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A production-theory-based framework for analysing recycling systems in the e-waste sector

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Abstract

Modern approaches in the production theory of business and management economics propose that objects (e.g. materials) be divided into good, bad or neutral. In transformation processes such as occur in production or recycling this makes it possible to distinguish stringently between the economic revenue of a process and the economic and ecological expenditures for it. This approach can be transferred to entire systems of processes in order to determine the system revenue and the system expenditure. Material flow nets or graphs are used for this purpose. In complex material flow systems it becomes possible to calculate not only the costs, but also the direct and indirect environmental impacts of an individual process or a system revenue (for example a product or the elimination of waste) consistently. The approach permits a stringent analysis as well as different analysis perspectives of a material flow system. It is particularly suitable for closed-loop economic systems in which material backflows occur. With the aid of an example developed jointly with Hewlett Packard Europe, the paper outlines how this approach can be employed in the field of e-waste management.

Keywords: Material flow management; Production theory; Material flow nets; E-waste management; LCA; MFA

1. Introduction

A most remarkable development is currently taking place in the segment of electronic waste. The electronics branch has long been a prime example of the use-and-throw-away

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society. Technical innovations and customer demand lead to ever shorter product lives. Mobile telephones now have a service life of just under two years. It is generally not worth repairing defective equipment. Consequently the typical life cycle of an electronic appliance is a linear progress from production, through use, to waste disposal.

The EU's WEEE Directive (*w*aste of *e*lectronic and *e*lectrical *e*quipment) obligates manufacturers of electronic and electrical equipment to take back old equipment from customers free of charge and to dispose of these wastes in an environmentally sound manner. The Directive specifies recycling quotas according to which the old appliances or their materials must be reused and channelled back into the economic cycle. In this way linear material flow management with a throw-away mentality becomes a closed-loop material flow management with a high recycling target – under duress on the basis of government stipulations.

The closed-loop material flow management is one of the meta-strategies of sustainable development. Economical handling of the natural resources of this world can be achieved not merely by renunciation, but also by reuse and recycling of the products. Despite this a question still to be answered concerns the price at which closed-loop material flow management is possible. Observance of the WEEE stipulations involves costs, which the manufacturing firms naturally want to minimise. Furthermore, for fundamental physical reasons a closed-loop material flow management system can never be completely closed and function as a self-contained entity. According to the rules of thermodynamics it requires at least energy in order to structure order and reduce the entropy. If this energy is not generated in an environmentally sound manner, e.g. solar energy, there is not necessarily an ecological benefit in the closed-loop material flow management system which then depends on the concrete structuring of the closed-loop system.

This makes it clear that in future methodology approaches are necessary that allow a holistic analysis of closed-loop material flow management systems under both economic and ecological aspects. Looking at the example of electronic waste, even social components have to be added. In Germany electrical equipment has so far chiefly been dismantled and recycled by workshops providing employment for handicapped or challenged persons. These workshops were granted subsidies by society. However, the strict stipulations of the WEEE Directive force manufacturers to build up efficient and cost-optimised reverse logistics and recycling systems. Facilities on a large technical scale with high-quantity throughputs will be given preference over manual dismantling by decentrally distributed social facilities.

The problem of the quantitative analysis methods customary so far is that they can hardly be applied for closed-loop material flow management systems. Classic management theory focuses on products, not on wastes, that for a long time did not cost anything. However, if these are taken into account despite this, then as costs for the establishments or as macro-economic damage, but not as possible secondary raw materials in a closed-loop material flow management system. On the other hand environmentally oriented analyses such as, for example, the Life Cycle Assessment of products and services only consider the impacts on the environment (ISO, 14.040). Admittedly recycling systems are analysed on a large scale here too (UBA, 1999), but so far the economic aspect and hence the costs have not been integrated.

In cooperation with Hewlett-Packard Europe possible waste disposal scenarios for electronic scrap in Europe were analysed using a new method in which the material and energy flows were tracked in a complex system and can be analysed both ecologically and economically. Methodology approaches that have been developed in the German-speaking area in recent years and are based on the one hand on the production theory of business and management economics (Dyckhoff, 1994) and on the other hand on the concept of material flow nets from environmental informatics (Möller, 1994, 2000) were applied. The basic features of these approaches are outlined here and their significance for closed-loop material flow management systems such as e.g. the electronic waste segment are pointed up. However, these methods can naturally also be applied to other sectors. They are now being used by the packaging waste collection organisation Duales System Deutschland to analyse material flows of packaging wastes labelled with the system's "Green Point" (DSD, 2003, 41f.), as well as for analysing and optimising operating production centres (LfU, 2004).

2. Production theory as the starting point

As Dyckhoff (2003, 710) ascertains, production theory focuses on the transformation of objects. "Objects" are here understood to mean products and goods. In a wider sense they are also considered to include undesirable objects such as emissions or waste, that Dyckhoff describes as "bads" and that Koopmans (1951, P. 38f.) already mentions as "undesired commodities". Transformations can be production processes, but the converse is also true in operations in which the purpose is not the output of goods, but instead elimination of bads – namely waste disposal or recycling processes. Production theory in the tradition of Gutenberg (1951) is therefore particularly suitable for analysing systems in which evaluation of materials and transformation processes depends on their economic and ecological context. It thus differs from purely scientific approaches to mapping material flow systems, as for instance in Bader and Baccini (1996), which remain bonded to the real flow system – without an economic analysis. In recent years environmental protection also represented the most important sector for further methodological development of the production theory (Dinkelbach and Rosenberg, 2003, Steven, 1998).

