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Eichner, Thomas; Pethig, Rüdiger

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Product Design and Alternative Market Schemes for Solid Waste Treatment and Disposal

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Product Design and Alternative Market Schemes for Solid Waste Treatment and Disposal

Thomas Eichner and Rüdiger Pethig

University of Siegen

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Product Design and Alternative Market Schemes for Solid Waste Treatment and Disposal

Thomas Eichner and Rüdiger Pethig, University of Siegen

1. The problem

The economics of waste treatment and disposal have been extensively studied in dynamic and static models. As in case of air-borne or water-borne 'material emissions', the principal reason for inefficient markets are environmental externalities. But with the focus on solid waste, additional potentials for 'market failure' are of great concern to waste management (see e.g. Conn (1977) and Spofford (1991)), in particular the failure of markets for consumption waste and the failure of markets to bring about the efficient ('green') product design. The latter issue did already receive some attention in the theoretical literature on recycling e.g. by Holm-Müller (1997, p. 171n.) and Fullerton and Wu (1998) who introduced a product design variable that increases production costs and reduces the cost of recycling.

The present paper focusses on the environmental relevance of product design in the setting of simple static general equilibrium analysis. But rather than introducing a product-design variable ad hoc we envisage a (durable) consumption good each unit of which contains a certain amount of some specific material which explicitly enters the analysis as a factor of production. The *embodied material per unit of output*, called the *material content*, for short, can be varied through product design and remains an intrinsic attribute of solid waste left over after consumption. The material embodied in consumption waste is assumed to have the potential of causing environmental damage but that damage can be reduced or even avoided when the consumption waste is treated before landfilling. For any given labor used for waste (material) treatment the environmental damage rises with both the total amount of consumption waste (weight) and its material content. Therefore, the analysis must keep track of the material content of output as determined in production (product design) and passed on all the way to the waste treatment firms. Insofar, the embodiment concept modeled here captures an important aspect of *product life-cycle analysis* which, in our view, is not adequately accounted for in the waste disposal literature.

Keeping track of embodied material in spent output first requires to model an economy with material-content features as outlined above and study its pertinent efficiency implications.

Then it is important to investigate the capacity of markets for coping with the product-design issue. This is the principal objective of the present paper. Waste treatment firms turn out to have an incentive, and willingness-to-pay, for reducing the material content of consumption waste when high material content cuts into their profits. We contend, however, that it is not at all clear, neither as a theoretical nor as an empirical matter, whether - and if so, how - that material content is driven by market forces and which concepts or types of markets will be active or do not emerge, respectively. To understand how markets determine product design is obviously a *conditio sine qua non* for any suitable recommendation for corrective regulation, since policy proposals ought to depend on the type of market failure identified. Solid waste management should clearly be designed to only fill the gap of inadequate market forces, but it should by no means replace reasonably well functioning markets.

Therefore, our attention is focused on clarifying how various types of market schemes affect the allocation of material content. We show that material content (as well as pollution) has the public-good property of joint consumption and hence choose the *Lindahl market scheme* as a benchmark. This scheme is known to be efficient, but which clearly lacks incentives to emerge in the real world. A less unrealistic approach is the concept of what we call *indirect markets for material content* suggested by Fullerton and Wu (1998) in the context of recycling where agents perceive the price of the consumption good and/or the price of consumption waste as a function of material content. Yet another way to strive for the efficient product design is to use *markets for embodied material*.

Our analysis shows that, if they are active, markets for embodied material as well as indirect markets for material content secure allocative efficiency under some qualifications. It turns out that indirect markets for material content are efficient, if the technologies take some special form which seems to be quite restrictive. Markets for embodied material are efficient, if, in addition, landfilling costs are absent or depend on the embodied material only. In the absence of all these markets the consumption good tends to be provided with excessively high material content.

Another dimension impacting on the structure of (competitive) markets is *property rights*. We distinguish the households and the producers property rights rules depending on whether households or producers are responsible for the proper, legally prescribed disposal of consumption residuals. As could be expected from Coasean economics both rules turn out to be efficient in the absence of transaction costs.

In section 2 a partly disaggregated model with pollution, waste treatment and landfilling is developed and its efficient allocation is characterized. For this model, section 3 formally defines, investigates and compares the market procedures described above and their efficiency properties. Section 4 concludes.

2. A Model of consumption waste treatment and landfilling

The economy to be studied is given by[1]

$$u_h = U^h\left(\underset{-}{e_h^d}, \underset{-}{\ell_h^s}, \underset{+}{x_h^d}\right) \qquad \text{utility of consumer } h \in H \qquad (1)$$

$$x^s \le X\left(\underset{+}{\ell_x^d}, \underset{+}{m^d}\right) \qquad \text{production of good } X \qquad (2)$$

$$v^s \le V\left(\underset{+}{\ell_v^d}\right) \qquad \text{(virgin) material production} \qquad (3)$$

$$e_j^s \ge E^j(\underset{-}{\ell_{ej}^d}, \underset{+}{q_j^d}, \underset{+}{w_j^d}) \qquad \text{treatment technology of firm } j \in J \qquad (4)$$

$$\ell_f^d = C(\underset{+}{f^d}) \qquad \text{cost of landfilling} \qquad (5)$$

$$q_x^s := \frac{m^d}{x^s} \qquad \text{material content supplied} \qquad (6)$$

$$f^d \ge \sum_j f_j^s \text{ and } f_j^s \ge w_j^d \text{ all } j \in J$$

$$\sum_i w_i^d \ge \sum_h w_h^s, \quad w_h^s \ge x_h^d \text{ all } h \in H \qquad \text{mandatory residuals processing} \qquad (7)$$

$$x^s \ge \sum_h x_h^d, \quad v^s \ge m^d$$

$$\sum_h \ell_h^s \ge \sum_j \ell_{ej}^d + \ell_f^d + \ell_v^d + \ell_x^d \qquad \text{supply constraints} \qquad (8)$$

$$q_x^s = q_h^d = q_h^s = q_j^d \text{ all } h \in H, \text{ all } j \in J \qquad \text{material content of good } X \qquad (9)$$

$$e_h^d = \sum_j e_j^s \text{ all } h \in H \qquad \text{pollution as a public good} \qquad (10)$$

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[1] A plus or minus sign underneath an argument of a function denotes the sign of the partial derivative of that function with respect to the respective argument. Upper-case letters are reserved to denote functions and subscript attached to them indicate first derivatives.

The structure of the model is quite simple. The amount x^s of a single consumption good, called *good X,* is produced with labor, ℓ_x^d, and two types of material which are embodied in the output. To keep the analysis simple, one of these materials is assumed to be costless and (therefore) not explicitly introduced into the formal model. The other type of material, referred to as *material,* for short, is an explicit production factor; its quantity is m^d. Each unit of good X is of constant weight, but the technology (2) allows for varying the material input mix as measured by the material-output ratio, q_x^s, defined in (6) as the share of (explicitly modeled) material per unit of output X. We will call q_x^s the *material content* of good X. After consumption, good X is turned into consumption waste of equal weight, w_h^s, with the potential of causing environmental damage. This damage can be reduced or even avoided[2], in turn, if treated before landfilling. According to the utility function (1), labor ℓ_h^s is endogenously supplied by each household who consumes x_h^d of good X, and suffers from pollution, e_h^d. Labor is used to produce good X, $X_\ell > 0$, to extract material, $V_\ell > 0$, to treat consumption waste, $E_\ell^j < 0$, and to landfill that waste (after treatment), $C_f > 0$.

Waste treatment as modeled in (4) allows for various interpretations. The waste under consideration may be hazardous and hence requires special treatment to reduce or avoid its ecotoxidity; it may cause leakages if landfilled without prior treatment or it is incinerated before being landfilled. Regarding the waste treatment technology (4), it appears plausible to assume that E^j is a convex function satisfying $E^j\left(\ell_{ej}, q_j^d, 0\right) = 0$, but $E^j\left(0, q_j^d, w_j^d\right) > 0$ for $w_j^d > 0$. The positive signs of the derivatives E_q^j and E_w^j indicate that both materials embodied in consumption waste may cause the emission of a pollutant (the same one, in fact). More specifically, if $E_q^j = 0$ but $E_w^j > 0$, both types of material are identical with respect to the emission of pollutants implying that emissions are a function of output only for any given labor input ℓ_{ej}^d. On the other hand, if $E^j\left(\ell_{ej}^d, q_j^d, w_j^d\right)$ takes the form $\tilde{E}^j\left(\ell_{ej}^d, q_j^d \cdot w_j^d\right)$, then pollution is caused exclusively by the (explicitly modeled) material, while the other type of material is environmentally neutral. But note that other functional forms are quite plausible, too. For example, if $E^j\left(\ell_{ej}^d, q_j^d, w_j^d\right) = \breve{E}^j\left(\ell_{ej}^d, q_j^d \cdot w_j^d, q_j^d\right)$ with $\breve{E}_q^j < 0$, then the (explicitly modeled)

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[2] The ambitious goal in solid waste management of requiring environmentally safe (inert) waste deposition in the future would amount to the constraint $E^j\left(\ell_{ej}^d, q_j^d, w_j^d\right) = 0$ for all $j \in J$, in terms of our model.

material is still the only pollutant, but its 'neutralization' is the easier, the greater is its concentration in total waste. The specification $\widetilde{E}^j$ of E^j will turn out to be of considerable interest in the subsequent analysis.

