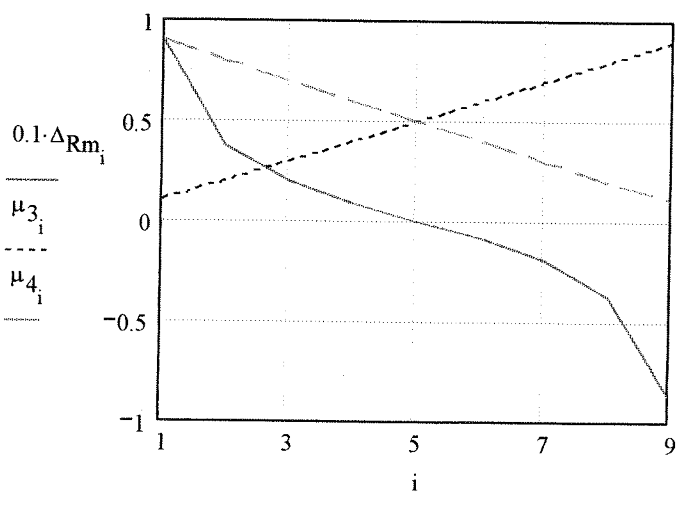


Fig. 2. Change of material resource consumption depending on increasing/decreasing mass conversion factors μ_3 and μ_4. ($0.1 \leq \mu_5 \leq 0.9$ while $0.9 \leq \mu_4 \leq 0.1$; Rem.: i is used as index for plotting purposes)

consumption of material resources. Figure 2 shows the dependency of material resource consumption from technologies applied by manufacturers M3 and M4, which are expressed by the mass conversion factors μ_3 and μ_4. An increasing value of μ_3 has been associated with a decreasing value of μ_4. (Furthermore, the figures of change concerning resource consumption have been divided by ten to better fit the chart's scale.)

3.1.2 3D plot of material resource consumption characteristics

Eq. (24) can further be simplified by defining the so-called specific material resource consumption ratio $r_m = R_m / m_{5e}$.

$$r_m = \left(\frac{1}{\mu_3} - \frac{1}{\mu_4}\right) \cdot p + \frac{1}{\mu_4} \tag{31}$$

We will now use this equation to study the influence of the three independent variables μ_3, μ_4 and p on the specific resource consumption r_m. All three variables represented by *var* fulfil the condition $0 \leq var \leq 1$. To check the influence of μ_3, μ_4 and p we need a repetitive pattern that allows to screen all possible combinations of these variables, which are mutually independent. To limit the number of data we will change the value of every variable in steps of 0.2, which gives a staircase function with the individual step levels 0.2, 0.4, 0.6, 0.8 and 1. Based on this concept the two staircase functions needed are generated by applying an algorithm, which is implemented as a user defined function using the Mathcad 2001 Professional[3) software package.

$$\text{Variable } \mu_3\text{:} \quad \mu_{3_i} := \frac{1}{5} \cdot \frac{(i-1) - \mathrm{mod}\,[(i-1),\, 25]}{25} + \frac{1}{5} \quad \text{for } 1 \leq i \leq 5^3 \tag{32}$$

$$\text{Variable } \mu_4\text{:} \quad \mu_{4_i} := \frac{1}{5} \cdot \mathrm{mod}\left[\frac{(i-1) - \mathrm{mod}\,[(i-1),\, 5]}{5},\, 5\right] + \frac{1}{5} \quad \text{for } 1 \leq i \leq 5^3 \tag{33}$$

Fig. 3 shows the staircase functions generated by these algorithms.

With $p = 1$ kept constant Eq. (31) is now used to create a surface map of the resource consumption behaviour of the system as shown by Fig. 4 (A). When p is decreased to $p = 0.5$ the surface map changes as Fig. 4 (B) shows and establishes an additional step pattern in orthogonal direction. Finally, when p becomes $p = 0$ the pattern simplifies as shown by Fig. 4 (C) to represent the consumption behaviour for the other extreme of p.