2.1. Good and bad

If production theory is to be applied to a closed-loop material flow management system, it cannot solely address the actual process of producing goods. In order to close the loop, waste and production residues must also be taken into account and recycling or waste elimination processes must be included in the analysis. Production, consumption and reduction form a cycle, as it were, in closed-loop material flow management (see Fig. 1). 'Reduction' is understood to mean the conversion of old products and wastes to secondary raw materials. Production, consumption and reduction are the transformations: raw materials become products, products become wastes, wastes become raw materials again. The technology used in the transformation processes not only determines whether these are possible at all (e.g. the recycling of certain materials). It also decides what

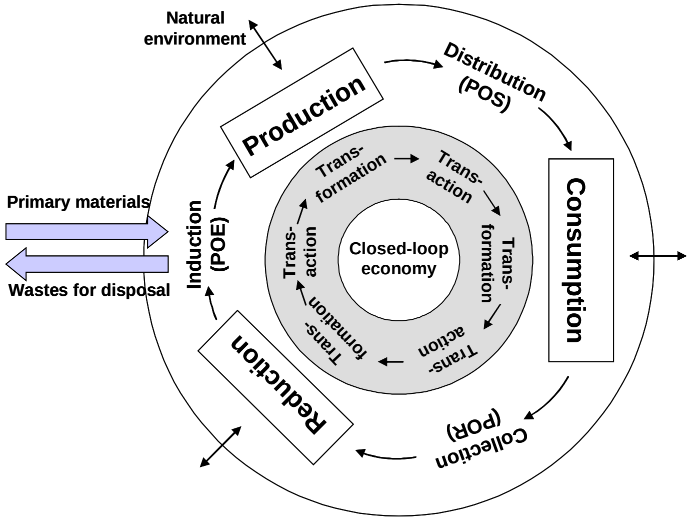

Fig. 1. A simple model for closed-loop material flow management (after Dyckhoff et al., 2004, p. 4).

environmental impacts occur as a result and how expensive an individual process and hence the entire closed-loop management becomes.

However, the transformation processes are only one important point of approach. For them to function in a real economic system the transactions are equally significant. Dyckhoff (2000) therefore placed the transactions of distribution (point of sale), collection (point of return) and induction (point of entry) between the processes of production, consumption and reduction (see Fig. 1), but these will not be discussed further in this paper.

If we wish to evaluate the systems not only economically but also ecologically, those materials that have not yet played any role in the economic operation of a company because they did not cost anything and were mainly available without restriction must be taken into account. Looking at a transformation process in quite general terms, materials enter the process as an input, while other materials leave it as an output. Under economic aspects only the most important materials were taken into account in the past, in other words those that caused costs or earned revenues, i.e. had a market price.

On the input side we traditionally consider factors that are connected with costs and reduce the profit, and reducts (wastes) when revenues are connected with them and they increase the profits. Reducts on the input side may for instance be wastes in the case of a waste incineration plant. The waste incineration plant earns its money by accepting (and converting) these wastes. On the output side, on the other hand, we consider the products – they increase the profit. Wastes, however, reduce the profit if eliminating them costs money. Ecologically relevant flows are only taken into account if they are connected with costs, e.g. scarce environmental factors, or wastes that have to be eliminated actively.

Houtman (1998) extends this view. He also considers material flows on the input and output sides that do not cause any costs, but might harm the environment (Fig. 2). Firstly there are success-neutral inputs and outputs that are subject to volume restrictions. Admittedly they do not cost anything, but due to restrictions imposed by authorities for

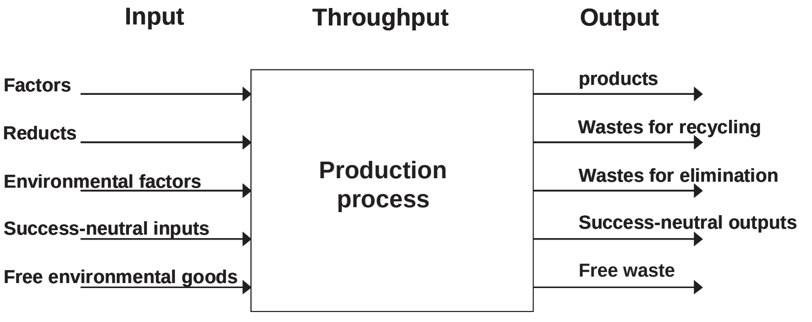

Fig. 2. Inputs and outputs of a generalised production process.

instance perhaps only certain volumes may be withdrawn or emitted. Withdrawing water from a river is an example here. This indirectly restricts production. Secondly there are success-neutral materials without any volume restrictions (free environmental goods or free wastes). These can be withdrawn from the environment or emitted to it directly and without restriction.

This extended consideration of a transformation process helps to capture the influence on the environment. In particular those materials without a market price play a major role in direct environmental impacts, e.g. emissions into the atmosphere, waste water, or wastes to be deposited in landfills. In most cases the crucial environmental influences of a process occur indirectly: through the use of special raw materials, energy, or the occurrence of wastes that have to be treated specially (Table 1). Often it is even the products that lead to environmental impacts. Distinguishing between inputs and outputs alone does not help us further here. It is the indirectly acting objects especially that have to be analysed within the context of the further supply chain or closed-loop material flow management system and traced back to direct environmental influences.

At this point the analysis must move away from the individual process and consider chains, or more precisely networks of transformation processes. It is no longer relevant to

Table 1
Classification of the inputs and outputs on the basis of their economic and ecological influence (after Houtman, 1998, 76)

Materials in the production process		Influence on profit	Influence on environment	
			Direct	Indirect
Input	Factors	Lowering		X
	Reducts	Increasing		X
	Environmental factors	Lowering	X	
	Success-neutral inputs	Limiting	X	
	Free environmental goods	Neutral	X	
Output	Products	Increasing		X
	Wastes for recycling	Lowering		X
	Wastes for elimination	Lowering	X	
	Success-neutral outputs	Limiting	X	
	Free wastes	Neutral	X	

focus on the product or the environmental impact of a single process, but to quantify those of the entire system. Two questions arise here:

- How can transformation processes be linked consistently with each other so that it becomes apparent, for instance, what the product of the system is?
- How can the environmental impacts of a system be related to a product?

Simple systematisation of the objects, as introduced by Dyckhoff (1994), contributes substantially to answering these questions. Economically the objects – in other words the materials on the input and the output side of a transformation process – only differ in whether they have a positive, a negative, or no market price at all. If they have a positive market price then they are desired objects: one pays to possess them. Such an object is called a “good”. If an object has a negative market price, one pays to get rid of it. This is a “bad”. For example waste is a bad. If it has no market price, it is neutral – it does not play any role in the economic analysis.

How is this classification of objects connected with direct environmental impacts? Something that is a bad may not only be expensive (elimination of waste), it can also harm the environment directly. In addition there are ecologically bad objects that do not cost anything, but endanger the environment despite this. Consequently bad objects are undesirable from both economic and/or ecological points of view (see Table 2).