The material content of good X as defined in (6) is an attribute of the (private) consumption good X. q_x is produced along with the quantity of good X without being itself an argument of the production function (2) in addition to ℓ_x^d and m^d. In fact, this feature distinguishes our approach to product design significantly from other theoretical contributions we are aware of as e.g. Fullerton and Wu (1998). In abstract economic terms, material content is a good which is costly to produce and which affects the productivity of waste treatment (and/or recycling). Moreover, empirical observations suggest that consumers may dislike the material content due to its environmentally detrimental effects (green preferences) or value it as a favorable consumption characteristic of good X. Such features could be easily added to the present model, but we refrain from this extra complexity to keep a clear focus on supply-side determinants of the material flows.

The equations (9) identify material content as a public good in the usual well-defined theoretical sense of this concept. But to avoid incorrect associations a careful interpretation of this public good is in order. Material content is not a public good in the sense that if some person owns good X with material content q then this attribute q is jointly consumable by other persons. The proper way to look at it is rather prescribed by (9): all sequential owners of good X or of spent good X have no choice but accepting the very same material content that resulted from the design and production of good X in the first place. Once good X with attribute q has been produced no subsequent owner of that good or its residual can be excluded from or reject the attribute q. All these rather obvious observations are reflected by the equality signs in (9).[3]

In (1) - (10) the superscripts s and d indicate quantities demanded and supplied, respectively, and this scheme is consistently applied to *all* economic variables. While the inequalities (8) are conventional (neoclassical) resource restrictions requiring that demand does not exceed supply, the constraints in (7) enforce the reverse inequalities formalizing the legal

[3] Our interpretation of the 'public good' material content implies a sequence of transaction which is not formally reflected in the static model (1) - (10). But adding an explicit time structure , e.g. along the lines of Dinan (1993), would not change the principal argument. Sequential transactions and static analysis is easily reconciled by interpreting the attainable allocations of the present model as stationary states in which all flows of good X, material, waste etc. are the same period after period.

constraint that free disposal (e. g. moonlight dumping) is effectively and costlessly ruled out. The rationale of this feature of the model is given below. It is quite unusual to apply the demand and supply scheme to the public goods 'material content' and 'emissions' as well. The reason for adopting this somewhat clumsy procedure is to make explicit the property rights structures that may play a role in the capacity of markets to allocate these goods.

To be more specific, observe first that the way in which the demands for and supplies of material content are specified in the economy (1) - (10) implies a certain institutional pattern of transactions: firm X offers $\left(x^s, q_x^s\right)$ to the consumers whose demand is $\left(x_h^d, q_h^d\right)$, all $h \in H$; the households, in turn, supply their consumption residuals $\left(w_h^s, q_h^s\right)$, all $h \in H$, to the waste treatment firms whose demand for these residuals is $\left(w_j^d, q_j^d\right)$ all $j \in J$; the waste treatment firms, finally, supply the consumption waste after treatment, f_j^s, to the landfilling firm whose demand is f^d. The arrangements of property rights underlying these trade flows are called the *households property rights rule* (the *HP rule*, for short). Under this scheme, consumers acquire the quantity, x^d, as their property when purchasing good X for consumption - implying that they are also responsible for the proper disposal of all residuals left over after consumption. Hence they are responsible for having their consumption waste orderly collected and landfilled.

An alternative property rights arrangement would be that consumers only acquire the right to consume when they buy good X in the market place while the physical units of good X and the consumption waste remain the property of firm X. In this case, firm X is responsible for the proper, legally prescribed disposal of the residuals. We refer to this scheme as the *producers property rights rule* (the *PP rule*, for short), also known as the take-back rule[4]. The model (1) - (10) is completely converted to reflect the PP rule when the equations (7) and (9), respectively, are replaced by

$$f^d \geq \sum_j f_j^s, \quad f_j^s \geq w_j^d \text{ all } j \in J \text{ and } \sum_j w_j^d \geq x^s \quad \text{mandatory residuals processing} \qquad (7')$$

$$q_x^s = q_j^d \text{ all } j \in J \qquad \text{material content of good } X \qquad (9')$$

[4] In principle, the PP rule has been adopted in the recent German packaging waste legislation. For more details see e.g. Holm-Müller (1997).

In the subsequent investigation our main focus will be on the HP rule. But we will also report on the relevant results under the PP rule.

The efficient allocation of the economy (1) - (10) is characterized by solving the Lagrangean

$$L = \sum_h \alpha_h U^h\left(e_h^d, \ell_h^s, x_h^d\right) + \lambda_{xx}\left[X\left(\ell_x^d, m^d\right) - x^s\right] + \lambda_v\left[V\left(\ell_v^d\right) - v^s\right] + \lambda_w\left(\sum_j w_j^d - \sum_h w_h^s\right) +$$

$$+ \lambda_\ell\left[\sum_h \ell_h^s - \sum_j \ell_{ej}^d - C(f^d) - \ell_v^d - \ell_x^d\right] + \sum_j \lambda_e^j\left[e_j^s - E^j\left(\ell_{ej}^d, q_j^d, w_j^d\right)\right] + \sum_h \lambda_w^h\left(w_h^s - x_h^d\right) +$$

$$+ \lambda_x\left(x^s - \sum_h x_h^d\right) + \lambda_m\left(v^s - m^d\right) + \sum_j \lambda_f^j\left(f_j^s - w_j^d\right) + \sum_h \lambda_e^h\left(e_h^d - \sum_j e_j^s\right) + \lambda_f\left(f^d - \sum_j f_j^s\right) +$$

$$+ \sum_h\left[\lambda_h\left(q_h^s - q_h^d\right) + \lambda_{qx}^h\left(q_h^d - q_x^s\right)\right] + \lambda_q\left(q_x^s - \frac{m^d}{x^s}\right) + \sum_h \sum_j \lambda_{qw}^{hj}\left(q_j^d - q_h^s\right) \qquad (11)$$

where $\alpha_h \in \Re_{++}$, all $h \in H$.

Following the standard procedure we suppose that the functions U^h are quasi-concave, X and V are concave, and E^j and C are convex functions. As a consequence all Lagrange constraints in (11), i.e. the bracketed terms following the Lagrange multipliers, are concave except for $(q_x^s - m^d / x^s)$. We want to show that there is an modified Lagrangean, equivalent to (11), for which the Kuhn-Tucker conditions are necessary and sufficient for a solution to exist. For this purpose we replace q_j^d (all j) by m^d / x^s and ignore the last four Lagrange constraints in (11). The resultant Lagrangean, say (11'), exhibits a solution provided that for all j the function $\hat{E}^j$ defined by $\hat{E}^j(\ell_{ej}^d, m^d, x^s, w_j^d) := E^j(\ell_{ej}^d, \frac{m^d}{x^s} \cdot w_j^d)$ is convex. To see that this requirement can be fulfilled when the function E^j is convex consider the parametric function $E^j(\ell_{ej}^d, q_j^d \cdot w_j^d) = (q_j^d)^a (w_j^d)^b (\ell_{ej}^d)^c$ and assign the function $\hat{E}^j$ by writing $E^j(\ell_{ej}^d, \frac{m^d}{x^s} \cdot w_j^d) = (m^d)^a (x^s)^{-a} (w_j^d)^b (\ell_{ej}^d)^c =: \hat{E}^j(\ell_{ej}^d, m^d, x^s, w_j^d)$. It is easy to see that both functions E^j and $\hat{E}^j$ as specified above are convex if $a > 1$, $b > 1$, $c < 0$, $a > 1 - b - c > 0$. Hence there are convex functions E^j for which a solution to (11) exists.

