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AN ENVIRONMENTAL AND ECONOMIC ANALYSIS

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Abstract:

In recent years the amount of waste generated by Danish firms has increased significantly.

In the present analysis we use the decomposition analysis, which has been widely used in the energy economics literature to explain the mechanisms influencing energy consumption and CO_2 emissions. In this paper the methodology is transferred to the topic of waste generation and is used to analyse why the amount of business waste is increasing. The empirical application is related to data for the volumes of waste generated in the Danish economy for the main sectors as well as the manufacturing sector covering the time span 1994-2005 has been included. By means of the Log-Mean Divisia Index Method (LMDI) an algebraic decomposition of the data for the waste amounts generated is performed. This methodology separates the increases in waste amounts into effects related to economic activity, industrial structure and waste intensity, respectively. The waste intensities are defined as the ratio between the waste amounts and the production in value added terms in the respective sectors and industries of the economy. The results indicate that the intensity effect is the main contributor to the increasing amounts of waste generated in Denmark followed by the activity effect. The results also indicate that the structural effect has a relatively small influence.

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1. Introduction

The generation of solid business waste is commonly claimed to be closely related to economic activity and thus the level of production in the different sectors and industries of the economy. Exactly how economic growth patterns, structural shifts concerning the sectors of the economy and the development in waste intensities interact to the observed total sum of waste is largely unknown, but will be the topic addressed in this paper dealing with a decomposition methodology for waste generation.

In Europe and the rest of the developed world some of the negative consequences of the urbanization and the industrial growth can be seen in the continued growth in the volumes of waste each country generates. Furthermore, although the service sector has grown relatively fast compared to e.g. the manufacturing sector, which generally produce relatively larger amounts of waste, the structural shifts of the economy do not seem to hinder continued high growth rates of waste generation. Presently, the disposal of waste is also an important environmental problem in Denmark as well as in the rest of the western world. Every year Denmark generates more than 12 million tonnes of waste, more than 200,000 tons per inhabitant and it is expected that the total volume of waste will increase by two-digit percentage growth rates in the coming decades, Andersen and Larsen (2007). Likewise, the waste problem is assumed to be of increasing importance internationally as expressed by e.g. the international waste agreements including the USA and OECD, and also in relation to the EU where the European parliament will be negotiating a new waste legislation in 2008.

Traditionally it is assumed that changes in real GDP causes changes in the volumes of waste a country generates – of course among other factors such as urbanization – and a constant ratio between production and waste generation is often assumed. If the latter is true it has important policy implications because this means that an increase in GDP will also translate into an increase in waste accumulation. Up until now no empirical study has been composed to test whether or not this assumption is reasonable.

Additionally, the structural composition of the economy with respect to the relative size of the sectors, i.e. agriculture, manufacturing industries, the service sector etc, will also influence the overall volumes of waste generated as well as the 'waste intensities' of the respective economic activities. The latter concept, 'waste intensity', is crucial for analysis of the involved mechanisms and is defined here as the ratio between waste (in quantity terms) and production (e.g. real GDP) in the respective sectors or industries. All materials that enter the production process, either as raw materials or as intermediates, end up as either produced goods or residuals, e.g. waste or pollutants, expressed as a trade-off between the quantity of produced goods and the generation of waste. This trade-off is reflected in the waste intensity, and it is revealed that the waste intensity is not a constant term. We can think of a number of variables that influence the waste intensity - one of these is relative changes in the factor input prices and another is technological change. Through technological change it is possible to increase the number of units produced, while the volume of generated waste remains unchanged. This reflects a more efficient use of material input, reducing the ratio between waste and production, i.e. the waste intensity, but the present decomposition analysis will reveal that this process has not taken place. We show that there is not a constant relationship between firm's productivity and waste generation.

The purpose of the present analysis is to address this issue by the use of formal decomposition methodologies and to the best of our knowledge there are no previous contributions concerning these methodologies in the context of waste generation. The opportunity to do arises from the unique Danish data situation that ensures diversified temporal and sectoral waste data. In the energy economics literature several methodologies have been applied in recent years when decomposing e.g. total energy consumption into effects related to income and structural shifts among the respective fuels used and finally effects related to energy intensity developments, see e.g. Ang & Liu (2003, 2007) and Ang (2004) for recent expositions of the topic in relation to energy. In the case of decomposing the growth in waste volumes a similar methodology can be applied with a small twist of the concept as 'waste' is a resultant output from production – whereas the analysis in the

energy economics case is related to factor inputs, e.g. the respective fuels. Technically, the decomposition method can be applied directly to any area within environmental economics – in the present case waste generation – and assuming the sufficient data are available, an empirical application is straightforward.