The question as to whether goods can harm the environment directly is more difficult to answer. Naturally there are many goods that admittedly have a market price, but are evidently bad for the environment. For instance, a PC costs a few hundred dollars or euros (and so is a good), yet it causes emissions through its electricity consumption. Furthermore it subsequently becomes electronic waste. At this point, however, the somewhat sophist definition is often advanced that economically desired objects are always basically “good” and do not represent any directly undesirable environmental impacts. However, naturally the production, consumption or reduction of these goods can be connected with directly environmental impacts, namely e.g. by releasing what is bad (emissions, waste water . . .). Possession of a PC is desirable, even if it causes emissions during the phase of use. These emissions (as bad) are undesirable, but necessary concomitant phenomena of PC use – in other words an indirect environmental impact. It will therefore be a major task to track these indirect environmental impacts along a supply chain or in a closed-loop material flow management system and to allocate them correctly.

Finally, when the PC becomes broken the aim is to get rid of it and one may well even be willing to pay money for this. Now the good becomes bad, in other words waste. However,

Table 2
Systematising objects in transformation processes

Market price	Direct environmental impact	
	No	Yes
Positive	Good	Not defined
0	Neutral	Bad
Negative	Bad	Bad

the PC remains good, if someone buys it to scavenge parts and recycle the individual components. Dyckhoff (1994, 70) already pointed out this ambivalence in assessing objects. It is essential for modelling recycling management systems in which objects – depending on the economic interest situation – can assume the role of good or bad.

2.2. Expenditure and revenue

This division of objects into goods and bads forms the framework with which closed-loop material flow management systems can be analysed. In systems consisting of many processes it is important to introduce the terms expenditure and revenue due to the ambivalence of the pair of concepts good/bad. Taking an individual transformation process as an example makes this clear. For a production process in which a product results, the revenue is the generation of a good on the output side (see Table 3). On the other hand the expenditure is everything that is undesirable, costs money, or harms the environment: factor consumption, emissions, waste etc. An ecological dimension is added to the economic expenditure concept here. An expenditure is then formed by goods on the input side (factor consumption) or bads on the output side (emissions, wastes . . .). This expenditure – considered economically as well as ecologically – is necessary to generate the benefit that can always only be substantiated economically in this system. In the case of an individual production process this allocation of revenue and expenditure is simple. In classic cost accounting it is the basis for costing products. One can even interpret the Life Cycle Assessment as a kind of ecological costing in which the ecological expenditure is added to the (economic) revenue, namely the functional unit.

However, there are also converse cases in which money is earned by eliminating bads, for instance in a waste incineration or recycling plant. Then the revenue is the input of bads. The expenditure is still everything connected with costs or environmental pollution: factor consumption, emissions, waste etc.

An important case arises when a multiple revenue appears in a process. This is then a joint production process, which by no means necessarily has only two coupled “products”. Today a modern waste incineration plant earns its money by accepting waste (bad on the input side) and selling heat or electricity (good on the output side). The revenue concept helps to identify coupling processes clearly. The difficulty remains in allocating the expenditure to the multiple benefit – the classic problem of joint production (Schmidt, 1998).

Revenue and expenditure can be considered not solely for individual processes, however, but also for entire systems, e.g. linear supply chains or recycling systems. The

Table 3
Economic and ecological importance of object categories for a transformation process dependent on their occurrence on input or output side

	Market price	Input	Output
Good	>0	Economic expenditure; any ecological expenditure	Economic revenue
Bad	<0	Economic revenue; any ecological revenue	Economic expenditure; any ecological expenditure
	=0	Ecological revenue	Ecological expenditure

revenue is obviously the sum of the bad entering and the good leaving the system, and the expenditure is the sum of the good entering and the bad leaving the system. Remember that the distinction between good and bad is made by the market at any time.

However, the purpose of a system is very often to create one specific revenue, e.g. to produce one good (the system is then called a production system) or to reduce one bad (the system is then called a recycling or disposal system). Given this intended revenue, the overall expenditure will be allocated to it. We call this purpose-based focus on a specific input or output of the system a perspective. Perspectives are useful for the analysis and communication of system properties, as will be shown in Section 4. Given a perspective, the indirect environmental impacts already mentioned simply represent a question of system boundaries. If the system has been selected suitably, the indirect environmental impacts of individual processes will be captured elsewhere in the system as direct environmental impacts.

3. System modelling with the aid of nets

One way of describing closed-loop systems as a model is to display them as nets or graphs. Möller (1994) introduced the “material flow nets” in which the nodes are interpreted as transformation processes and the arrows as material flows. By introducing a second type of node – by analogy with the Petri net from theoretical informatics – it is also possible to map storage processes. This allows a distinction to be made between activities and states, thus also permitting time-based analysis for instance.

Fig. 3a) shows a simple net as an input/output graph. Each process is described through its input flows and its output flows that can stand in a functional connection with each other (Schmidt and Keil, 2002). By linking the processes it is possible to build up systems

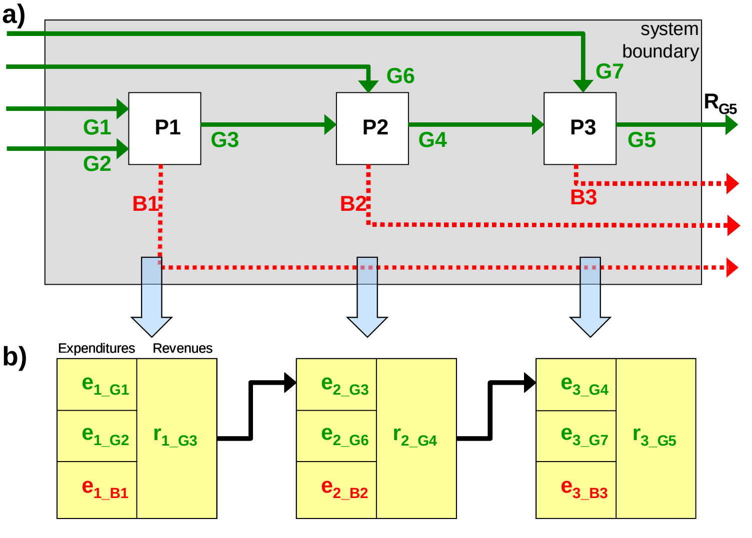

Fig. 3. a) An I/O graph of a chain of three processes; b) the corresponding expenditure–revenue graph.

of optional complexity. In this case a linear chain of three processes is shown that are connected to each other by the flow of goods (G3–G4). Thus for example process P1 requires goods G1 and G2 as raw materials "from the exterior" and produces product G3 with these. In addition a bad B1 results. It soon becomes clear that the system revenue is the production of G5. The system expenditure for this is made up of the goods G1, G2, G6 and G7 on the input side, and the bads B1, B2 and B3 on the output side.