	row	Pareto efficiency	Lindahl markets for material content	Indirect markets for material content	Markets for embodied material
column		1	2	3	4
consumption	1	$\frac{U_e^h}{U_\ell^h} = \mu_e^h > 0$	$\frac{U_e^h}{U_\ell^h} = -p_e^{h*} > 0$	$\frac{U_e^h}{U_\ell^h} = -p_e^h$	$\frac{U_e^h}{U_\ell^h} = -\hat{p}_e^h$
	2	$-\frac{U_x^h}{U_\ell^h} = \mu_x + \mu_w > 0$	$-\frac{U_x^h}{U_\ell^h} = p_x^* - p_w^* > 0$	$-\frac{U_x^h}{U_\ell^h} = p_x - p_w$	$-\frac{U_x^h}{U_\ell^h} = \hat{p}_x - \hat{p}_w$
	3	$\mu_{qx}^h = \sum_j \mu_{qw}^{hj} > 0$	$p_{qx}^{h*} = p_{qw}^{h*} < 0$	$P_q^x x_h = P_q^w w_h$	
production of good X	4	$(\mu_x + \frac{\mu_q q^*}{x^*}) X_\ell = \mu_\ell > 0$	$(p_x^* - \frac{p_{qx}^* q^*}{x^*}) X_\ell = p_\ell^* > 0$	$(p_x - P_q^x \cdot x \cdot \frac{q}{x}) X_\ell = p_\ell^*$	$\hat{p}_x X_\ell = \hat{p}_\ell$
	5	$(\mu_x + \frac{\mu_q q^*}{x^*}) X_m = \mu_m + \frac{\mu_q}{x^*} > 0$	$(p_x^* - \frac{p_{qx}^* q^*}{x^*}) X_m = p_m^* - \frac{p_{qx}^*}{x^*} > 0$	$(p_x - P_q^x \cdot x \cdot \frac{q}{x}) X_m = p_m - P_q^x \cdot x \cdot \frac{1}{x}$	$\hat{p}_x X_m = \hat{p}_m - \hat{p}_b$
	6	$\mu_q = \sum_h \mu_{qx}^h > 0$	$p_{qx}^* = \sum_h p_{qx}^{h*} < 0$	$P_q^x x = \sum_h P_q^x x_h$	
disposal	7	$\mu_\ell C_f = \mu_f > 0$	$p_\ell^* C_f = -p_f^* > 0$	$p_\ell C_f = -p_f$	$\hat{p}_\ell C_f = -\hat{p}_f$
material	8	$\mu_m V_\ell = \mu_\ell > 0$	$p_m^* V_\ell = p_\ell^* > 0$	$p_m V_\ell = p_\ell$	$\hat{p}_m V_\ell = \hat{p}_\ell$
waste treatment	9	$\mu_e^j E_w^j = \mu_w - \mu_f > 0$	$p_e^* E_w^j = p_w^* - p_f^* < 0$	$p_e E_w^j = p_w - p_f$	$\hat{p}_e E_w^j = \hat{p}_w + q\hat{p}_b - \hat{p}_f$
	10	$-\mu_e^j E_\ell^j = \mu_\ell > 0$	$p_e^* E_\ell^j = p_\ell^* > 0$	$p_e E_\ell^j = p_\ell$	$\hat{p}_e E_\ell^j = \hat{p}_\ell$
	11	$\mu_e^j E_q^j = \sum_h \mu_{qw}^{hj} > 0$	$p_e^* E_q^j = p_{qw}^{j*} < 0$	$p_e E_q^j = P_q^w w_j$	
	12	$\mu_e^j = \sum_h \mu_e^h > 0$	$p_e^* = \sum_h p_e^{h*} < 0$	$p_e = \sum_h p_e^h$	$\hat{p}_e = \sum_h \hat{p}_e^h$

Table I: Efficiency and various concepts of markets in the economy (1) - (10) under the HP rule (notation: $\mu_x := \lambda_x / \lambda_\ell$ etc.; $\mu_\ell \equiv 1$)

In case of an interior solution all Lagrange multipliers can be shown to be positive[5]. To see the meaning of this observation with respect to (7), consider the problem of solving (11) with all inequalities in (7) reversed. The pertinent solution would imply $f^d = f_j^s = w_j^d = w_h^s = 0$ all $h \in H$, all $j \in J$, unless the associated Lagrange multipliers were equal to zero (which is an irrelevant case). This result has a straightforward interpretation: the constraints with reversed inequalities implicitly provide costless disposal options that are strictly superior to costly waste treatment (4) and landfilling, (5). Hence the (optimal) demand for these services is zero, and the supply is not positive unless the shadow price of residuals is zero. These unwarranted and unrealistic free-disposal options are avoided by reversing the inequality signs, i.e. by imposing (7), which denies to the agents to supply less negatively valued goods ('bads') than were generated or demand less of these goods than were supplied[6]. Hence (7) not only implies *mandatory* collection, treatment and deposition of *all* consumption waste, it also assumes that this legal requirement is met without any compliance problems and/or enforcement costs[7].

Solving (11) yields the marginal conditions listed in the first column of table I, where letters with an asterix denote variables at their efficient values. These conditions contain the following information:

Proposition 1[8] *(Properties of the efficient allocation)*:

(i) The efficient allocation of the economy (1) - (10) is characterized by

$$\sum_h \frac{U_e^h}{U_\ell^h} = -\frac{1}{E_\ell^j}, \qquad (all\ j \in J) \tag{12}$$

$$\sum_j \frac{E_q^j}{E_\ell^j} = -\frac{x^* \cdot A}{X_\ell}, \qquad where\ A := \left(X_m - \frac{X_\ell}{V_\ell} \right) > 0 \tag{13}$$

$$-\frac{U_x^h}{U_\ell^h} = \frac{1}{X_\ell} - \frac{q^* A}{X_\ell} - \frac{E_w^j}{E_\ell^j} + C_f, \qquad (all\ h \in H,\ all\ j \in J) \tag{14}$$

---

[5] This restriction excludes the case $e>0$ (see footnote 2). Note, however, that one can show that $\lambda_e^h > 0$, all h, independent of whether $e > 0$ or $e = 0$.

[6] Since the greater signs in (7) imply infeasible allocations we clearly have to ensure the equality signs to hold when an efficient or a market eqilibrium allocation is under consideration. In such an allocation all supply constraints (8) must also hold as equalities, but for a different reason: commodities cannot be freely disposed of.

[7] We realize, of course, that this is a strong and unrealistic assumption (Hecht 1991, Jenkins 1993, Morris and Holthausen 1994, Fullerton and Kinnaman 1995). Yet, as argued in the introduction, it appears to be useful to investigate the principal issues of market allocation *before* the policy options are investigated; for policy implications see Eichner and Pethig (1999b).

[8] The proof of proposition 1 is available from the authors upon request.

If $E^j(\ell^d_{ej}, q^d_j, w^d_j) = \tilde{E}^j(\ell^d_{ej},\ q^d_j \cdot w^d_j)$ *for all* $j \in J$, *then*

$$-\frac{U^h_x}{U^h_\ell} = \frac{1}{X_\ell} + C_f \qquad (all\ h \in H) \qquad (14')$$

(ii) The efficient allocation is the same under the households property rights rule and the producers property rights rule.

(iii) Suppose the production function X is linear homogenous, the function V is linear and assume $E^j_q > 0$, *all* $j \in J$. *It then follows that the efficient material content is smaller than it would be if all* E^j *were independent of* q_j.

(iv) The Lagrange multipliers solving (11) have the following properties:

There is a matrix $[\hat{\mu}^{hj}_{qw}]$ *satisfying* $\sum_h \mu^{hj}_{qw} = E^j_q \sum_h \frac{U^h_e}{U^h_\ell}$ $(all\ j \in J)$ *such that*

$$\frac{\mu_q}{x^*} = \frac{\mu^h_{qx}}{x^*_h} = \frac{\sum_j \hat{\mu}^{hj}_{qw}}{w^*_h} \qquad (all\ h \in H,\ all\ j \in J) \qquad (15)$$

If $E^j(\ell^d_{ej}, q^d_j, w^d_j) = \tilde{E}^j(\ell^d_{ej},\ q^d_j \cdot w^d_j)$ *for all* $j \in J$, *then*

$$\frac{\sum_h \hat{\mu}^{hj}_{qw}}{w^*_j} = \frac{\mu_w - \mu_f}{q^*} = \frac{\mu_q}{x^*}. \qquad (all\ j \in J) \qquad (16)$$

Otherwise (16) does not hold, in general.

Observe that equation (12) represents the well-known summation rule for the efficient allocation of a public good (here: pollution), where the LHS indicates the total marginal environmental damage and the RHS the marginal waste treatment costs. Similarly, equation (13) is the summation rule for the public good 'material content'. The LHS is the aggregate marginal damage (in terms of labor) from a small increase in q, while the RHS represents the associated marginal cost, a 'distortion' of the production process. Since $A > 0$ implies $X_m V_\ell > X_\ell$, the distortion consists of the (positive) wedge between the *indirect* marginal labor productivity, $X_m V_\ell$, and the *direct* one, X_ℓ. $X_m V_\ell$ is the marginal productivity of labor with respect to good X, when labor is employed in material extraction and when that material is used to produce good X.