In case of Fig. 4 (A) the material resource consumption is only dependent from the material resource efficiency μ_3 as Eq. (25) shows. This creates a single staircase in direction of the μ_3-axis, which steps have different height being reciprocally proportional to the value

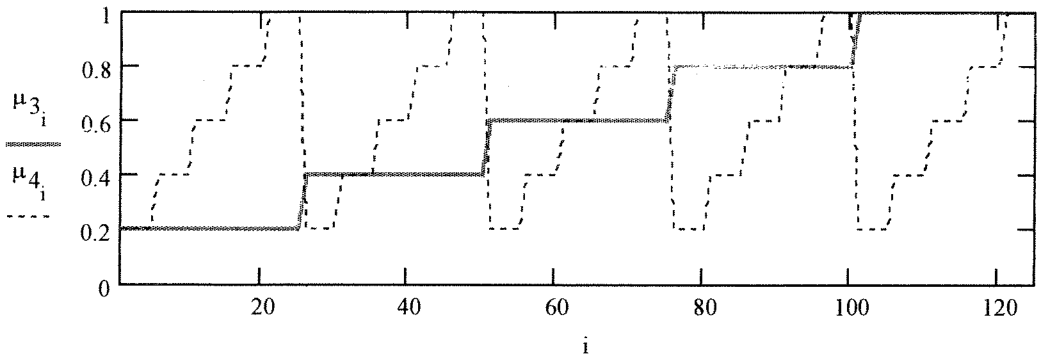
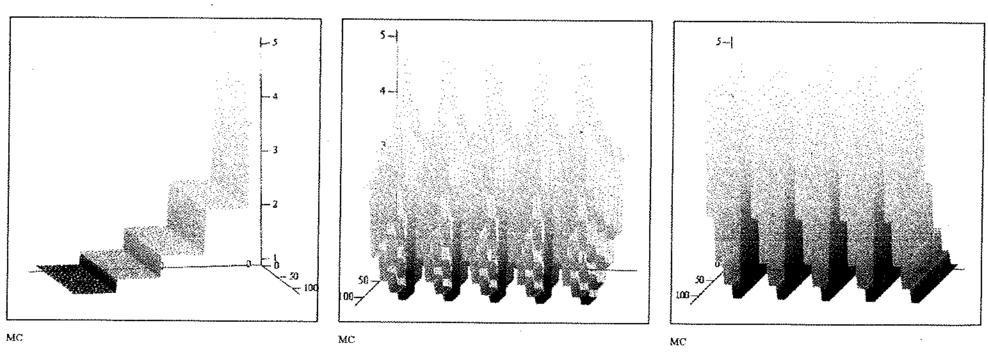


Fig. 3. Staircase function of the variables μ_3, μ_4 used to investigate the material resource consumption behaviour of the system.



A (p=1) B (p=0.5) C (p=0)

Fig. 4. Staircase pattern of the material resource consumption function for three cases A ($p=1$), B ($p=0.5$) and C ($p=0$).

of μ_3. When $p=0.5$ the amount of products purchased from both manufacturers is equal and the shape of the staircase chages into a double sided one as Fig. 4 (B) shows. Finally, when $p=0$ this double-staircase converts into a single staircase according to Fig. 4 (C) with a step shape that is reciprocal to the shape of the μ_4- sweep step curve shown in Fig. 3.

3.2 Consumption of energy resources

The analysis of how to make the appropriate choice of a material product supplier has lead to simple expressions, which could be interpreted easily with respect to consumption of material resources. We will now extend the analysis to investigate the impact of decision-making with respect to the consumption of energy resources.