From a policy point of view it is important to have knowledge about how to deal most efficiently with the growing volumes of waste, and in this connection a needed or useful analysis will address which factors 'cause' the waste generation and thereby contribute to a serious environmental problem. In line with this purpose, the topic analyzed in the present paper is how to decompose the increasing volumes of waste into effects related to economic activity (measured as real GDP), structural shifts in the economy and finally, the effects from shifts in waste intensities where the empirical part of the analysis is an application to waste data from the Danish economy covering the period 1994-2005. The policy implications of this are notable both in a Danish as well an in an international context as e.g. a 'waste tax' might have positive influence on waste intensities – and thus lower the total waste generation - but will probably be much less effective in case the increasing waste volumes are caused by activity or structural effects and are not due to increasing waste intensities. The paper is organized as follows. In part two the decomposition techniques are discussed in relation to an application concerning environmental (waste) economics and the Log-Mean Divisia Index method (LMDI) is selected as being a suitable technique – with a formal exposition in the Appendix. The empirical application takes place in part three and part four concerning the main sectors of the Danish economy, including a detailed analysis of the manufacturing sector. Part five concludes the paper.

2. Decomposition methodologies

Index decomposition analysis is by now a widely accepted analytical tool for policymaking on national energy and environmental issues, cf. Ang (2004) and Fan et al. (2007). The method first appeared in the beginning of the 1970's and since then the decomposition methodology has become a useful and popular tool not only used in industrial energy demand analysis but also in energy and environmental analysis in general. This can be

deduced from the number of studies which applies the method and a survey article on the subject, Ang and Zhang (2000), showed that more than 100 case studies applying decomposition analysis had been published at that time; many more have followed since then. The number of available articles clearly shows that decomposition analysis is widely accepted and one of the most applied approaches for studies of energy and CO_2 -emission topics.

There are, however, a wide range of other methods available for analyzing the breakdown of the changes in any environmental emission accumulation into explanatory factors, for example the econometric regression as used in Andersen and Larsen (2007). Another example is the macroeconomic method used by Bruvoll and Ibenholt (1997), but this method is mostly used to forecast future waste generation. There are a number of different decomposition analysis approaches available in the economic literature, where most of these decomposition studies of energy use and CO_2 -emissions apply either the Laspeyres or the Divisia index methodology, cf. Ang and Zhang (2000) and Sun (1998). The main difference between the Laspeyres and Divisia index methods build upon the choice of weights – with the Laspeyres index using the base year weights. In the present analysis the so-called Log-Mean Divisia Index method (LMDI) is applied. This method is linked to the Divisia index and is calculated as a weighted sum of logarithmic growth rates and the weights are the components' share in total value and hence, the method is quite different from the methods linked to the Laspeyres index based on the well-known concept of percentage change and base year weights. The building block of methods linked to the Divisia index is based on the concept of logarithmic change, where Törnqvist et al. (1985) presented the merit of using the log change and pointed out that it is the only symmetric and additive indicator of relative change, whereas the ordinary percentages are asymmetric and non-additive.

In spite of this there is no overall consensus among researchers and analysts as to which is the optimum decomposition method. The Laspeyres method is straightforward and easy to apply, but e.g. the LMDI version of the Divisia methodology is a more preferred method

due to the theoretical foundation, adaptability and interpretation of results, as well as other desirable properties in the context of decomposition analysis where the method gives a so-called perfect and complete decomposition, leaving no unexplained residual terms as in some of the alternative (Laspeyres) methods. Another advantage of the method is that it gives accurate estimates even for really small changes in the respective variables and is a very good approximation for short-term changes and the method is also able to handle cases with zero values.