Equation (14) governs the optimal allocation of good X. It requires each consumer's marginal willingness-to-pay for good X in terms of labor, $-(U_x^h / U_\ell^h)$, to equal the sum of marginal production cost $(1-q^* A)/X_\ell$, the marginal environmental damage, $-(E_w^j / E_\ell^j)$, and marginal landfilling cost, C_f. If it is only (the explicitly modeled) material that causes pollution ($E^j = \tilde{E}^j$ for all $j \in J$) the allocation rule for good X takes the special form (14') which is the same optimization rule as in case of no pollution at all (i. e. in case of $E^j(\ell_{ej}^d, q_j^d, w_j^d) = 0$ for all non-negative $\ell_{ej}^d, q_j^d,$ and w_j^d, all $j \in J$). The rationale of this result being that if good X is not involved at all in the environmental externality, because the externality is earmarked to material, then its efficient allocation must be ruled by the same marginal condition as in case of the absence of any externality.

The insight that neither property rights regime places a binding constraint on the set of attainable allocations does not come as a surprise. In fact, such an equivalence result is obvious in the light of Coasean economics for all conceivable property rights regimes so long as property rights are exclusive and costlessly enforced. Institutions do not matter in such a world without transaction costs. The empirically important point is, of course, whether the property-rights regimes under scrutiny differ with respect to some procedural costs or information costs. A thorough discussion of this issue is beyond the scope of the present paper, however. But nonetheless we find it useful to show in the next section how the property rights regime is translated into a specific pattern of markets.

Proposition 1iii tells us that if material content matters in waste treatment ($E_q^j > 0$), then the efficient material content is smaller than in case of $E_q^j = 0$. Note that $E_q^j = 0$ for all $j \in J$, or $A = 0$ is not equivalent to the absence of an environmental externality. When combined with $E_w^j > 0$ it rather implies that both types of material have an identical impact on the emission of pollutants. If this is not the case, that is, if - as assumed here - (the explicitly modeled) material is particularly harmful or hazardous ($E_w^j > 0$ and $E_q^j > 0$), improving efficiency requires to diminish q, to reduce the material intensity, (m/ℓ_x), of producing good X and to increase the marginal rate of technical substitution, $(-X_m/X_\ell)$, in absolute value which, in turn, increases A for any given value of V_ℓ.

Proposition 1iv is somewhat technical in nature. It spells out some properties of the efficient Lagrange multipliers for convenience of later reference. These properties will turn out to have far reaching economic implications for the existence of efficient competitive equilibria in sections 3.2 and 3.3.

3. Markets for consumption waste treatment and landfilling

In this section we discuss various market concepts and their potential to decentralize the efficient allocation by prices. In the model (1) - (10) markets have to cope with two different public goods: pollution and material content. Since we wish to focus our attention on the latter, the allocation of emissions is assumed to be perfectly guided by Lindahl prices in all market procedures under investigation. Thus any (remaining) market failure is immediately identified as a failure of attaining the efficient material content. The basic issue will be whether the producers of good X, in designing their product, have appropriate regard for the impacts of material content in the post-consumption phase of the product's life. If the producer of good X does not receive any price signal concerning the material content, she only reacts to the given prices of labor, good X and material. As a consequence, her production plan satisfies $A = X_m - X_\ell / V_\ell = 0$ which implies an excessive material content in view of (13), $\sum_J E_q^J > 0$ and the proof of proposition 1iii. Hence the principal question is how effective market forces are in driving the material content down towards its efficient level.

3.1 Lindahl markets for material content

Since pollution suffered by consumers as well as the material content of good X are public goods, the concept of perfectly competitive markets for private goods must be appropriately extended to include public goods. In an idealized way this is done by introducing Lindahl markets with 'personalized prices' for the public goods (Foley 1970; Roberts 1974). Even though such artificial markets clearly do not emerge in the real world, the competitive equilibrium with Lindahl markets for material content and pollution (to be specified below) serves as an important benchmark helping to better understand how markets (or tax-subsidy schemes) direct the material flow in the absence of those Lindahl markets.

To be more specific, consider the price vectors[9]

$$p^L_{PP} := \left[p_\ell, p_x, p_m, p_w, p_f, \left(p^h_e\right), p_e, p_{qx}, \left(p^j_{qw}\right)\right] \text{ and } p^L_{HP} := \left[p^L_{PP}, \left(p^h_{qx}\right), \left(p^h_{qw}\right)\right]$$

for the PP rule and the HP rule, respectively, and define:

Prices p^L_{HP} [prices p^L_{PP}, respectively] *and the allocation resulting from solving [1] - [5] in the appendix for* p^L_{HP} [from solving [3] - [7] for p^L_{PP}] *constitute a* ***competitive equilibrium with Lindahl markets for material content*** *and pollution, if all constraints in (7) - (10) hold as equalities.*

The existence of such a competitive equilibrium with Lindahl markets obviously presupposes the existence of solutions to [1] - [7] in the appendix. Eichner and Pethig (1999a) show that a solution to [1] may fail to exist even if the function X is concave, but they also provide conditions under which [1] - [7] can be solved[10].

In case of the HP rule, there is a Lindahl market for pollution and there are two Lindahl markets for the material content of good X, one of them between firm X and the consumers and the other one between the consumers and the waste treatment firms. Firm X sells q^s_x to the households along with good X and the households resell the material content to the waste firms along with the consumption residuals. Since consumers have no preferences over q, they are indifferent with respect to its size so long as the prices, $\left(p^h_{qx}\right)$, at which consumers purchase the material content equal the sales prices, $\left(p^h_{qw}\right)$. This equality is, in fact, a necessary equilibrium condition, and, if it holds, the consumers' role regarding q is simply that of *neutral intermediators* between the producer's and the waste treatment firms' diverging evaluations of the material content.

The solution to the equations [1] - [5] (appendix) is summarized in the second column of table I. In case of the PP rule, the associated marginal conditions are the same as those in

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[9] For convenience of notation, we denote by $\left(p^h_e\right)$ the price vector $\left(p^1_e, \ldots, p^h_e, \ldots, p^h_e\right)$ etc.

[10] Eichner and Pethig (1999a) also demonstrate that similar existence issues emerge - and can be overcome by some classes of functions - in the context of the market concepts discussed in sections 3.2 and 3.3 below. In the present paper the Lagrangeans [1] - [15] in the appendix are assumed to have a solution in the relevant domain of prices.

column 2 (for the HP rule) with the modification that the equations[11] (I.2.2), (I.4.2) - (I.6.2), respectively, are replaced by[12] $-\left(U_x^h/U_\ell^h\right)=\tilde{p}_x$, $\left(\tilde{p}_x+\tilde{p}_w-\tilde{p}_{qx}q^*/x^*\right)X_\ell=\tilde{p}_\ell$, $\tilde{p}_m-\tilde{p}_{qx}/x^*=\left(\tilde{p}_x+\tilde{p}_w-\tilde{p}_{qx}q^*/x^*\right)X_m$ and $\tilde{p}_{qx}=\sum_j\tilde{p}_{qw}^j$.

Proposition 2 *(Efficient Lindahl markets)*:

(i) Under the households property rights rule, set $p_\ell^*\equiv 1$, $p_x^*=\mu_x$, $p_m^*=\mu_m$, $p_w^*=-\mu_w$, $p_f^*=-\mu_f$, $p_e^{h*}=-\mu_e^h$, $p_e^*=\sum_h p_e^{h*}=-\mu_e^j$, $p_{qx}^*=\sum_h p_{qx}^{h*}=\sum_j p_{qw}^{j*}=-\mu_q$, $p_{qw}^{j*}=-\sum_h\mu_{qw}^{hj}$ *and* $p_{qw}^{h*}=p_{qx}^{h*}=-\mu_{qx}^h$. *Then all markets clear and the pertinent allocation is Pareto efficient.*

(ii) Under the producers property rights rule, ignore the prices p_{qx}^h *and* p_{qw}^h *altogether, replace* p_x^* *by* $\tilde{p}_x=p_x^*-p_w^*$, *and set all other prices as in proposition 2i. Then all markets clear and the pertinent allocation is Pareto efficient.*

Observe that consumption waste is negatively priced ($p_w^*<0$ and $p_f^*<0$), and the market-clearing prices of pollution and material content are negative, too. With costless implementation of (7) the negative equilibrium prices for consumption waste do not come as a surprise in proposition 1. Usually, negative prices for consumption waste are called charges or fees. But the market connotation appears to be appropriate in the present context, since it has been demonstrated that a negative equilibrium price *does* emerge in competitive markets provided that the legal interdiction of 'free disposal' is effectively and costlessly enforced.

To see how the allocation of material content is driven by prices, consider the limiting case[13] $E_q^j=0$, all $j\in J$. Then all prices of q are zero and firm X chooses q - as in textbooks - by optimally adjusting to given factor and output prices. However, since with $E_q^j>0$, all $j\in J$, the waste treatment firms prefer a lower value of q, firm X has to pay for selling the material content while the (final) demanders of q, the waste treatment firms, incur 'negative costs' from purchasing the input q. It does not follow, however, that the waste treatment firms are interested in buying arbitrarily large amounts of q, since raising q increases their negatively priced output, e_j. Similarly, firm X is not interested in reducing q to arbitrarily

[11] Reference to an equation in a table is made by *(a.b.c)*, where *a* is the table, *b* is the row, and *c* is the column.
[12] Equation (I.3.2) has no equivalent under the PP rule.
[13] This specification of the functions E^j implies that both types of material exert the same detrimental effects on the environment, if landfilled.

small amounts (to avoid negative revenues from selling it) because the reduction in q distorts production and hence is costly.