This input–output graph can be converted into an expenditure and revenue graph in accordance with Fig. 3b) with the aid of good/bad classification (Möller, 2000). Each process is now broken down by the expenditures and the revenues. The quantities e and r stand for the associated coefficients of production of expenditures and revenues, whereby a linear functional connection is assumed and the data are stated in physical quantity units (e.g. kg). The expenditure connected with the system revenue R_{G5} throughout the entire system can thus be calculated easily by determining the production level x_i of processes 1 to 3 and the expenditures of the individual processes derived from these.

This approach makes it possible to map material cycles such as occur in recycling processes without any problem too. Fig. 4 shows such a case. The good 4 that is produced in process 2 is used as a raw material in process 1. To calculate the system expenditure for the system revenue R_{G5}, the production levels x_i of processes 1–3 are solved with a linear equation system:

$$\begin{aligned} x_3 &= R_{G5} \\ -e_{1\_G4}/r_{1\_G3}\cdot x_1 + x_2 - e_{3\_G4}/r_{3\_G5}\cdot x_3 &= 0 \\ x_1 - e_{2\_G3}/r_{2\_G4}\cdot x_2 &= 0 \end{aligned}$$

This results in the system expenditure $E_{B1}=e_{1\_B1}/r_{1\_B1}\cdot x_1$ etc., for example. It should be noted that this expenditure is determined on the physical quantity level. The advantage

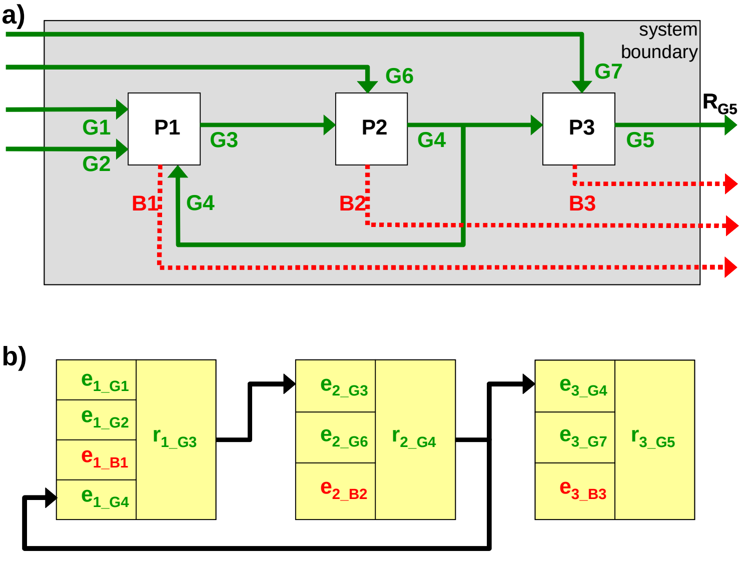

Fig. 4. a) An I/O graph of a chain of 3 processes with recycling of good 4; b) the corresponding expenditure–revenue graph.

of this is that it can be used for both economic and ecological analyses. In the economic analysis the quantities of the expenditures (e.g. raw materials) simply have to be multiplied by the market prices. This results in the costs incurred by the material input for producing good 5. The concept can be extended easily by the costs of further process-related factors (labour, capital...), so that complete cost and result accounting can be drawn up on this quantity structure of costs (cf. Möller, 2000).

The quantity relation of the material flows can, however, also be used to conduct an ecological analysis. For instance all greenhouse-relevant emissions of the system can be condensed to the global warming potential (GWP). The emissions then relate to the system revenue considered in the specific case, for instance in this example the production of good 5.

The attractiveness of this method lies in the fact that a real material flow system in which many different system revenues occur can be analysed very flexibly. The expenditure associated with each system revenue can be determined. For the environmental sector this means that the indirect environmental impacts of a product or, more precisely, of a revenue can be determined too.

An interesting special case occurs when a cycle is operated with a material as bad (Fig. 5a). B2 occurs in process 2 and is needed in process 1. For process 1 this now means an additional revenue, in other words the elimination of the bad B2. As a result the expenditure/revenue graph looks different (Fig. 5b): The expenditures in process 1 are set against two revenues. This is a typical case of joint production. It has to be solved at the individual process level by allocating the expenditures to the two revenues. Process 1 is subdivided into two new processes with only one revenue each, as it were. At this point, however, it also becomes understandable that allocation in the case of a joint process can

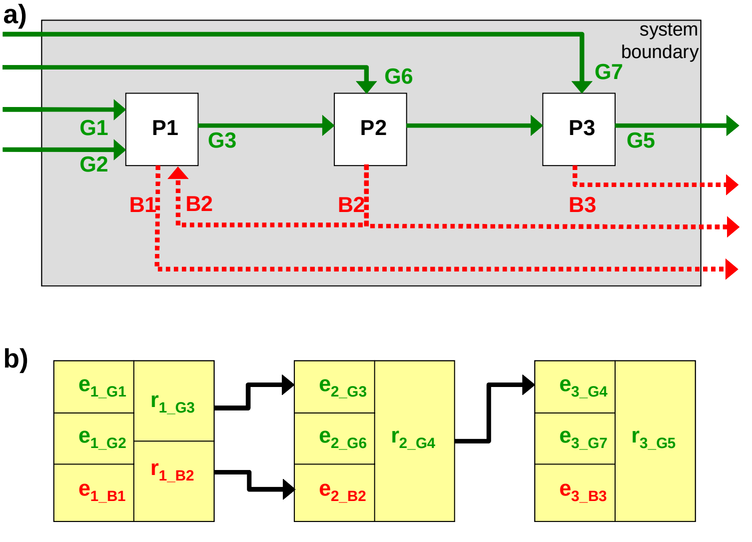

Fig. 5. a) An I/O graph of a chain of three processes with recycling of bad 2;. b) the corresponding expenditure–revenue graph.