The total energy consumption of the system is represented by Eq. (26). Since the system has the function to provide the consumer with material product m_{5e}, the system's energy requirement R_E can be related to this figure, which gives the expression

$$\frac{R_E}{m_{5e}}=r_E \tag{34}$$

The specific energy demand r_E is then being calculated as shown.

$$r_E=\left[\frac{e_3}{\eta_1}+\frac{(1-e_3)}{\eta_2}\right]\cdot\left(\frac{\varepsilon_3}{\mu_3}\cdot p\right)+\left[\frac{e_4}{\eta_1}+\frac{(1-e_4)}{\eta_2}\right]\cdot\left[\frac{\varepsilon_4}{\mu_4}\cdot(1-p)\right]$$
$$+\left[\frac{e_5}{\eta_1}+\frac{(1-e_5)}{\eta_2}\right]\cdot\varepsilon_5+\left[\frac{e_6}{\eta_1}+\frac{(1-e_6)}{\eta_2}\right]\cdot(\varepsilon_6\cdot\mu_5) \tag{35}$$

Eq. (35) consists of four terms. All terms contain the energy conversion efficiencies η_1 and η_2 of the power generators E1 and E2. The term $r_{E.3}$ in Eq. (35a) represents the specific energy resource consumption caused by manufacturer M3. The manufacturer can influence this consumption by selecting the appropriate power generator (η_1, η_2) as well as improving the energy performance (ε_3) and/or yield (μ_3) of his own processes. However, even this manufacturer runs his operations based on environmental conscious management principles, the consumption of energy resources is fully dependent from the choice (p) of the consumer. If the consumer is not aware of the manufacturer's efforts these are in vain.

$$r_{E.3}=\left[\frac{e_3}{\eta_1}+\frac{(1-e_3)}{\eta_2}\right]\cdot\left(\frac{\varepsilon_3}{\mu_3}\cdot p\right) \tag{35a}$$

What has been said when interpreting term $r_{E.3}$ can also be applied in a similar manner to the second term $r_{E.4}$ of Eq. (35) with respect to manufacturer M4.

$$r_{E.4}=\left[\frac{e_4}{\eta_1}+\frac{(1-e_4)}{\eta_2}\right]\cdot\left[\frac{\varepsilon_4}{\mu_4}\cdot(1-p)\right] \tag{35b}$$

The third term $r_{E.5}$ represents the impact of the consumers. Once they know the performance of the power generators the consumers can principally make the right choice (e_5) concerning the "right" power generator. However, the consumers have an additional responsibility. They chose the way they consume a material product, which includes means of transport, the way of preparing a good etc., which is expressed by the specific energy consumption ε_5 at the use stage shown by Eq. (35c).

$$r_{E.5}=\left[\frac{e_5}{\eta_1}+\frac{(1-e_5)}{\eta_2}\right]\cdot\varepsilon_5 \tag{35c}$$

Eq. (35d) shows the last term, which is the disposal operation.

$$r_{E.6}=\left[\frac{e_6}{\eta_1}+\frac{(1-e_6)}{\eta_2}\right]\cdot(\varepsilon_6\cdot\mu_5) \tag{35d}$$

This equation and the previous one [Eq. (35c)] have the same structure. Increasing preference for the respective power generator lets become his efforts with regard to consumption of energy resources more and more dominating. However, independent from the power generators performance collection and disposal operations have their own energy performance expressed by ε_6. The improvement of this figure is part of the responsibility of the enterprises that run these operations.

3.2.1 Influence of the consumer by choosing a specific material product supplier

Before we look at the influence caused by the variation of p, Eq. (35) will be simplified by substituting constant elements we don't intend to change.

$$\text{const}=\left[\frac{e_5}{\eta_1}+\frac{(1-e_5)}{\eta_2}\right]\cdot\varepsilon_5+\left[\frac{e_6}{\eta_1}+\frac{(1-e_6)}{\eta_2}\right]\cdot(\varepsilon_6\cdot\mu_5) \tag{36}$$

gives

$$r_E=\left[\frac{e_3}{\eta_1}+\frac{(1-e_3)}{\eta_2}\right]\cdot\left(\frac{\varepsilon_3}{\mu_3}\cdot p\right)+\left[\frac{e_4}{\eta_1}+\frac{(1-e_4)}{\eta_2}\right]\cdot\left[\frac{\varepsilon_4}{\mu_4}\cdot(1-p)\right]+\text{const} \tag{37}$$