Proposition 2 also establishes the equivalence (and hence the irrelevance) of the property rights regimes for the Lindahl market solution. Under the HP rule the consumers adopt the role of intermediators with respect to the trade of material content and consumption waste: they buy both goods from firm X (at negative prices) and resell them to the waste treatment firms. In case of the PP rule, the price $\tilde{p}_x$ already accounts for the costs of processing the consumption waste whereas under the HP rule consumers pay for these services themselves after having consumed good X. Clearly, $\tilde{p}_x$ is the price for the right to consume good X (leasing price) and $p_x^* = \tilde{p}_x + p_w^*$ is the price to acquire the property when purchasing good X.

3.2 Indirect markets for material content

Acknowledging that Lindahl markets for material content cannot be expected to emerge in the real world does not mean that agents are not able to somehow account for the material content of the consumption good and its residuals in their optimization calculus. Following the procedure suggested by Fullerton and Wu (1998) we now investigate a market model where agents actively express a demand for or a supply of material content - just as in the Lindahl economy of the previous section. But the personalized Lindahl prices for material content are replaced by the agents' indirect valuation of material content and/or of consumption waste through the prices of these commodities. Hence the *concept of indirect markets* exploits the fact that the material content is an 'intrinsic' attribute of good X and of consumption waste which are both marketed. It utilizes this complementarity for restoring efficiency in the absence of Lindahl markets by reflecting the negative value of increasing material content in the price for good X and in the price for consumption waste.

In their optimization calculus the agents are assumed to be aware that changes in material content have an impact on the price of consumption waste, p_w, and on the commodity price, p_x. In other words, they perceive of these prices as being a *function of the material content*, q, and take the functional relationship into consideration in their consumption or production decisions. Heuristically speaking, the Walrasian auctioneer now announces prices

$$p_{HP}^F := \left[p_\ell, p_m, p_f, \left(p_e^h\right), p_e, P^x(q), P^w(q)\right]$$

under the HP rule[14], where P^w and P^x are *price functions* taken as given by all agents. In other words, we have $p_x = P^x(q)$ for $q = q_x^s$ or $q = q_h^d$ and $p_w = P^w(q)$ for $q = q_h^s$ or $q = q_j^d$. With this concept of price functions the pertaining equilibrium definition is:

Prices p_{HP}^F and the allocation resulting from solving [4], [5] and [8] - [10] in the appendix A constitute a ***competitive equilibrium with indirect markets for material content****, if all constraints in (7) - (10) hold as equalities.*

Proposition 3 *(Competitive equilibrium with indirect markets for material content)*:

Consider the price vector p_{HP}^{F*} consisting of the prices p_ℓ^*, p_f^*, p_m^*, $\left(p_e^{h*}\right)$, and p_e^* from proposition 2i and of the price functions P^{x*} and P^{w*} satisfying $p_x^* = P^{x*}(q^*) = \mu_x$,

$$p_w^* = P^{w*}(q^*) = -\mu_w, \quad P_q^{w*}(q^*) = -\frac{\sum_j \mu_{qw}^{hj}}{w_h^*} = -\frac{\sum_h \mu_{qw}^{hj}}{w_j^*} \quad \text{and} \quad P_q^{x*}(q^*) = -\frac{\mu_{qx}^h}{x_h^*} = -\frac{\mu_q}{x^*}.$$

With this price vector p_{HP}^{F*} an efficient competitive equilibrium with indirect markets for material content is attained

- *if either $\#J = 1$ and $\#H = 1$*
- *or if $E^j(\ell_{ej}^d, q_j^d, w_j^d) = \tilde{E}^j(\ell_{ej}^d,\ q_j^d \cdot w_j^d)$ for all $j \in J$.*

Otherwise, the efficient allocation cannot be implemented as a competitive equilibrium with indirect markets for material content, in general.

To verify proposition 3 we compare the second and the third column in table I to find that a competitive equilibrium with indirect markets for material content implements the Pareto efficient allocation, characterized by the marginal conditions of the second column, if and only if

$$\frac{\mu_q}{x^*} = \frac{\mu_{qx}^h}{x_h^*} = \frac{\sum_j \hat{\mu}_{qw}^{hj}}{w_h^*} = \frac{\sum_h \hat{\mu}_{qw}^{hj}}{w_j^*} \qquad (\text{all } h \in H,\ \text{all } j \in J) \tag{17}$$

In view of (I.3.1) and (I.6.1) the equality signs in (17) hold, if $\#J = 1$ and $\#H = 1$. But they do not hold, in general, if $\#J > 1$, $\#H > 1$ and if for some $j \in J$ the function E^j does not take

[14] The subsequent analysis is restricted to the HP rule, because the extension to the PP rule is done exactly as shown in section 3.1. We keep listing the agents' optimization problems in appendix A for both types of property rights rules so that the corresponding results for the PP rule can be easily established.

the form $E^j = \tilde{E}^j$. Proposition 1iv also shows that if $E^j = \tilde{E}^j$ for all $j \in J$, then (17) is satisfied.

The remarkable message of proposition 3 is that the number of waste treatment firms matters. Since in the real world there are probably no economies with one waste treatment firm only (this assumption is usually made for heuristic reasons only), the market solution with indirect markets for material content fails to be efficient whenever $E^j \neq \tilde{E}^j$ for some $j \in J$. What the waste treatment technologies are like, is, of course, an empirical issue. But we mentioned in section 2 that $E^j\left(\ell_{ej}^d, q_j^d, w_j^d\right) = \breve{E}^j\left(\ell_{ej}^d, q_j^d \cdot w_j^d, q_j^d\right)$ with $\breve{E}_q^j < 0$ does not appear an implausible specification. Hence the market scheme with indirect markets for material content is hardly capable to implement an efficient allocation[15].

It is an appealing idea that the value of an attribute is reflected in the price of the commodity to which that attribute belongs to. The value of the attribute appears, in fact, as a mark-up to the commodity price. That mark-up must not be constant, and all agents involved in trading that commodity are required to express a demand or a supply for that attribute in addition to their demand or supply for the commodity. One and the same market price must equate demand and supply on the markets for two 'goods'. The conditions under which such a market concept works is an empirical issue that cannot be settled here. Ist functioning is likely to depend on the specificities of the waste under consideration and on institutional arrangements and their associated transaction costs.

3.3 Markets for embodied material

Suppose now, the value of material content is neither reflected in Lindahl markets nor captured in indirect markets for material content, but the value of q is common knowledge. It is, literally speaking, printed on each unit of good X (and is still readable when good X has been turned into consumption waste). In that case no agent other than the producer of good X is capable of optimizing with respect to the level of material content of good X. Since all agents but firm X take the level of material content as exogenously given, they exhibit a Nash-like behavior of optimally responding to the 'prevailing' level of q.

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[15] If $E^i \neq \tilde{E}^i$ for some $j \in J$, $\#H > 1$ and $\#J > 1$, it is an open question whether an equilibrium exists. The usual fixed point theorems cannot accommodate for the price functions which form a constitutive component of the concept of competitive equilibrium with indirect markets for material content.

In the absence of direct or indirect markets for material content it is conceivable that *markets for embodied material* emerge, where for any given material content, q, the material embodied in the quantity x of good X or in the quantity w of consumption waste is, respectively, $b = qx$ or $b = qw$. More specifically, when the agents trade the quantities x^s, x_h^d, w_h^s and w_j^d, the pertinent *embodied material* is

$$b_x^s := q \cdot x^s,\ b_h^d := q \cdot x_h^d,\ b_h^s := q \cdot w_h^s \text{ and } b_j^d := q \cdot w_j^d,$$

respectively. All this embodied material is supposed to be traded at a uniform price

Under the HP rule the prices $p^B := \left[p_\ell, p_x, p_m, p_w, p_f, \left(p_e^h\right), p_e, p_b\right]$ *and the allocation resulting from solving [4], [5] and [12] - [14] in the appendix constitute a* ***competitive equilibrium with markets for embodied material****, if all constraints (7), (8) and (10) hold as equalities.*

Proposition 4 *(Competitive equilibrium with markets for embodied material)*:

(i) The competitive equilibrium with markets for embodied material is inefficient.

(ii) The competitive equilibrium with markets for embodied material is inefficient, in general, if there are no markets for consumption waste ($\hat{p}_w \equiv 0$).