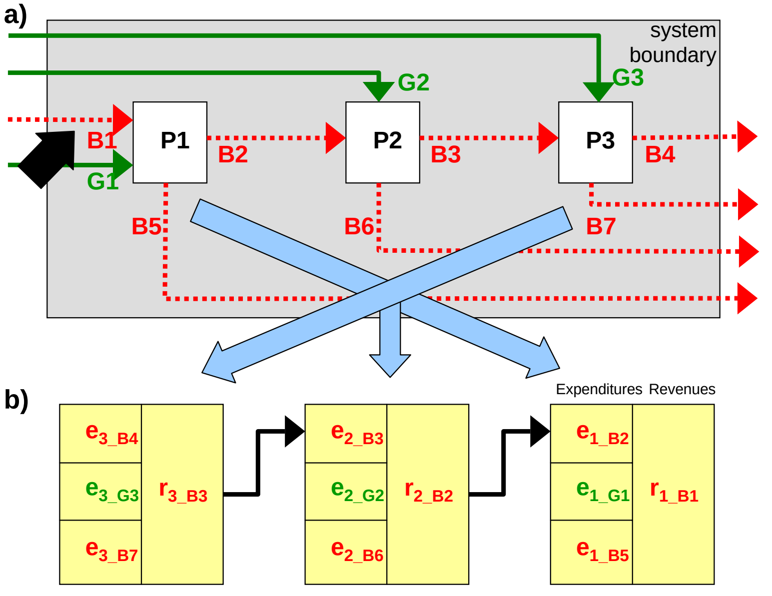

Fig. 6. a) An I/O graph for a waste disposal chain to eliminate B1 (black arrow); b) the corresp. expenditure-revenue graph.

only be oriented to the revenues of a process. A purely physical allocation such as is proposed e.g. by ISO 14.041 is problematic. After all, the question as to what is revenue and what is expenditure is decided by the economic analysis.

While so far goods have been passed on through the process chain – in accordance with a supply chain – a waste disposal chain is considered in the following example (Fig. 6). The bad B1 is eliminated by this system, and this is also the system revenue. This revenue is connected with a certain expenditure, including the development of new bads as system output (B4–B7).

To summarise it can be ascertained that the graph display together with the classification of the materials based on production theory provides an approach for calculating the system revenue in complex systems and determining the system expenditure. The expenditure can be allocated to one or more different revenues in the style of cost and result accounting – however on a physical quantity–related level. This procedure serves both to calculate costs and to determine the indirect environmental impacts.

4. Change of perspective in analysis

The methodology described above is ideally suited for analysing production and waste disposal structures. To this end input/output process nets are formed in which the economically and ecologically relevant materials, energies, services etc. appear as flows. These flows are ascertained. This can be done empirically by measuring, but calculations based on mathematical process models are also possible.

The flow objects, usually the materials, simply have to be classified ordinally as good, neutral or bad in order to specify their quality. Thus it is set out for each process what is expenditure and what is revenue. From this it is possible to develop an expenditure and revenue graph from which it can be derived what is system expenditure and what is system revenue at a quantity level. The necessary system expenditure for each system revenue can be determined – under both ecological and economic perspectives.

The following example shows an important analysis potential of this approach (Fig. 7). Electronic waste is collected in various fractions in a number of different collection areas (left). The waste fractions are then conveyed to sorting plants. Finally the waste is processed to a secondary raw material in two recycling plants (right). The transport, sorting and recycling require energy and cause emissions. They also involve costs.

In Fig. 7 the electronic waste in the system is interpreted as a bad. The only revenue of the system lies on the input side, namely the various fractions of electronic waste from the various collection areas. The expenditure in the system can be tracked easily for such a revenue. It is set out in Fig. 8, where the selected system revenue is marked with an arrow. The flows (including the pro-rated energy and emissions) occurring in the system to provide a system revenue can be seen here.

In this way it is possible to answer the question of where the waste goes, what material flows it causes, and what consequential costs it has. These questions can in principle be answered for each process and/or system revenue, in other words for the other waste fractions too.

Whereas Fig. 8 answers the question regarding the system expenditure at a physical quantity level, Fig. 9 shows the volumes analysed in monetary terms. The costs of the processes are quasi pro-rated to the relevant system revenue, as can be seen from the Cost Sankey Diagram. This results in a clear presentation indicating which waste fraction causes what costs.

A substantial change is made for Fig. 10. The electronic waste fractions are no longer interpreted as bad, but instead as good, because of rising market prices for secondary materials. Otherwise nothing is changed in the system by comparison with Fig. 7. According to this new perspective, the system revenue now lies on the output side, namely with the secondary raw materials produced (black arrow). The electronic waste fractions on the input side of the system are now considered as goods, because the market reacts to the new perspective in creating a positive price for them too. Accordingly Fig. 10 answers the question: where does the secondary raw material come from? What material flows are connected with this system revenue (including energy and emissions)? The pro-rated costs in the system are now credited against the secondary raw material. A Cost Sankey Diagram for a production chain would show the increasing added value.

This makes it clear that the ambivalence in classifying materials into good or bad mentioned in Section 2 opens up an interesting analysis option. If the waste is considered to be bad, its whereabouts in the system is examined. Resulting costs or environmental pollution will be debited to it. However, if the waste is considered to be good, it is treated as a factor input that contributes to the production of a new secondary raw material. In this case the costs and environmental pollution will be credited to the secondary raw material. Finally, the market decides which perspective is adequate.