With $p=1$ and $p=0$ respectively we get

$$p=1\colon r_{E.p\_1}=\left[\frac{e_3}{\eta_1}+\frac{(1-e_3)}{\eta_2}\right]\cdot\frac{\varepsilon_3}{\mu_3}+\text{const} \tag{38}$$

$$p=0\colon r_{E.p\_0}=\left[\frac{e_4}{\eta_1}+\frac{(1-e_4)}{\eta_2}\right]\cdot\frac{\varepsilon_4}{\mu_4}+\text{const} \tag{39}$$

The specific energy consumption is determined by a constant amount according to Eqs. (38) and (39). This amount is influenced by the selection p of the manufacturer, and in consequence by the technology ε/μ the manufacturer applies as well as the technology η of the power generator, which has been chosen by that manufacturer.

These results are used to calculate the difference of the specific energy consumption r_E with respect to the boundary limits of p.

$$\Delta r_{E.p\_10}=r_{E.p\_1}-r_{E.p\_0} \tag{40}$$

$$\Delta r_{E.p\_10}=\left[\frac{e_3}{\eta_1}+\frac{(1-e_3)}{\eta_2}\right]\cdot\frac{\varepsilon_3}{\mu_3}-\left[\frac{e_4}{\eta_1}+\frac{(1-e_4)}{\eta_2}\right]\cdot\frac{\varepsilon_4}{\mu_4} \tag{41}$$

If the difference $\Delta r_{E.p\_10}$ is positive, then $r_{E.p\_1} > r_{E.p\_0}$ and the purchase of products from manufacturer M4 ($p=0$) leads to lower consumption of energy carrying resources. In case $r_{E.p\_1} > r_{E.p\_0}$ the opposite is true and products made by manufacturer M3 should be preferred.

The difference $\Delta r_{E.p\_10}$ is influenced by several factors. At first, there are the production technologies of both manufacturers M3 and M4 expressed by the figures ε_3, ε_4, μ_3 and μ_4 as well as their ratios ε_3/μ_3 and ε_4/μ_4, respectively. In addition, the difference $\Delta r_{E.p\_10}$ depends on the choice these manufacturers make with respect to the power generators E1 and E2, which is expressed by the value of the figures e_3 [E1], $(1-e_3)$ [E2], e_4 [E1] and $(1-e_4)$ [E2]. Both power generators have their own technology, which is expressed by the specific energy conversion yield η_1 and η_2 for the processes they apply.

3.2.2 Additional influence of the manufacturer by choosing a specific power generator

We will now study the influence on the consumption of energy carrying resources caused by a manufacturer who selects a specific power generator. — With $e_3 = 1$ and $e_3 = 0$ respectively we get

$$e_3=1:\ \Delta r_{E.p\_10.e3\_1}=\frac{1}{\eta_1}\cdot\frac{\varepsilon_3}{\mu_3}-\left[\frac{e_4}{\eta_1}+\frac{(1-e_4)}{\eta_2}\right]\cdot\frac{\varepsilon_4}{\mu_4} \tag{42}$$

$$e_3=0:\ \Delta r_{E.p\_10.e3\_0}=\frac{1}{\eta_2}\cdot\frac{\varepsilon_3}{\mu_3}-\left[\frac{e_4}{\eta_1}+\frac{(1-e_4)}{\eta_2}\right]\cdot\frac{\varepsilon_4}{\mu_4} \tag{43}$$

and the difference becomes

$$\Delta r_{E.p\_10.e3\_10}=\Delta r_{E.p\_10.e3\_1}-\Delta r_{E.p\_10.e3\_0} \tag{44}$$

$$\Delta r_{E.p\_10.e3\_10}=\left(\frac{1}{\eta_1}-\frac{1}{\eta_2}\right)\cdot\frac{\varepsilon_4}{\mu_4} \tag{45}$$