(iii) Consider the price vector $\hat{p}_{HP}^B$ *defined by the prices* $\hat{p}_\ell \equiv 1$, $\hat{p}_w \equiv 0$, $\hat{p}_m = \mu_m$, $\hat{p}_f = -\mu_f$, $\hat{p}_b = -\mu_w / q^*$, $\hat{p}_e = \sum_h \hat{p}_e^h = -\mu_e^j$, $\left(\hat{p}_e^h\right) = \left(-\mu_e^h\right)$, *and* $\hat{p}_x = \mu_x + \mu_w$. *With this price vector* $\hat{p}_{HP}^B$ *an efficient competitive equilibrium with indirect markets for material content is attained, if there are no markets for consumption waste* ($\hat{p}_w \equiv 0$), *if the functions* E^j *satisfy* $E^j(\ell_{ej}^d, q_j^d, w_j^d) = \tilde{E}^j(\ell_{ej}^d,\ q_j^d \cdot w_j^d)$ *for all* $j \in J$ *and if* $C(f^d) = 0$ *for all* $f^d \geq 0$.

Solving [4], [5] and [12] - [14] in the appendix yields column 4 in table I. There is no way to link the $\hat{p}'s$ from column 4 with the $\mu's$ from column 1 such that all equations pairwise coincide. This is still true when we set $\hat{p}_w \equiv 0$ in column 4 of table I unless the functions E^j take the form $\tilde{E}^j$ for all $j \in J$ and unless $C(f^d) = 0$ for all $f^d \geq 0$ (which implies $\hat{p}_f \equiv 0$). To see this observe that with $\hat{p}_f \equiv 0$ the prices $\hat{p}_{HP}^B$ as specified in proposition 4iii satisfy (17). Hence the proof is completed along the lines proposition 3 had been proved.

Propositions 4 establishes that markets for embodied material are efficient only if a number of qualifications are met that appear to be more restrictive than those needed to secure efficiency of indirect markets for material content (proposition 3). In both cases a basic efficiency condition of the equilibrium allocation is that the emissions are caused by q_j^d and w_j^d through the product $q_j^d \cdot w_j^d$ only, i.e. that the functions E^j take the form $\tilde{E}^j$ for all $j \in J$ (see propositions 3 and 4iii)[16]. This technological restriction somewhat limits the scope of both market scenarios.

The fact that the market for negatively priced embodied material ($\hat{p}_b < 0$) is required to *substitute* rather than to *complement* the markets for negatively priced consumption waste ($\hat{p}_w < 0$) is not restrictive in itself. But the consequence is that markets cannot handle the total waste to be landfilled anymore which causes inefficiency results unless landfilling is costless ($C(f^d) = 0$ for all $f^d \geq 0$). However, the empirical evidence shows that landfilling costs may be significant even for waste material that is not environmentally harmful which leads us to conclude (from proposition 3) that markets for embodied material can hardly be expected to be efficient.

Recall finally that both schemes differ considerably in their behavioral assumptions regarding the material content: while the indirect market approach considers material content as an action variable for all agents involved, the concept of markets for embodied material assumes that no agent except firm X optimizes over material content. In that respect the markets for embodied material appear to be more realistic as indirect markets for material content.

3.4 Markets for consumption waste (only)

We maintain the assumption from the previous section that firm X determines $q_x^s = q$ which, in turn, all other agents take as given. But we now proceed to study an economy where neither markets for material content nor markets for embodied material are active. There are, however, markets for consumption waste - unlike in propositions 4ii and 4iii (section 3.3), but like in the sections 3.1 and 3.2. A competitive equilibrium of the pertinent economy is characterized by the marginal conditions of column 4 in table I when $\hat{p}_b$ is set equal to zero. It is

[16] In contrast to the markets for embodied material the indirect markets for material content also work well in case of a single waste treatment firm and a single household. This difference is intriguing, but it is of no practical significance, in our view.

easy to see that the resultant conditions do not coincide with those in the first column of table I. Hence the missing markets for material content or embodied material render the equilibrium allocation *inefficient* - even though the Lindahl market for pollution is still active by assumption.

In what follows we aim at answering the question *how* the market allocation deviates from the efficient one. This is not an easy undertaking, because the pertinent partial derivatives of the functions $U^h, X, V, C,$ and E^j in column 2 and in (the modified) column 4 of table I are taken at different values of their respective arguments. Yet we are able to infer from the rows 4, 5 and 8 of the columns 2 and 4 that

$$X_m^M V_\ell^M = X_\ell^M \quad \text{and} \quad X_m^* V_\ell^* > X_\ell^*, \tag{18}$$

where the superscript M refers to the market allocation of (the modified) column 4 and the asterix to the efficient one in column 2. When the assumptions on technology are made slightly more restrictive we use (18) to show

Proposition 5 *(Inefficiencies, when markets for material content and embodied material are absent)*:

Consider the following simplifying assumptions:

(a) the technology for material extraction is linear: $V(\ell_v) = \bar{v} \cdot \ell_v$;

(b) the production function for good X is linear homogeneous;

(c) the utility functions U^h *are such that the price elasticity of demand for good X is not positive in its relevant domain;*

(d) there is no waste treatment and no landfilling cost: $E_\ell^j = 0$ *for all* $\ell_{ej}^d \geq 0$ *and all* $j \in J$ *and* $C_f = 0$ *for all* $\ell_f^d \geq 0$.

If the conditions (a) - (d) hold, the competitive equilibrium without markets for material content and without markets for embodied material is characterized by an inefficiently high material content and an excessive use of material in the production of good X.

To see that the material content is too high, recall from the proof of proposition 1iii that for X linear homogeneous and V linear it follows that $k^* > k^M$ and $q^M > q^*$. Since, by defini-

tion, $m^M := q^M x^M$ and $m^* := q^* x^*$ we conclude that $x^* \leq x^M$ is sufficient for $m^M > m^*$. To show that $x^* \leq x^M$ holds, we first make use of $q = m/x$ and $m = \ell_x / k$ to turn *1/q = F(k)* into

$$x = \frac{F(k)}{k} \cdot \ell_x \tag{19}$$

Since k is constant under either regime ($k = k^*$ or $k = k^M$), (19) means that, essentially, good X is produced with labor only according to a fixed-coefficient technology. Moreover, labor has no other use than purchasing good X ($E_\ell^j = 0$ for all $\ell_{ej} \geq 0$) so that (19) can be considered as an individual consumer's budget line (after having replaced ℓ_x by ℓ_h^s in (19)). Labor is more productive in the market economy than in the efficient allocation, because $F(k^M)/k^M > F(k^*)/k^*$. It follows that $x^* \leq x^M$, unless X is a Giffen good.

The obvious message of proposition 5 is that in a competitive economy where neither markets for material content nor those for embodied material exist the throughput of environmentally detrimental material is excessive. This conclusion is derived under a few simplifying assumptions to avoid tedious calculations, but our conjecture is that the result is fairly robust under less restrictive conditions. It is important to understand that the use of material is not excessive here because emission control is inadequate - as in conventional environmental management analysis. In fact, in the present model consumption waste *is* negatively priced and a Lindahl market for pollution *does* exists which would take perfect care of the externality in models where product design does not matter. Hence the inefficiency revealed in proposition 5 stems from inadequate product design: firm X simply chooses the product design (i.e. the material content) in an effort to minimize (input) costs without paying attention to the post-consumption impact of this design.

Recall that in the market models studied in sections 3.3 and 3.4 the material content was assumed to be exogenous to all agents other than firm X. In such a setting the waste treatment firms respond to exogenous changes in the material content they process. In fact, it is easy to derive a money measure of how they value an exogenous change in material content[17]. But the values derived in this way do not provide a foundation for the price functions employed in

[17] The far more complex case of measuring the value to consumers of an incremental change in the supply of a public good that is (weakly) complementary to a private marketed consumption good has received considerable attention in the literature. See Mäler (1971), Bradford and Hildebrandt (1977) and Willig (1978).

section 3.2, because these price functions must hold for all agents on both sides of the market. Moreover, in the market procedure of section 3.2 the waste treatment firms take the price function $P^w\left(q_j^d\right)$ as given and actively express a demand for material content, q_j^d, all $j \in J$.

4. Concluding remarks

The preceding analysis reexamined the issue of allocating a natural resource (called *material*) that is first extracted, then used for producing a consumption good, and that may cause environmental damage when it is finally landfilled. Waste treatment is considered, in addition, as an option to reduce the impact of waste material on pollution.