In the present analysis the LMDI methodology, cf. Ang (2005), will be applied to the decomposition of effects related to the generation of waste. The aggregate waste production in the economy is the sum of waste from n different sectors (e.g. manufacturing, construction, services, etc.) where the waste generation is measured in tonnes and data available for some time periods. Assuming a multiplicative decomposition is appropriate, the total waste generation in time period t (W, time period suppressed in the notation) can be split into three components:

$$W = \sum_i W_i = \sum_i Y \frac{Y_i}{Y} \frac{W_i}{Y_i} = \sum_i Y S_i I_i \tag{1}$$

W_i: Volume of waste generated in industry i in period t (measured in tonnes)
Y_i: GDP of sector i in period t (measured in constant prices)
S_i: the share of sector i of the total economy (Y) in period t (i.e. the structural component)
I_i: the waste intensity in sector i in period t; $I_i = W_i/Y_i$ (i.e. the intensity component)

The aggregate decomposition analysis thus assumes that the change in the total generation of waste (W) is a result of the contributions from changes in the overall economic activity as measured by GDP, structural effects and finally effects from changes in sector 'waste intensities'. Decomposing multiplicatively the total *change* in waste generation (C_{tot}) from period 0 to period T into an activity effect (C_{act}), a structural effect (C_{str}) and an intensity effect (C_{int}) is given by (2):

$$C_{tot} = W_T/W_0 = C_{act}C_{str}C_{int} \tag{2}$$

Applying the LMDI methodology, see the Appendix for a full derivation of the expressions, the before-mentioned three effects are calculated from (3), (4) and (5) using the logarithmic weights for the respective effects:

$$C_{act} = \exp\left(\sum_{i=1}^{n} \frac{(W_{iT} - W_{i0})/(\ln W_{iT} - \ln W_{i0})}{(W_T - W_0)/(\ln W_T - \ln W_0)} \ln\left(\frac{Y_T}{Y_0} \right) \right) \tag{3}$$

$$C_{str} = \exp\left(\sum_{i=1}^{n} \frac{(W_{iT} - W_{i0})/(\ln W_{iT} - \ln W_{i0})}{(W_T - W_0)/(\ln W_T - \ln W_0)} \ln\left(\frac{S_{iT}}{S_{i0}} \right) \right) \tag{4}$$

$$C_{int} = \exp\left(\sum_{i=1}^{n} \frac{(W_{iT} - W_{i0})/(\ln W_{iT} - \ln W_{i0})}{(W_T - W_0)/(\ln W_T - \ln W_0)} \ln\left(\frac{I_{iT}}{I_{i0}} \right) \right) \tag{5}$$

Assuming a sufficient data set for production (Y) and waste amounts (W) of the respective sectors of the economy is available, these formulas are straightforwardly applied in relation to calculating the respective components – or 'causes' – of waste generation. The application studies are tentatively presented in the next two sections, one that covers the main sectors of the Danish economy and a section which covers the manufacturing sector in depth.

3. Decomposing waste generation in the Danish economy

The data spanning the time period 1994-2005 used in the empirical application were taken from Danish government statistics. The dataset combines detailed national accounts data with information that covers the quantity of waste generated in the Danish economy. Data regarding GDP were extracted from Statistics Denmark and the information on the

production of waste was extracted from the ISAG database which is the official Danish waste database maintained by the Danish Environmental Protection Agency (The Danish Ministry of the Environment). Waste data for a few aggregated main sectors of the economy are available from 1994, but detailed industry-data are only available from 2001, and in both cases the most recent data available is from 2005.

Nonetheless, there are some limitations in the waste data that should be accounted for. The data in the analysis from the ISAG database was established to provide reliable data on Danish waste disposal and the database builds upon statutory reports from the industry, waste handling facilities and the municipalities. Even though the Danish Environmental Protection Agency carries out thorough quality control of the reported data they are still encumbered with considerable uncertainty, and additionally, the waste statistics do not pick up all information concerning the volumes of waste generated – and disposed of, legally or illegally - in the economy. Hence, there might be a bias in the data and in the subsequent empirical analysis as not all sectors and industries of the economy are equally obliged to inform the authorities about the waste generation. For three main sectors of the Danish economy figure 1 presents indices of the development in waste generation.