If we apply the same procedure to e_4 we get

$$e_4=1:\ \Delta r_{E.p\_10.e4\_1}=\left[\frac{e_3}{\eta_1}+\frac{(1-e_3)}{\eta_2}\right]\cdot\frac{\varepsilon_3}{\mu_3}-\frac{1}{\eta_1}\cdot\frac{\varepsilon_4}{\mu_4} \tag{46}$$

$$e_4=0:\ \Delta r_{E.p\_10.e4\_0}=\left[\frac{e_3}{\eta_1}+\frac{(1-e_3)}{\eta_2}\right]\cdot\frac{\varepsilon_3}{\mu_3}-\frac{1}{\eta_2}\cdot\frac{\varepsilon_4}{\mu_4} \tag{47}$$

and the difference becomes

$$\Delta r_{E.p\_10.e4\_10} = \Delta r_{E.p\_10.e4\_1} - \Delta r_{E.p\_10.e4\_0} \tag{48}$$

$$\Delta r_{E.p\_10.e4\_10} = \left(\frac{1}{\eta_2} - \frac{1}{\eta_1}\right) \cdot \frac{\varepsilon_4}{\mu_4} \tag{49}$$

As can be seen at a glance, Eq. (45) and (49) possess the same structure, but the differences $\Delta r_{E.p\_10.e3\_10}$ and $\Delta r_{E.p\_10.e4\_10}$ get opposite influence by the technologies (η_1 and η_2) used by the power generators E1 and E2.

3.2.3 Changing the selection sequence

The energy analysis performed so far has started with the selection of the material product supplier M3 or M4 followed by the selection of the power generator E1 or E2 from the view-point of both material manufacturers. We will now take a different approach by starting with the selection of the power generator by the manufacturer and then analysing the possibilities to decide upon the selection of the appropriate material supplier.

The specific energy consumption r_E, which is related to the amount of material product m_{e5} consumed by the customer is expressed by Eq. (35).

$$r_E = \left[\frac{e_3}{\eta_1} + \frac{(1-e_3)}{\eta_2}\right] \cdot \left(\frac{\varepsilon_3}{\mu_3} \cdot p\right) + \left[\frac{e_4}{\eta_1} + \frac{(1-e_4)}{\eta_2}\right] \cdot \left[\frac{\varepsilon_4}{\mu_4} \cdot (1-p)\right]$$
$$+ \left[\frac{e_5}{\eta_1} + \frac{(1-e_5)}{\eta_2}\right] \cdot \varepsilon_5 + \left[\frac{e_6}{\eta_1} + \frac{(1-e_4)}{\eta_2}\right] \cdot (\varepsilon_6 \cdot \mu_5) \tag{35}$$

When the material product manufacturer M3 prefers to choose power generator E1 as energy supplier the supply ratio e_3 is 1. In this case we get

$$r_{E.e3\_1} = \frac{1}{\eta_1} \cdot \frac{\varepsilon_3}{\mu_3} \cdot p + \left[\frac{e_4}{\eta_1} + \frac{(1-e_4)}{\eta_2}\right] \cdot \frac{\varepsilon_4}{\mu_4} \cdot (1-p)$$
$$+ \left[\frac{e_5}{\eta_1} + \frac{(1-e_5)}{\eta_2}\right] \cdot \varepsilon_5 + \left[\frac{e_6}{\eta_1} + \frac{(1-e_6)}{\eta_2}\right] \cdot \varepsilon_6 \cdot \mu_5 \tag{50}$$

If $e_3 = 0$, the similar expression is

$$r_{E.e3\_0} = \frac{1}{\eta_2} \cdot \frac{\varepsilon_3}{\mu_3} \cdot p + \left[\frac{e_4}{\eta_1} + \frac{(1-e_4)}{\eta_2}\right] \cdot \frac{\varepsilon_4}{\mu_4} \cdot (1-p)$$
$$+ \left[\frac{e_5}{\eta_1} + \frac{(1-e_5)}{\eta_2}\right] \cdot \varepsilon_5 + \left[\frac{e_6}{\eta_1} + \frac{(1-e_6)}{\eta_2}\right] \cdot \varepsilon_6 \cdot \mu_5 \tag{51}$$