The distinctive feature of our theoretical approach is that the material is modeled as being *embodied* in the output of a consumption good thus constituting an important aspect of (green) product design. The material content per unit of output is the decisive economic variable, a public good (!), which cannot be efficiently allocated unless the marginal willingness-to-pay of both the producers who design the product and the waste treatment firms (here as custodians of consumers preferences) are adequately reflected in the allocation procedure. The central message of the paper is that even though efficient Lindahl markets are assumed to be 'installed' to control pollution, the efficient level of material content is unlikely to be brought about by market forces. We found that efficiency can be achieved under some fairly restrictive technological conditions and depending on which types of markets emerge. Promising candidates for an efficient market scheme turned out to be markets for embodied material as well as indirect markets for material content. But even if such markets should be found to be active in the real world which is an open question, in our view, efficiency is not achieved unless the waste treatment technologies exhibit specific properties which we do not regard as plausible.

To keep complexity tractable the present paper refrained from considering recycling which is, of course, an emirically important activity to reduce both environmental damage and the net material consumption. In a similar way as in case of waste treatment the productivity of recycling is likely to depend on the material content of consumption waste used as recycling input. To reach efficiency in an economy with waste treatment and recycling, market prices would have to 'coordinate' the 'diverging demands' on product design of the producers of the consumption good, the recycling firms and the waste treatment firms. Dispensing with the dis-

aggregate approach (of the present paper) for analytical relief, 'Eichner and Pethig (1999b) elaborate on that hybrid model.

Our theoretical analysis raises the important and challenging question what the empirical relevance is of the various market schemes studied above. Most likely, the market procedures emerging in the real world depend on the specificities of the solid waste problem at hand. Unfortunately, we are not aware of empirical investigations along the lines of our theoretical framework that would provide clear-cut evidence about which markets and which optimizing individual behavior can be expected to emerge in the real world. But, as mentioned in the introduction, it is clearly important to know which types of markets can be expected in any given product-related solid waste allocation problem, because that information would be needed to design the appropriate institutional arrangement for solid waste management which should be one that improves allocative efficiency where markets fail, but that does not intervene where markets operate reasonably well.

To the extend that markets fail, corrective environmental and resource management is called for. In the present paper we refrained from jumping to policy conclusions as is done in much of the related literature. We focused our attention, instead, on the capacity of markets to bring about allocative efficiency which is not to say that our theoretical framework does not lend itself well to study policy issues. These are, in fact, dealt with by Eichner and Pethig (1999b) in a systematic way. An obvious link to the policy dimension - but only one out of several - to be mentioned here in passing are those markets in the above analysis whose equilibrium prices are negative. These are likely candidates for market failure in which case government might want to intervene simply by substituting the (non-existing) market prices by taxes or subsidies. This straightforward procedure is not always practical and/or incentive compatible, however, so that one should also investigate less obvious efficiency restoring tax-subsidy schemes whose rationale depends, among other things, on which types of markets are active.

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Appendix

A1: Economy (1) - (10) with Lindahl markets for material content

$$\hat{L}^H = U^h\left(e_h^d, \ell_h^s, x_h^d\right) + \gamma_b\left[p_\ell \ell_h^s + p_{qw}^h q_h^s + p_w w_h^s + \tau - p_x x_h^d - p_{qx}^h q_h^d - p_e^h e_h^d\right] +$$

$$+\gamma_w(w_h^s - x_h^d) + \gamma_q(q_h^d - q_h^s) \qquad [1]$$

$$\hat{L}^X = p_x x^s + p_{qx} q_x^s - p_\ell \ell_x^d - p_m m^d + \beta_x\left[X\left(\ell_x^d, m^d\right) - x^s\right] + \beta_q\left(q_x^s - m^d / x^s\right) \qquad [2]$$

$$L^W = p_e e_j^s + p_f f_j^s - p_\ell \ell_{ej}^d - p_w w_j^d - p_{qw}^j q_j^d + \beta_{ej}\left[e_j^s - E^j\left(\ell_{ej}^d, q_j^d, w_j^d\right)\right] + \beta_{fw}\left(f_j^s - w_j^d\right) \qquad [3]$$

$$L^V = p_m v^s - p_\ell \ell_v^d + \beta_v\left[V\left(\ell_v^d\right) - v^s\right] \qquad [4]$$

$$L^F = -p_f f^d - p_\ell C(f^d) \qquad [5]$$

$$\tilde{L}^H = U^h\left(e_h^d, \ell_h^s, x_h^d\right) + \gamma_b\left[p_\ell \ell_h^s + \tau - p_x x_h^d - p_e^h e_h^d\right] \qquad [6]$$

$$\tilde{L}^X = p_x x^s + p_{qx} q_x^s + p_w w^s - p_\ell \ell_x^d - p_m m^d + \beta_x\left[X\left(\ell_x^d, m^d\right) - x^s\right]$$

$$+\beta_q\left(q_x^s - m^d / x^s\right) + \beta_{wx}\left(w^s - x^s\right) \qquad [7]$$

In [1] τ are lumpsum transfers of profit shares to the households. The notation in [1] and in all other Lagrangeans listed here strictly follows the usual convention that revenues or incomes are received from sales (price times quantity sold) and costs or expenditures are incurred from purchases (price times quantity bought) independent of whether the associated prices are positive or negative. The equations [1] - [5] refer to the market economy under the HP rule and the equations [3] - [7] refer to the market economy under the PP rule.

A2: Economy (1) - (10) with indirect markets for material content

$$\hat{L}^H = U^h\left(e_h^d, \ell_h^s, x_h^d\right) + \gamma_b\left[p_\ell \ell_h^s + \tau + P^w\left(q_h^s\right) w_h^s + \tau - P^x\left(q_h^d\right) x_h^d - p_e^h e_h^d\right] + \gamma_w\left(w_h^s - x_h^d\right)$$

$$+\gamma_q(q_h^d - q_h^s) \qquad [8]$$

$$\hat{L}^X = P^x\left(q_x^s\right) x^s - p_\ell \ell_x^d - p_m m^d + \beta_x\left[X\left(\ell_x^d, m^d\right) - x^s\right] + \beta_q\left(q_x^s - m^d / x^s\right) \qquad [9]$$

$$\hat{L}^W = p_e e_j^s + p_f f_j^s - p_\ell \ell_{ej}^d - P^w\left(q_j^d\right) w_j^d + \beta_{ej}\left[e_j^s - E^j\left(\ell_{ej}^d, q_j^d, w_j^d\right)\right] + \beta_{fw}\left(f_j^s - w_j^d\right) \qquad [10]$$

$$\tilde{L}^X = p_x x^s + P^w\left(q_x^s\right)w^s - p_\ell \ell_x^d - p_m m^d + \beta_x\left[X\left(\ell_x^d, m^d\right) - x^s\right]$$

$$+\beta_q\left(q_x^s - m^d / x^s\right) + \beta_{wx}\left(w^s - x^s\right) \qquad [11]$$

The equations [4], [5] and [8] - [10] refer to the market economy under the HP rule and the equations [4] - [6], [10] and [11] refer to the market economy under the PP rule.

A3: Economy (1) - (10) with markets for embodied material

$$\hat{L}^H = U^h\left(e_h^d, \ell_h^s, x_h^d\right) + \gamma_b\left[p_\ell \ell_h^s + \tau + p_w w_h^s + p_b b_h^s + \tau - p_x x_h^d - p_b b_h^d - p_e^h e_h^d\right] +$$

$$+\gamma_w(w_h^s - x_h^d) + \gamma_d(qx_h^d - b_h^d) + \gamma_s(b_h^s - qw_h^s) \qquad [12]$$

$$\hat{L}^X = p_x x^s + p_b b_x^s - p_\ell \ell_x^d - p_m m^d + \beta_x\left[X\left(\ell_x^d, m^d\right) - x^s\right] + \beta_q\left(q - m^d/x^s\right) + \beta_b\left(b_x^s - qx^s\right) \qquad [13]$$

$$L^W = p_e e_j^s + p_j f_j^s - p_\ell \ell_{ej}^d - p_w w_j^d - p_b b_j^d + \beta_{ej}\left[e_j^s - E^j\left(\ell_{ej}^d, q, w_j^d\right)\right] + \beta_b\left(b_j^d - qw_j^d\right)$$

$$+\beta_{fw}\left(f_j^s - w_j^d\right) \qquad [14]$$

$$\tilde{L}^X = p_x x^s + p_w w^s + p_b b_x^s - p_\ell \ell_x^d - p_m m^d + \beta_x\left[X\left(\ell_x^d, m^d\right) - x^s\right] + \beta_q\left(q - m^d/x^s\right)$$

$$+\beta_b\left(b_x^s - qx^s\right) + \beta_{wx}\left(w^s - x^s\right) \qquad [15]$$

The equations [4], [5] and [12] - [14] refer to the market economy under the HP rule and the equations [4] - [6], [14] and [15] refer to the market economy under the PP rule.