Figure 1. Waste generation and GDP, Denmark 1994-2005 (Indices, 1994=100).
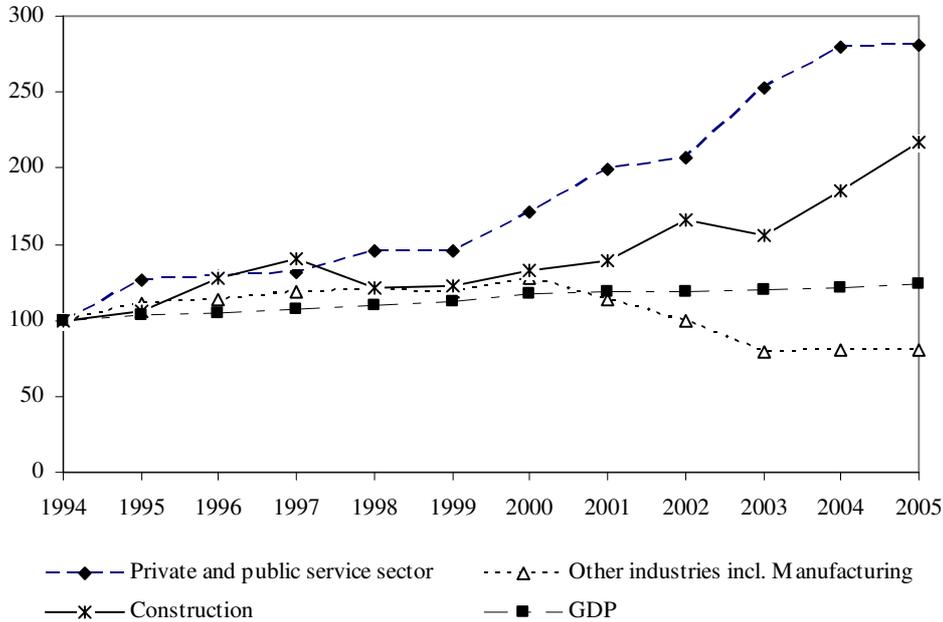
Note: The waste volumes are measured in tonnes, and converted to indices in the graph. GDP is measured at factor costs and in constant prices.
Sources: The ISAG database (the Danish EPA); The Statistical Database, National Accounts, Statistics Denmark.

The level of waste generation in Denmark for the three main sectors exhibited in figure 1 was 5.4 million tonnes in 1994 and this increased to nearly 9 million tonnes in 2005. The most rapid growth in waste generation is taking place in construction and the private and public service industries as revealed by figure 1, whereas other industries including the manufacturing sector, which was growing very slowly in this period, in recent years have managed to lower the level of waste generated. The increase in real GDP is approximately 25 per cent for the ten-year time period and obviously, this measure of the general economic activity is not closely linked to the development in the quantities of waste produced.

In order to decompose the development in waste quantities – as e.g. exhibited in figure 1- into activity, structural and intensity effects, the LMDI- methodology is applied to the waste data, and the results are reported in table 1.

Table 1. Decomposing the waste volumes for the Danish economy, 1994-2005.

	C_{act}	C_{str}	C_{int}	C_{tot}
1994-1995	1.028	1.017	1.059	1.108
1995-1996	1.017	0.990	1.097	1.104
1996-1997	1.030	0.990	1.044	1.065
1997-1998	1.020	1.025	0.912	0.954
1998-1999	1.029	1.008	0.959	0.994
1999-2000	1.043	0.984	1.068	1.095
2000-2001	1.008	0.964	1.033	1.003
2001-2002	1.004	0.984	1.068	1.054
2002-2003	1.005	1.004	0.935	0.944
2003-2004	1.016	0.992	1.115	1.124
2004-2005	1.016	1.004	1.074	1.096
1994-2005	1.231	0.962	1.404	1.661

Note: The decomposition analysis performed for the three sectors appear in figure 1 and the effects are calculated from the formulas (3), (4) and (5).

The general conclusion from table 1 – with the total effects for the whole-sample period in the last row - is that especially the structural effect is minor and therefore does not explain very well the huge increase of 66 per cent in the volumes of waste generated. A relatively big shift is taking place in the waste intensities which is also revealed by figure 1 with a 40 per cent increase for the whole-sample period and the activity effect comes in second with a 23 per cent contribution concerning waste amounts. Finally, the three separate effects from table 1 can be linked and exhibited in a graphical form as illustrated in figure 2.