The difference of both equations, which represent boundary situations is defined as

$$\Delta r_{E.e3\_10} = r_{E.e3\_1} - r_{E.e3\_0} \tag{52}$$

Substitution and rearrangement leads to the simple expression

$$\Delta r_{E.e3\_10} = \left(\frac{1}{\eta_1} - \frac{1}{\eta_1}\right) \cdot \frac{\varepsilon_3}{\mu_3} \cdot p \tag{53}$$

If the difference $\Delta r_{E.e3\_10}$ is negative, which means $r_{E.e3\_1} < r_{E.e3\_0}$ then the supply of energy by power generator E1 should be preferred. This is the case when $1/\eta_1 < 1/\eta_2$ and therefore $\eta_1 > \eta_2$, that is to say power generator E1 has a better energy conversion efficiency than E2. If under this premise factor p is increased, the difference $\Delta r_{E.e3\_10}$ becomes larger, which means material supply from manufacturer M3 leads to lower environmental burdens. The opposite is true when the difference becomes positive.

If we apply the same approach to e_4 we get the result

$$\Delta r_{E.e4\_10} = \left(\frac{1}{\eta_1} - \frac{1}{\eta_1}\right) \cdot \frac{\varepsilon_4}{\mu_4} \cdot (1-p) \tag{54}$$

With respect to interpretation of this equation the same holds true what is said in the previous case of e_3. However, since the factor p is involved as difference $(1-p)$, selection of increasing supply from manufacturer M4 leads to lower environmental burden.

We will now use both equations that represent the influence on the resource consumption change $\Delta r_{E.e3\_10}$ and $\Delta r_{E.e4\_10}$ depending on the selection of manufacturer M3 or M4 to study the total impact. Since the change of p and $(1-p)$ moves into the opposite direction, we will use the sum $\Delta r_{E.e3\_10.e4\_10}$ of differences depending on p and $(1-p)$ according to Eq. (53) and (54), which we will define as

$$\Delta r_{E.e3\_10.e4\_10} = \Delta r_{E.e3\_10} + \Delta r_{E.e4\_10} \tag{55}$$

Substitution gives

$$\Delta r_{E.e3\_10.e4\_10} = \left(\frac{1}{\eta_1} - \frac{1}{\eta_2}\right) \cdot \frac{\varepsilon_3}{\mu_3} \cdot p + \left(\frac{1}{\eta_1} - \frac{1}{\eta_2}\right) \cdot \frac{\varepsilon_4}{\mu_4} \cdot (1-p) \tag{56}$$

and rearrangement of corresponding terms leads to the expression

$$\Delta r_{E.e3\_10.e4\_10} = \left(\frac{1}{\eta_1} - \frac{1}{\eta_2}\right) \cdot \left[\left(\frac{\varepsilon_3}{\mu_3} - \frac{\varepsilon_4}{\mu_4}\right) \cdot p + \frac{\varepsilon_4}{\mu_4}\right] \tag{57}$$

This equation gives valuable information when the following conditions are fulfilled: Both manufacturers have made up their mind and chosen that power generator they think is serving them best. Based on their analysis they chose either E1 or E2. This fact is expressed by the differences $\Delta r_{E.e3\_10}$ and $\Delta r_{E.e4\_10}$ respectively, which might be positive or negative. When the consumer starts to select manufacturer M3 or M4 as his supplier he is confronted with the result of the choice the manufacturers have already made concerning their power supply. That is to say, the consumer has to tackle the task to find the minimum of the sum of differences, which is $\Delta r_{E.e3\_10.e4\_10}$. One must remember, that $\Delta r_{E.e3\_10.e4\_10}$ is but a local minimum and per se not the minimum of the total system, however it can coincide.