B: Proof of proposition 1

Equation (12) is straightforward from the equations[18] (I.1.1), (I.10.1) and (I.12.1). To derive equation (13) we first sum (I.11.1) over *j*. Then we substitute μ_e^j by (I.10.1) and use (I.3.1) and (I.6.1) to replace $\sum_j \sum_h \mu_{qw}^{hj}$ by μ_q. Hence we obtain $\sum_j (E_q^j / E_\ell^j) = -\mu_q$, and therefore it remains only to show that $x^* A / X_\ell = \mu_q$. From (I.4.1) we know that $\mu_x = \frac{1}{X_\ell} - \frac{\mu_q q^*}{x^*}$,

[18] Reference to equations in a table is made by (a.b.c), where a is the table, b is the row, and c is the column.

and the equations (I.4.1) and (I.5.1) yield $\frac{\mu_q}{x^* X_m} = -\frac{\mu_m}{X_m} + \frac{1}{X_\ell}$. Under consideration of equation (I.8.1) this equation can be rearranged to read

$$\mu_q = x^*\left(\frac{X_m}{X_\ell} - \frac{1}{V_\ell}\right) = \frac{x^*}{X_\ell}\left(X_m - \frac{X_\ell}{V_\ell}\right) = \frac{x^* \cdot A}{X_\ell}. \qquad [16]$$

In view of [16], $A > 0$ is implied by $\mu_q > 0$. To establish equation (14) we substitute μ_x and μ_w in (I.2.1). Clearly, $\mu_w = -E_w^j / E_\ell^j + C_f$ follows from (I.7.1), (I.9.1), (I.10.1).

As shown above, $\mu_x = \frac{1}{X_\ell} - \frac{\mu_q q^*}{x^*}$. With μ_q from [16] the equation (14) follows after some rearrangement of terms.

By definition of $\tilde{E}^j$ we obtain $E_q^j = \tilde{E}_b^j w_j^*$ and $E_w^j = \tilde{E}_b^j q^*$, where $\tilde{E}_b^j := \partial \tilde{E}^j / \partial (q_j^d w_j^d)$. Inserting A from (13) into (14) and using the partial derivatives of $\tilde{E}^j$ leads to

$$-\frac{U_x^h}{U_\ell^h} = \frac{1}{X_\ell} + \frac{q^*}{x^*}\left[\sum_j \left(\frac{\tilde{E}_b^j}{\tilde{E}_\ell^j} w_j^*\right) - \frac{\tilde{E}_b^j}{\tilde{E}_\ell^j} x^*\right] + C_f \qquad [17]$$

From (I.10.1) we know $\tilde{E}_\ell^j = \tilde{E}_\ell$ for all j and (I.9.1) together with (I.12.1) ensures $\tilde{E}_b^j = \tilde{E}_b$ for all j. Then factoring out $\tilde{E}_\ell$ and $\tilde{E}_b$ on the RHS of [17] and checking that $\sum_j w_j^* = x^*$ establishes equation (14').

The above arguments referred to the Lagrangean (11) and the associated FOCs in column 1 of table I, hence to the HP rule. The Lagrangean associated to the PP rule is obtained from (11) as follows: the terms $\sum_h \lambda_w^h \left(w_h^s - x_h^d\right)$ and $\sum_h \left[\lambda_h \left(q_h^s - q_h^d\right) + \lambda_{qx}^h \left(q_h^d - q_x^s\right)\right]$ are deleted and the terms $\lambda_w \left(\sum_j w_j^d - \sum_h w_h^s\right)$ and $\sum_h \sum_j \lambda_{qw}^{hj} \left(q_j^d - q_h^s\right)$ are replaced by $\lambda_w \left(\sum_j w_j^d - x^s\right)$ and $\sum_j \lambda_{qw}^j \left(q_j^d - q_x^s\right)$, respectively. As a consequence, column 1 of table I is then modified as follows: (I.3.1) as well as μ_w in (I.2.1) is deleted; $(\mu_x + \mu_q q^* / x^*)$ in (I.4.1) and (I.5.1) is replaced by $(\mu_x + \mu_q q^* / x^* - \mu_w)$; $\sum_h \mu_{qw}^{hj}$ is replaced by μ_{qw}^j in (I.11.1) and $\sum_h \mu_{qx}^h$ by $\sum_j \mu_{qw}^j$ in (I.6.1). The proof of the efficient allocation properties of the PP rule then follows along the lines of the HP rule proof.

To show proposition 1iii, observe that in view of (13) the term A attains the value $A = A^o := X_m^o - X_\ell^o / V_\ell^o = 0$ for $\sum_j E_q^j = 0$ and the term $A = A^* := X_m^* - X_\ell^* / V_\ell^* > 0$ for $\sum_j E_q^j > 0$. Since proposition 1iii presupposes that the function X is linear homogenous and the function V is linear we clearly have $V_\ell^* = V_\ell^o$, and there is a function F, strictly concave and increasing, such that $1/q = F(k)$ where $k := \ell_x / m$. Moreover, $X_\ell = F_k$ is strictly decreasing and X_m is strictly increasing in k. Hence it follows from $A^o < A^*$ that $X_m^o < X_m^*$ and $X_\ell^* < X_\ell^o$. Therefore $k^* > k^o$ and $q^o > q^*$.

We now proceed to prove proposition 1iv. Observe first that in the solution to (11) the $\bar{h} \times \bar{j}$ multipliers μ_{qw}^{hj} are underdetermined, since the first-order conditions of the first column in table I constrain these multipliers by $\bar{j}$ equations only. To exploit this underdetermination (for later use) define the $\bar{h} \times \bar{j}$ matrix $[\hat{\mu}_{qw}^{hj}]$ by its generic element $\hat{\mu}_{qw}^{hj} := c_{qw}^{hj} \cdot x_h^*$ such that the coefficients c_{qw}^{hj} satisfy

$$\sum_j c_{qw}^{hj} = c := \frac{\mu_q}{x^*} \qquad (\text{all } h \in H) \qquad [18]$$

$$\text{and } \sum_h c_{qw}^{hj} \cdot x_h^* = c = E_q^j \sum_h \frac{U_e^h}{U_\ell^h} \qquad (\text{all } j \in J) \qquad [19]$$

The $\bar{j}$ equations [19] see to it that $[\hat{\mu}_{qw}^{hj}]$ satisfies $\sum_h \hat{\mu}_{qw}^{hj} = E_q^j \sum_h \frac{U_e^h}{U_\ell^h}$, and the $\bar{h}$ additional equations [18] do not overdetermine the Lagrange multipliers $\hat{\mu}_{qw}^{hj}$, because for any $\bar{h} \geq 2$ and $\bar{j} \geq 2$ it is true that $\bar{h} \times \bar{j}$, the total number of variables, is not smaller than $\bar{h} + \bar{j}$, the total number of equations in [18] and [19]. It is straightforward that [18] implies $\sum_j \hat{\mu}_{qw}^{hj} = c x_h^*$ for all $j \in J$. Hence (15) follows from (I.3.1) and $w_h^* = x_h^*$. Combining (I.9.1) and (I.11.1) leads to

$$\sum_h \hat{\mu}_{qw}^{hj} = (\mu_w - \mu_f) \frac{E_q^j}{E_w^j}. \qquad [20]$$

The partial derivatives of $\tilde{E}^j$ imply $E_q^j / E_w^j = w_j^* / q^*$ which yields immediately the first equality of (16) when combined with [20]. Now we rewrite the first equality of (16) as

$w_j^* \dfrac{\mu_w - \mu_f}{q^*} = \sum_h \hat{\mu}_{qw}^{hj}$ and take the sum over all j to obtain $\dfrac{\mu_w - \mu_f}{q^*} \sum_j w_j^* = \sum_j \sum_h \hat{\mu}_{qw}^{hj}$.

This equation clearly yields the second equality sign in (16) when we account for $\sum_j w_j^* = x^*$ and $\sum_j \sum_h \hat{\mu}_{qw}^{hj} = \mu_q$.

To show that (16) does not hold, in general, when $E^j \neq \tilde{E}^j$, consider the class of functions $\breve{E}^j$ specified by $\breve{E}^j(\ell_{ej}^d, q_j^d \cdot w_j^d, q_j^d)$. We define $\breve{E}_b^j := \partial \breve{E}^j / \partial(q_j^d \cdot w_j^d)$ and obtain the derivatives $E_q^j = \breve{E}_b^j \cdot w_j^* + \breve{E}_q^j$ and $E_w^j = \breve{E}_b^j \cdot q^*$ which turn [21] into

$$\sum_h \hat{\mu}_{qw}^{hj} = \frac{(\mu_w - \mu_f)[w_j^* + (\breve{E}_q^j / \breve{E}_b^j)]}{q^*} \quad \text{or} \quad \frac{\sum_h \hat{\mu}_{qw}^{hj}}{w_j^*} = \frac{\mu_w - \mu_f}{q^*} + \frac{(\mu_w - \mu_f)\breve{E}_q^j}{w_j^* q^* \breve{E}_b^j}.$$

The last equation deviates from (16) whenever $\breve{E}_q^j \neq 0$ even if the functions $\breve{E}^j$ are the same for all $j \in J$.□

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