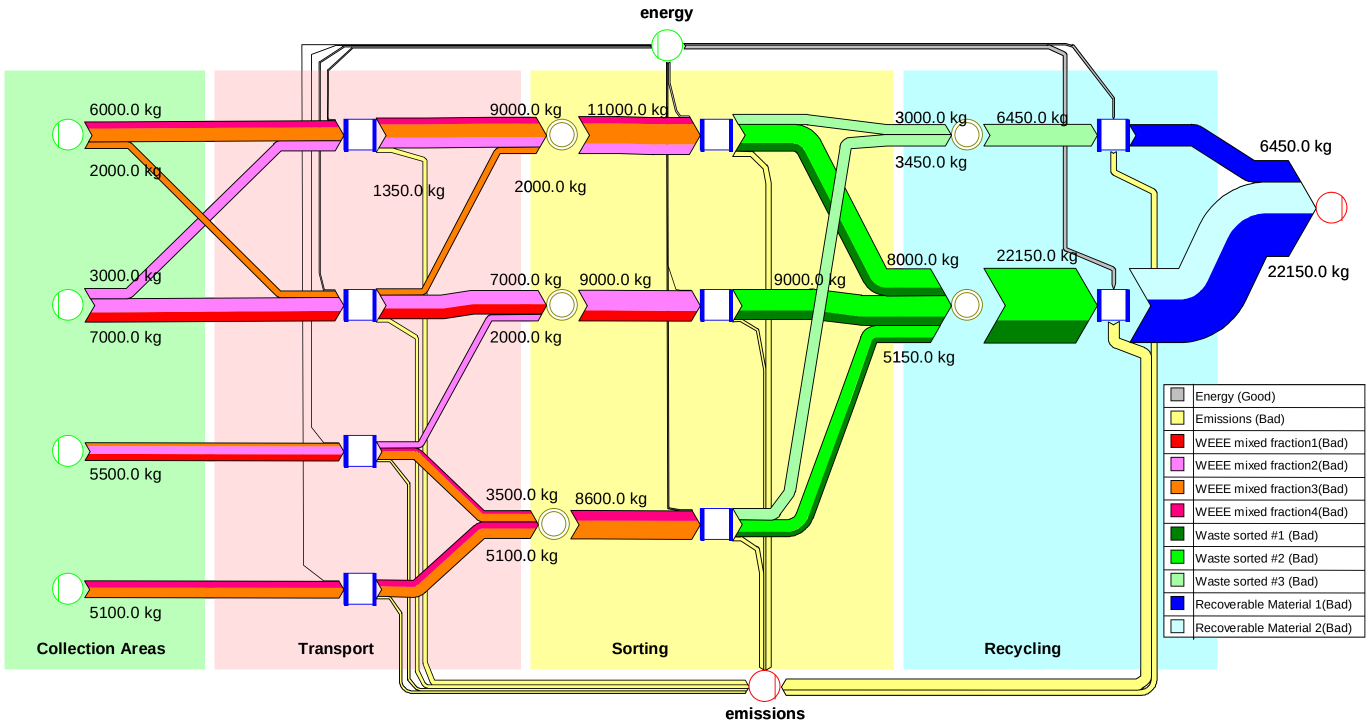

Fig. 7. Input/Output net of the reverse logistics of various electronic waste fractions along the waste disposal path.

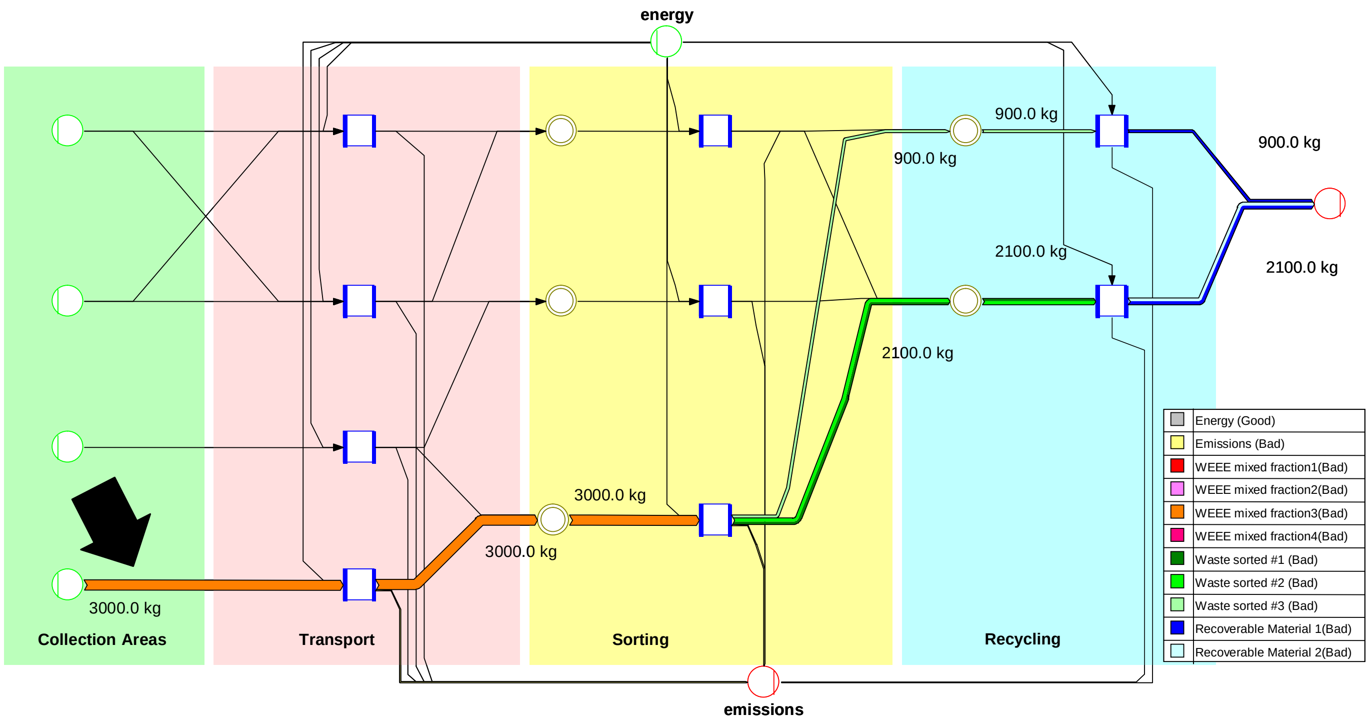

Fig. 8. Electronic waste as bads: tracking the material expenditure of a special system revenue (black arrow).