Figure 2. The activity, structural and intensity effects in waste generation, Denmark 1994-2005 (Indices, 1994=100).
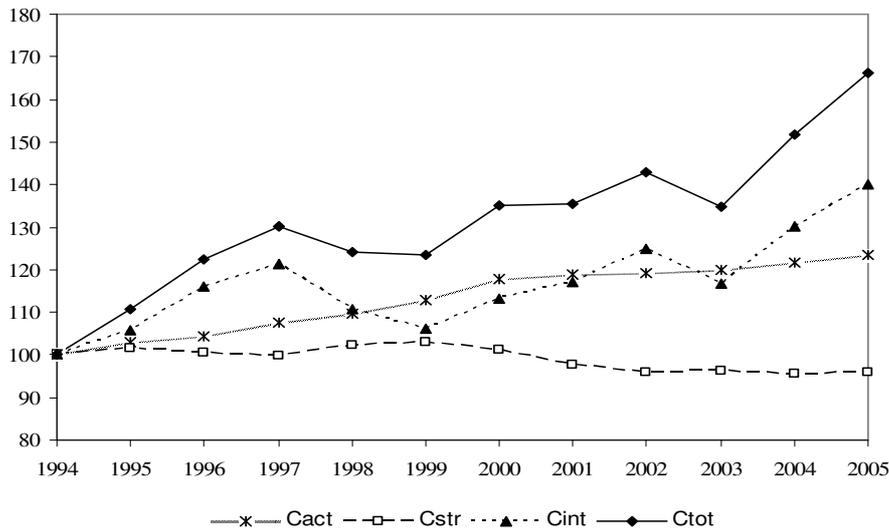
Note: The graph is constructed from the three effects calculated in table 1 for the respective periods.
Sources: The ISAG database (the Danish EPA); The Statistical Database, National Accounts, Statistics Denmark.

The interpretation of the lines in figure 2 is as follows. The 'total effect' is simply an index of the total waste volumes for the three sectors. Assuming no structural shifts in the economy regarding the relative size of the sectors, and constant waste intensities, the line for the 'activity effect' illustrates the development in waste quantities (as in index), given these two assumptions. Likewise, the other two lines illustrate the separate effects from changes in the economic structure and waste intensities, respectively. The conclusion from figure 2 is that the intensity effects seem to be a dominant feature of the increasing volumes of waste produced in this period. Assuming the waste intensities had remained stable at the 1994-levels there would only have been a modest increase in this environmental problem – in line with the increase in GDP - and therefore a deeper insight into why the intensities are increasing is wanted and thus a subject for further research. As this analysis only includes three main sectors of the economy the data used are aggregated at a relatively high level and therefore care must be exercised when it comes to final conclusions. For the

manufacturing sector data are available for a more detailed decomposition analysis which will be presented in part 4.

4. Decomposing waste generation in the Danish manufacturing sector

For the manufacturing sector – as the only sector in the Danish environmental statistics – a detailed dataset covering the waste generation in the respective industries is available and hence, in this case a deeper analysis is possible. The dataset covers six industries of the manufacturing sector for the time period 2001 to 2005, and these are listed in table 2 which reports some descriptive data for GDP and employment.

Table 2. GDP, labour and waste in the manufacturing sector, 2001 and 2005.

| | 2001 | | | 2005 | | |
	GDP	Labour	Waste	GDP	Labour	Waste
Food, beverages and tobacco	29.8	79.4	164.4	27.0	69.9	215.8
Textile and clothing	4.5	13.9	5.9	3.4	9.4	12.9
Wood and furniture	30.4	95.8	266.0	29.4	80.0	255.4
Chemicals	30.8	50.4	94.0	33.5	49.7	107.5
Non-metallic mineral products	7.0	18.9	49.1	7.2	14.8	44.5
Basic metals	75.3	189.8	222.2	74.8	165.1	281.1
Sum	177.6	448.0	801.5	175.2	388.8	917.1

Note: The waste volumes are measured in tonnes (in thousands), GDP is measured at factor costs and in constant 2000-prices (billion DKK) and labour is measured as the total number of employees (in thousands) in each industry.
Sources: The ISAG database (the Danish EPA); The Statistical Database, National Accounts, Statistics Denmark.

Table 2 exhibits that, generally, GDP and employment in the manufacturing industries have been declining in this decade, but the waste produced has been growing. The drop in production and rise in waste generation indicate an increasing waste intensity, of course, and there does not seem to be any obvious connection between these intensities and GDP or employment. In table 3 the results from the decomposition analysis of the six industries from the manufacturing sector are reported.

Table 3. Decomposing the waste volumes for the manufacturing sector, 2001-2005.

	C_{act}	C_{str}	C_{int}	C_{tot}
2001-2002	0.970	0.994	0.999	0.964
2002-2003	0.973	1.001	1.140	1.110
2003-2004	1.028	0.999	1.010	1.037
2004-2005	1.017	0.994	1.021	1.032
2001-2005	0.987	0.989	1.173	1.144

Note: The decomposition analysis performed for the six sectors appear in table 2 and the effects are calculated from the formulas (3), (4) and (5).