3.2.4 3D plot of energy resource consumption characteristics

The specific energy resource consumption of the system is expressed by Eq. (35). The system's fundamental behaviour is determined by the energy efficiencies η_1, η_2 of the power generators E1 and E2. Depending on the selection e_3, e_4, e_5 and e_6 of energy supply sources as well as the product manufacturer (p) the energy consumption can be minimised. Of course, there are constraints of applied technologies that define boundary conditions.

$$r_E = \left[\frac{e_3}{\eta_1} + \frac{(1-e_3)}{\eta_2}\right] \cdot \left(\frac{\varepsilon_3}{\mu_3} \cdot p\right) + \left[\frac{e_4}{\eta_1} + \frac{(1-e_4)}{\eta_2}\right] \cdot \left[\frac{\varepsilon_4}{\mu_4} \cdot (1-p)\right]$$
$$+ \left[\frac{e_5}{\eta_1} + \frac{(1-e_5)}{\eta_2}\right] \cdot \varepsilon_5 + \left[\frac{e_6}{\eta_1} + \frac{(1-e_6)}{\eta_2}\right] \cdot (\varepsilon_6 \cdot \mu_5) \tag{35}$$

Of special interest is the behaviour of the system when manufacturers make their choice concerning their power supply and the consumers decide on the manufacturer. We will look at the possible constellations by limiting the number of variables. To simplify Eq. (35) we have introduced the constant *const* as shown in Eq. (36).

$$\text{const} = \left[\frac{e_5}{\eta_1} + \frac{(1-e_5)}{\eta_2}\right] \cdot \varepsilon_5 + \left[\frac{e_6}{\eta_1} + \frac{(1-e_6)}{\eta_2}\right] \cdot (\varepsilon_6 \cdot \mu_5) \tag{36}$$

This has lead us to

$$r_E = \left[\frac{e_3}{\eta_1} + \frac{(1-e_3)}{\eta_2}\right] \cdot \left(\frac{\varepsilon_3}{\mu_3} \cdot p\right) + \left[\frac{e_4}{\eta_1} + \frac{(1-e_4)}{\eta_2}\right] \cdot \left[\frac{\varepsilon_4}{\mu_4} \cdot (1-p)\right] + \text{const} \tag{37}$$

In addition, we define now $\eta_1 = 0.75$, $\eta_2 = 0.25$, $\varepsilon_3 = \varepsilon_4 = 100$, $\mu_3 = \mu_4$ 0.5 and *const* = 100. The large difference in energy efficiency of the power generators has been chosen to better see the influence of the remaining variables e_3, e_4 and p. For the variables e_3, e_4 we generate two staircase-like sweeping patterns based on the following algorithms.

$$e_{3_i} := \frac{1}{5} \cdot \frac{(i-1) - \mathrm{mod}\,[(i-1), 36]}{36} \quad \text{for } 1 \leq i \leq 6^3 \tag{58}$$

$$e_{4_j} := \frac{1}{5} \cdot \mathrm{mod}\left[\frac{(j - \mathrm{mod}\,(j, 6))}{6}, 6\right] \quad \text{for } 1 \leq j \leq 6^3 \tag{59}$$

Fig. 5 shows how these patterns look like.