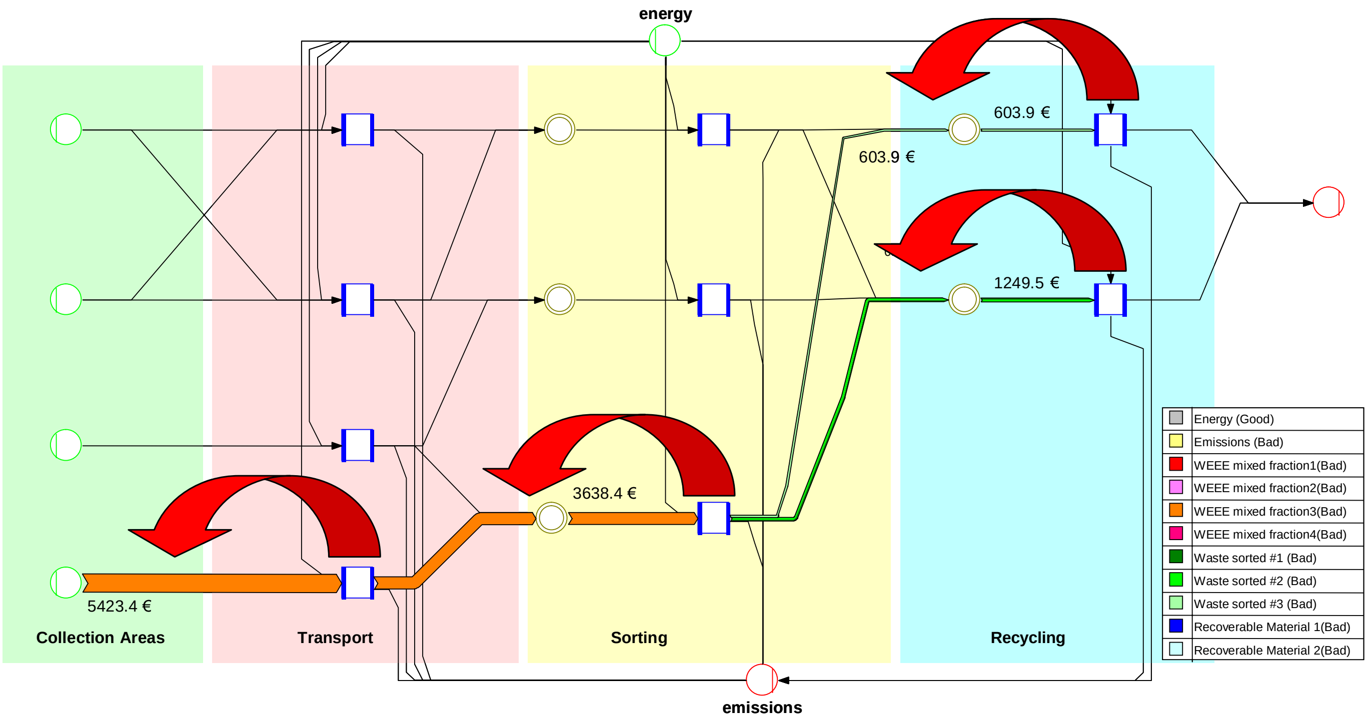

Fig. 9. Pro-rated costs of recycling the relevant waste (left), shown in the form of a Cost Sankey Diagram.

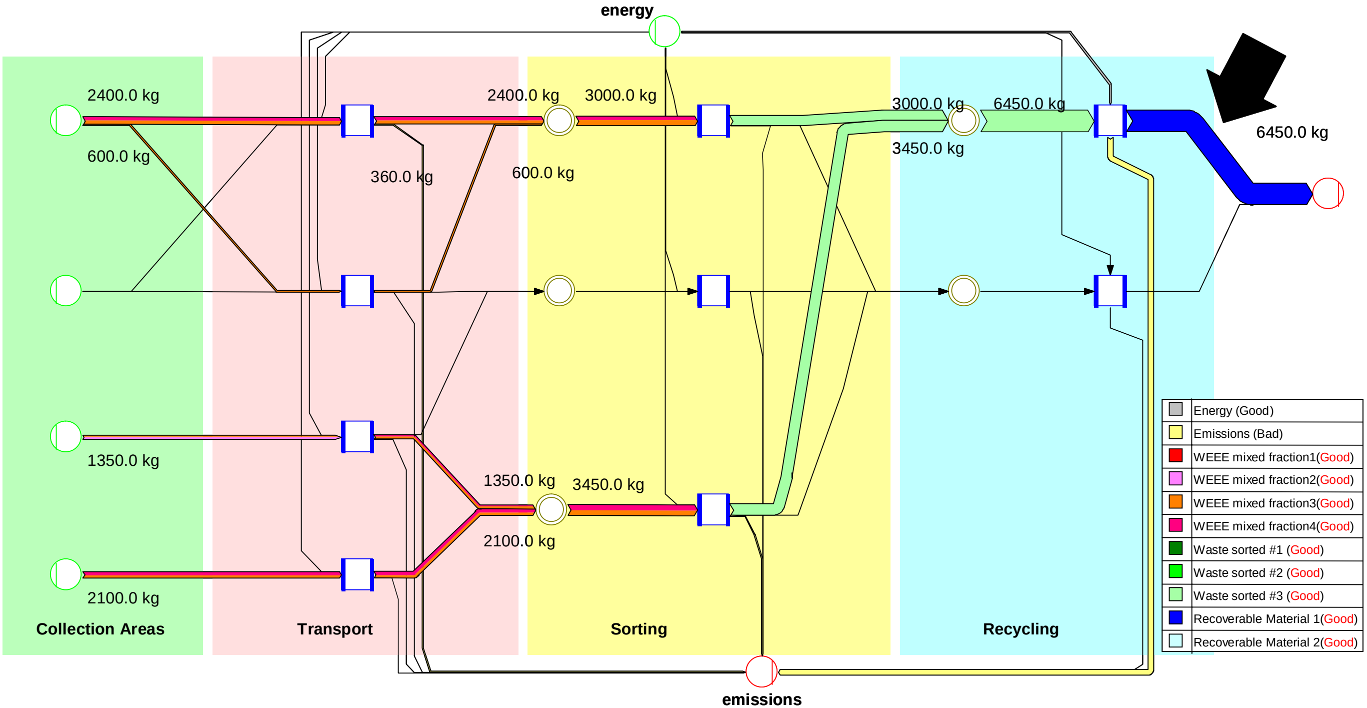

Fig. 10. Electronic waste as goods: tracking the material expenditure of a special system revenue (black arrow).