The main conclusion from table 3 is that most of the changes in the volumes of waste generated in the Danish manufacturing sector in the period from 2001 to 2005 can be explained by the intensity effect; both the structural and activity effects are negligible (less than 2 per cent) and mostly negative, and the intensity effects influence the waste volumes upwards – *ceteris paribus* – by 17 per cent. The three separate effects are exhibited in figure 3 as cumulated magnitudes, similar to figure 2.

Figure 3. The activity, structural and intensity effects in waste generation, the Danish manufacturing sector, 2001-2005 (Indices, 2001=100).
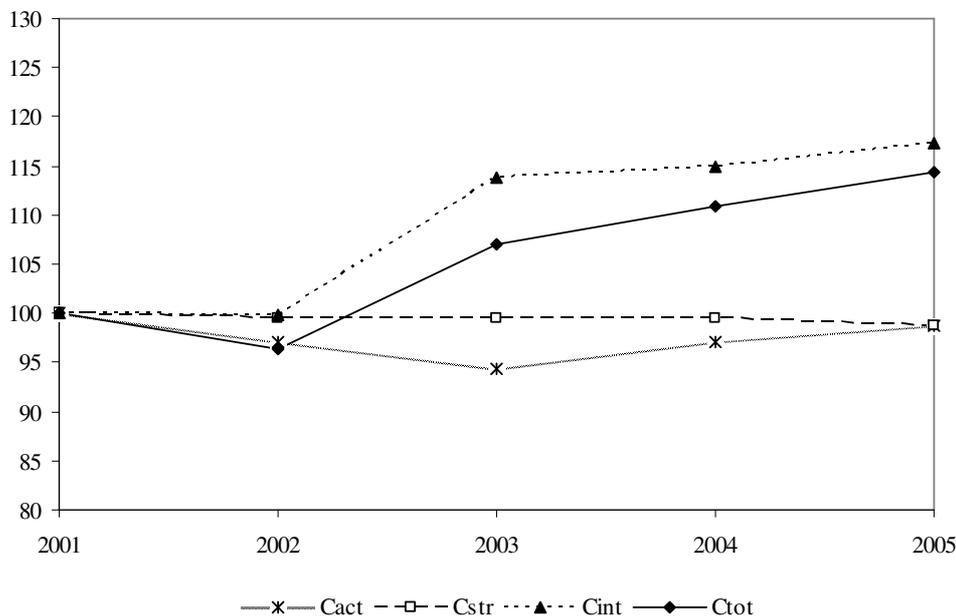
Note: The graph is constructed from the three effects calculated in table 3 for the respective periods.
Sources: The ISAG database (the Danish EPA); The Statistical Database, National Accounts, Statistics Denmark.

The results indicate that the activity and structural effects are very modest and without importance, whereas the intensity effect, which peaks in the period 2002-2003, is positive for all periods and more or less 'explains' the total increase in the waste volumes generated. This result is in line with the conclusion from analysing the main sectors of the economy in part 3 and emphasises the importance of 'intensities' in relation to waste management.

5. Discussion

In the previous sections we have shown that the waste intensities are increasing more than what can be explained by economic activity and growth. The analysis carried out in this paper indicates that there is an inefficient surplus in the amount of waste the Danish firms generates over time. There are many possible explanations of this phenomenon; one is that the firms' gross value added production has decreased while the firms have maintained the same level of input in the production – that is the firms have become less efficient. The data indicates that this in some extent is the case - the firms gross value added production has

gone down a little but the input in production has not decreased as much – this does not necessarily mean that the firms discard the excessive goods or that they are more wasteful, some firms will store the goods they currently cannot sell at the market, therefore this can only be part of the explanation.

Another explanation is that the waste management system - the waste tax especially - is not living up to its full potential. The regulation of the Danish waste management system has not changed significantly in the period from 2001-2005. Consequently the tax on waste has remained constant at the 2001 level - the incineration tax has been stable at 330 DKK per tonnes and the land filling tax is 375 DKK per tonnes. The tax, however, seems minute when compared to the cost of treating the waste. For waste sent to incineration the handling fee lies between 140 and 620 DKK per tonnes. Table 4 illustrates the price differences between the Danish treatment facilities for four main ways of treating the waste.

Table 4. Handling fees at the treatment facilities.