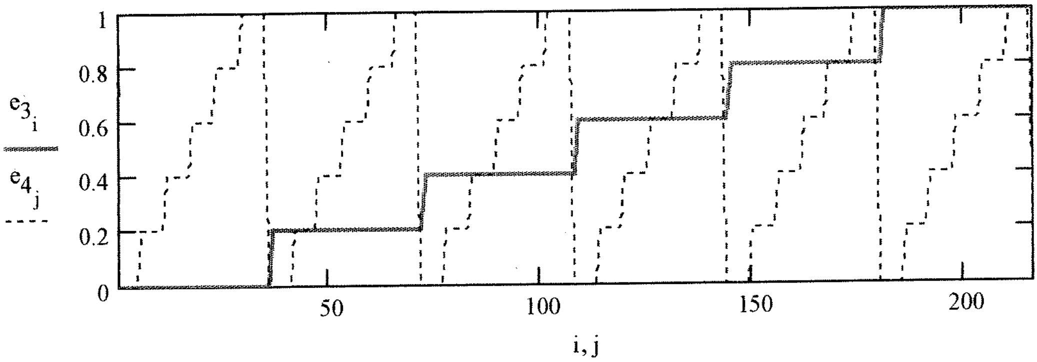
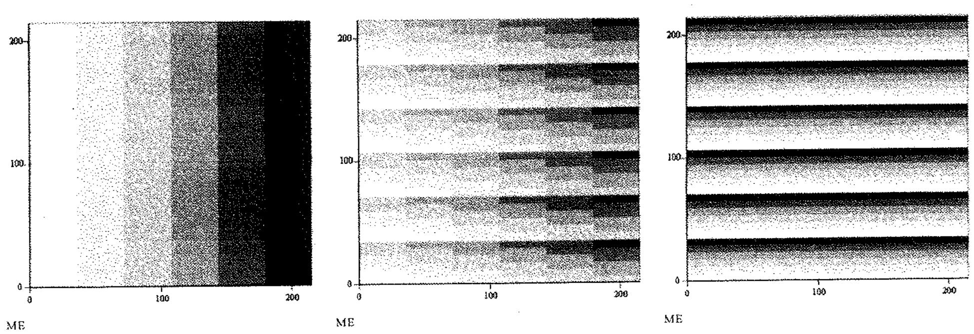


Fig. 5. Staircase function of the variables e_3, e_4 used to investigate the energy resource consumption behaviour of the system.

Using these sweeping patterns, we now investigate the system's behaviour depending on different values of p.



A ($p=1$) B ($p=0.5$) C ($p=0$)

Fig. 6. Area map of the energy resource consumption function for three cases A ($p=1$), B ($p=0.5$) and C ($p=0$).

The light areas (bands) indicate higher energy consumption whereas the dark ones show combinations of variables that lead to lower use of energy resources. In case of Fig. 6 (A) the second term of Eq. (37) disappers, because $p=1$. The shadowed areas change in direction of the x-axis according to the sweeping pattern of variable e_3 shown in Fig. (5). When $p=0$ the pattern switches into y-axis direction following the sweeping pattern of variable e_4. In case of $p=0.5$ we can identify band-like areas that show combinations of e_3 with e_4, which can lead to a similar reduction of energy consumption on a medium level.

This finding is important, because it indicates the necessity to check the activities of manufacturers in a semi-continuous interval regarding the status of how they have selected their power generator. Otherwise the consumer would only be able to base his decision on outdated information like annual reports etc. that have become obsolete, already. This finding therefore emphasises the necessity to establish a new type of stakeholder communication to be initiated by manufacturers as well as consumer groups.

4. Conclusion

A simple linear system consisting of one consumer, two power generators, two manufacturers and one disposal operation has been described by using symbolic notation. The system characteristics with regard to consumption of material and energy resources have been studied. Constraints and dependencies have been revealed that are helpful for decision-making by different stakeholders in the system. By using a non-numeric concept of system analysis, it is possible to better understand the characteristics of the system's behaviour, which often is disguised behind a wall of figures when performing LCA studies in the traditional way.

Finally, the necessity has become obvious to establish a new type of communication among stakeholders as long as it is seriously intended to put life into the concept of sustainable development.

References

1) K.-H. Feuerherd: Dual-Choice Production Systems (1) - Describing Resource Consumption Characteristics of Linear Systems with Symbolic Notation, Seminar Materials Series No. 2E, Kobe Yamate University, 2003.
2) K.-H. Feuerherd: Dual-Choice Production Systems (2) - Analysing Resource Consumption Characteristics of Linear Systems by 3D Plotting Techniques, Seminar Materials Series No. 4E, Kobe Yamate University, 2003.
3) Mathcad 2001 Professional, MathSoft International, Bagshot Surrey, UK, http://www.mathsoft.co.uk/jp