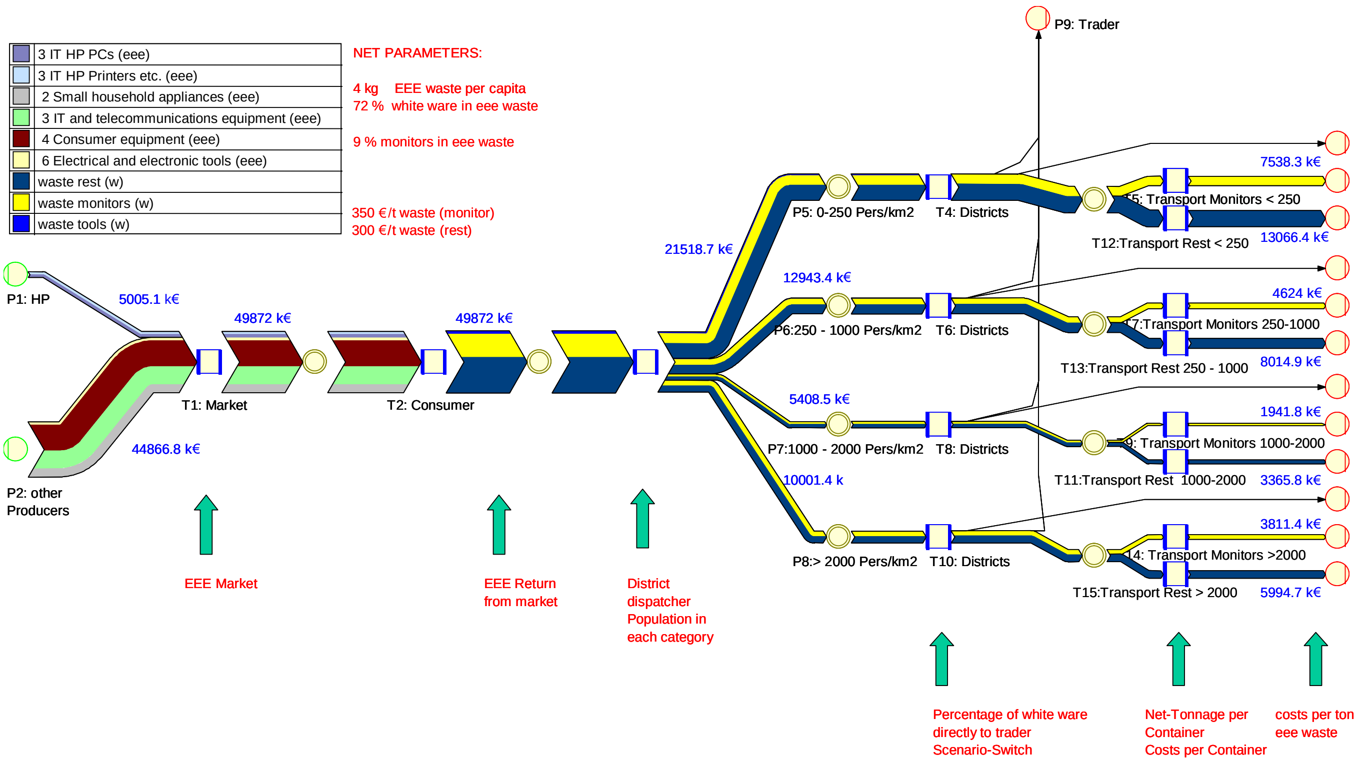

Fig. 11. Scenario for recycling several e-waste components showing the costs incurred along the chain (figures are fictitious).

Other, mixed forms between these two pure perspectives are also conceivable, for instance when the electronic waste is interpreted as bad and the secondary raw material as good. This is then a coupled system in which the expenditures have to be allocated to the two revenues.

The display form selected using the Sankey diagrams in Figs. 7–10 allows a clear representation even for complex systems. These Sankey diagrams can be used not only for displaying quantities (in kg), but also for tracking costs clearly, as illustrated in the example in Fig. 10.

5. Reverse logistic scenarios as a model case

With the implementation of the WEEE Directive, it is interesting for firms such as e.g. Hewlett-Packard to know what quantity flows of electronic waste will be generated per year in a national market, how they are made up, what possibilities exist for collecting, grading and recycling, what costs are connected with each of these operations, and how these costs are distributed between the individual manufacturers.

Since these questions are connected strongly with the physical quantity flows and the various transformation processes of collection/transport/grading/recycling, and as both economic and ecological analyses are necessary after this, the approach presented appears expedient. Such analyses have been developed together with Hewlett-Packard for Germany, France, Spain, the United Kingdom and Italy. Uncertainties, for instance because input data (quantity flows, prices, quotas etc.) are as yet unknown, were parameterised in the model and mapped as scenarios. The parameters that can be adjusted in the model are shown at the relevant points in the system with grey arrows in Fig. 11.

Fig. 11 shows as a result not the quantity flows, but the quantities valued with prices, in other words the costs. That is why the Sankey arrows are provided with data in €. Since according to the WEEE Directive the manufacturers are responsible for the costs of recycling the historical electronic waste, the waste is set as bad here. With such scenarios the manufacturers can determine their cost share and identify any possible parameters for optimising the system.

The ideal picture is naturally that one day the technical prerequisites will be created for producing high-grade and marketable secondary raw materials from the electronic waste. The electronic waste will then have to be considered as a good and the questions will revolve around those already posed in Section 4.

6. Conclusions

It was shown that modern production theory contains efficient approaches for analysing recycling systems and closed-loop systems more adequately. While the categorising of objects as good or bad may appear a little unusual to start with, it soon proves to be a very expedient concept, since it allows distinctions to be made between expenditure and revenue at the process level, as well as at the system level. In addition the linking of processes in the form of graphs, such as e.g. the Petri net approach, is also helpful for analysing systems.

A kind of "non-monetary" cost and result accounting can be drawn up solely with the ordinal distinction of materials as good, bad or neutral for a complex material flow system. Since this is not immediately carried out at a monetary level (in other words in € or $), but instead at a physical level (in kg or kJ), it can be used subsequently for both economic and ecological analyses. After all, ecological analyses presuppose physical data and can generally not be derived from economic quantities. Altogether this makes it possible to determine the indirect environmental impacts caused as a result for individual processes in larger system linkages.

As shown here with the example of electronic waste, it is expedient to interpret waste as good in an advanced closed-loop economy too – in other words as a production factor – and no longer as an undesired bad. As regards the allocation of costs and environmental pollution, we ultimately reach the chicken-and-egg problem in a material cycle. Are we to eliminate the bad, or are we already producing a new good?

Production theory could help further here by relating the costs and the environmental impacts in a closed-loop material management system consistently to the benefit, for example the service of the products. In any case the methodology described here helps to analyse complex production and reduction systems transparently, to understand them better, and ultimately to optimise them.

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