	Land filling	Incineration	Composting – garden waste	Reuse - Gypsum
Average	311	259	175	556
Minimum	95	140	110	200
Maximum	750	620	308	825
Number of observations	19	20	19	7
Standard deviation	132,88	128,25	58,24	194,17

Note: The prices are exclusive of the waste tax
Sources: Public pricelists from the Danish waste treatment facilities, obtained in September 2008

From table 4 it is apparent that the prices differ significantly between the treatment facilities. For waste sent to land fills the price difference is more than 650 DKK per tonnes from the cheapest to the most expensive place. This means that the national waste tax 'drowns' when compared to the costs of handling the waste, the firms faces different cost across the country, which could be part of the explanation of the phenomenon of the increasing waste intensities.

Another aspect of the problem is the indistinguishable economic incitements in the Danish waste management system, if a firm wishes to reduce the amount of waste generated it will

need to make changes in the production processes but the costs of this will most likely surpass the potential economic gains. The waste treatment facilities have no incentive to encourage the firms to reduce the amount of waste they generate, as this will reduce the treatment facilities own production. The municipalities which have the regulating role in the sector have ambiguous incentives since they also own many of the waste treatment facilities and therefore have a dual role as both regulator and owner of treatment facilities. The combination of these effects contributes considerably to the system's low degree of transparency. It is, however, not possible in the context of this paper to test how the combination of these effects will influence the amount of business waste generated in Denmark; this will be subject for future research.

8. Conclusions

The application of the empirical analysis of aggregate data for the quantities of waste generated in Denmark has clearly revealed that much of the increase in waste is associated with increasing waste intensities, defined as the ratio between waste and the value-added production. When decomposing the development in total waste generation into activity, structural and intensity effects – applying the Log-Mean Divisia Index method – only a small share of the growth in waste can be explained or linked to increasing activity or structural shifts concerning the sectors and industries of the economy. This general conclusion seems to hold when applying the decomposition techniques to the main sectors and also when making an analysis using more disaggregated data for the specific industries of the manufacturing sector. Put differently, today the same amount of economic activity is associated with more waste than 10 years ago. However, the conclusion about the intensity effect mainly explaining the changes in waste production is not as apparent for the main sectors as within the manufacturing sector solely.

The analysis does not claim to solve - or present answers to - the questions of causality regarding waste production but deals with a standardized methodology in order to separate the total increase in waste generation into the three before-mentioned effects. This analysis

of the change mechanisms can provide policy-makers both in Denmark and internationally with a deeper understanding of the impact factors that contribute to the increasing waste production. The fact that most of the change in Denmark is caused by the intensity effect indicates that it will be possible to stem the growth in the volumes of waste produced by the industrial sectors e.g. by introducing minimum requirements to the production technology regarding residual or waste generation. Likewise, it is important to be aware of the increasing waste intensities in the design of future waste strategies and waste reduction policies. It is especially important concerning environmental and waste taxes to have knowledge about whether it is intensity effects or activity-structural effects that drive the development in waste production. Waste taxes might have positive (environmental) effects due to a lowering of waste intensities – which is the purpose of the taxation – but it is not likely that waste taxes will have any beneficial purpose in case of activity-structural effects, apart from raising a tax revenue. However, a waste tax is not likely to work, the tax would have to be unpopular large to affect the choice of materials considering these are often only a small part of a product's cost, another problem with the waste tax is that it tends to "drown" when compared to the costs of treating the waste.

Hence, a decomposition analysis of total waste production also offers useful tools for a better understanding of how to influence positively on the environment via e.g. waste taxes. Additionally, future research on decomposition into the waste types, especially hazardous waste, is definitely needed for detailed investigations. Further research could also include a country comparison which will indicate whether the tendencies which have come to light in the present analysis reveal a general trend that applies to other countries in the EU or the OECD.

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Appendix. The Log-Mean Divisia Index (LMDI) method and waste decomposition.

Let Y be the total industrial production (e.g. in value added terms) and W the volume of waste from the industry, which is assumed to consist of n sectors.

The total volume of W can be decomposed according to:

$$W = \sum_{i=1}^{n} YS_iI_i \qquad \text{where:} \qquad S_i = \frac{Y_i}{Y} \; ; \; I_i = \frac{W_i}{Y_i} \qquad (A1)$$

Thus, Y is the activity or output component, S_i the structural component and I_i is the 'waste intensity' component. Any change in W is therefore multiplicatively decomposed into activity, structural and intensity effects.

From (A1) it follows:

$$\frac{dW}{dt} = \sum_{i=1}^{n} S_iI_i \frac{dY}{dt} + \sum_{i=1}^{n} YI_i \frac{dS_i}{dt} + \sum_{i=1}^{n} YS_i \frac{dI_i}{dt} \qquad (A2)$$

$$\Rightarrow \frac{dW}{dt} \cdot \frac{1}{W} = \sum_{i=1}^{n} \frac{S_iI_i}{W} \frac{dY}{dt} \frac{Y}{Y} + \sum_{i=1}^{n} \frac{YI_i}{W} \frac{dS_i}{dt} \frac{S_i}{S_i} + \sum_{i=1}^{n} \frac{YS_i}{W} \frac{dI_i}{dt} \frac{I_i}{I_i} \qquad (A3)$$

$$\Rightarrow \frac{d\ln W}{dt} = \sum_{i=1}^{n} \frac{YS_iI_i}{W} \frac{d\ln Y}{dt} + \sum_{i=1}^{n} \frac{YS_iI_i}{W} \frac{d\ln S_i}{dt} + \sum_{i=1}^{n} \frac{YS_iI_i}{W} \frac{d\ln I_i}{dt} \qquad (A4)$$

$$\Rightarrow \ln\left(\frac{W_T}{W_0}\right) = \sum_{i=1}^{n} \int_0^T \delta_{it} \left(\frac{d\ln Y_t}{dt} + \frac{d\ln S_{it}}{dt} + \frac{d\ln I_{it}}{dt}\right) dt \qquad (A5)$$

Where:

$$\delta_{it} = \frac{Y_tS_{it}I_{it}}{\sum_{i=1}^{n} Y_tS_{it}I_{it}} \qquad (A6)$$

From (A5) after exponentiation:

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$$\frac{W_T}{W_0} = \exp\left(\sum_{i=1}^{n}\int_{i=0}^{T}\delta_{it}\frac{d\ln Y_t}{dt}dt\right)\cdot\exp\left(\sum_{i=1}^{n}\int_{0}^{T}\delta_{it}\frac{d\ln S_{it}}{dt}dt\right)\cdot\exp\left(\sum_{i=1}^{n}\int_{0}^{T}\delta_{it}\frac{d\ln I_{it}}{dt}dt\right) \qquad (A7)$$

Finally, an approximation in discrete time will be:

$$\frac{W_T}{W_0} = \exp\left(\sum_{i=1}^{n}\delta_{it}'\ln\left(\frac{Y_T}{Y_0}\right)\right)\cdot\exp\left(\sum_{i=1}^{n}\delta_{it}'\ln\left(\frac{S_{iT}}{S_{i0}}\right)\right)\cdot\exp\left(\sum_{i=1}^{n}\delta_{it}'\ln\left(\frac{I_{iT}}{I_{i0}}\right)\right) \qquad (A8)$$

The total change in W is thus decomposed multiplicatively into three effects (Y, S and I, respectively):

$$\frac{W_T}{W_0} = C_{act}\cdot C_{str}\cdot C_{int} \qquad (A9)$$

The weight function δ_{it}' (in discrete time) is given by the logarithmic mean (of the end points) in the LMDI method. The log mean (L) of a pair of numbers (a,b) is by definition:

$$L(a,b) = (b-a)/(\ln b - \ln a) \qquad (a,b>0; a\neq b)$$

The final expressions from the empirical application of the decomposition according to the LMDI method will therefore be:

$$C_{act} = \exp\left(\sum_{i=1}^{n}\frac{(W_{iT}-W_{i0})/(\ln W_{iT}-\ln W_{i0})}{(W_T-W_0)/(\ln W_T-\ln W_0)}\ln\left(\frac{Y_T}{Y_0}\right)\right) \qquad (A10)$$

$$C_{str} = \exp\left(\sum_{i=1}^{n}\frac{(W_{iT}-W_{i0})/(\ln W_{iT}-\ln W_{i0})}{(W_T-W_0)/(\ln W_T-\ln W_0)}\ln\left(\frac{S_{iT}}{S_{i0}}\right)\right) \qquad (A11)$$

$$C_{int} = \exp\left(\sum_{i=1}^{n}\frac{(W_{iT}-W_{i0})/(\ln W_{iT}-\ln W_{i0})}{(W_T-W_0)/(\ln W_T-\ln W_0)}\ln\left(\frac{I_{iT}}{I_{i0}}\right)\right) \qquad (A12)$$

This decomposition is both consistent and complete, cf. Ang and Liu (2001) for a proof in relation to energy decomposition.

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