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Structural path decomposition

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ABSTRACT

We combine Structural Decomposition Analysis (SDA) and Structural Path Analysis (SPA) in order to examine the temporal changes within a full production chain perspective. To our knowledge this work constitutes the first formulation of what we call Structural Path Decomposition (SPD). SPD provides noteworthy insight in two instances: first it extracts and ranks those interactions within an economy that are most important in driving change; second it provides a temporal perspective to standard input–output-based Life-Cycle Assessment. In this paper, we develop the mathematical model of SPD and provide two case studies of the most important changes in structural paths in Australia from 1995 to 2005.

1. Introduction

In this article, we combine two well-established techniques in input–output analysis, Structural Decomposition Analysis (SDA) and Structural Path Analysis (SPA). The motivation for this work is twofold—1) to aid policy applications from SDA, by enabling the tracing of the change in key production chains over time; 2) to aid input–output life-cycle analysis techniques by modelling temporal developments in production chains.

Aggregate indicators often hide many competing trends within an economy, and improvements in some sectors are often offset by deteriorations in others. It is generally not possible to appreciate the scale of these competing trends, unless a more detailed breakdown is undertaken. The application of what we call Structural Path Decomposition (SPD) is designed to act at the production chain level such that aggregate results are informed by the changing relationships at the industry level.

1.1. Structural Decomposition Analysis

The application of Structural Decomposition Analysis (SDA) is aimed at identifying the driving factors for change in key variables over time. All variants of SDA are static comparative methods that examine time series of either sector-level and/or country-level data. In essence, SDA formulates an explained variable, such as energy use, as a sum or product of explanatory determinants, such as energy efficiency, technology, per-capita consumption and population. A pair-wise comparison of changes at two points in time is undertaken, by each determinant and the explanatory variable.

Predecessors to the technique of SDA can be found in the work on structural economic changes by (Leontief, 1941; Leontief, 1953), and were first applied to environmental issues by Leontief and Ford (1971) when they analysed structural effects on air pollution and projected future emission scenarios. Following Leontief's pioneering work, energy analysis became the focus of SDA investigation (Proops, 1988; Chen and Rose, 1990; Rose and Chen, 1991), and has been examined in terms of output mix (Pløger, 1984), and also technology and demand change (Gowdy and Miller, 1987). This was later extended to SDAs of carbon dioxide and other impacts within economies (Common and Salma, 1992; Proops et al., 1993; Casler and Rose, 1998; Chang and Lin, 1998; Wier, 1998; de Haan, 2001; Hoekstra and van den Bergh, 2002; De Nooij et al., 2003; Wilting et al., 2006; Llop, 2007; Peters et al., 2007; Roca and Serrano, 2007; Guan et al., 2008; Pablo Muñoz and Hubacek 2008; Wachsmann et al., in press).

Whilst SDA generally concerns itself with the macro-indicators of change within an economy, its application to policy formulation usually requires a breakdown at higher levels of detail, such as by production sector (e.g. Chang and Lin, 1998; Dietzenbacher and Los, 1998; Wier, 1998; Dietzenbacher and Los, 2000; Jacobsen, 2000; de Haan, 2001; De Nooij et al., 2003; Alcántara and Duarte, 2004). In this paper, we seek to extend the relevance to policy formulation with the integration of SPA. By so doing, we are able to extract and rank the actual production paths contributing most to changes in the dependent variable (energy/carbon etc). This is particularly relevant when analysing changes within the Leontief representation of the structure of the economy.

1.2. Structural Path Analysis

The use of input–output tables in such applications as Life-Cycle Assessment (LCA) has greatly benefited from the technique of

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Structural Path Analysis (SPA), introduced in the early 1980s (Defourny and Thorbecke, 1984). Recently, this has seen increasingly widespread use, both in an LCA context (Treloar, 1997; Treloar et al., 2001; Lenzen, 2002; Lenzen, 2003; Wood and Lenzen, 2003; Suh, 2004; Wood et al., 2006; Llop, 2007; Strømman et al., 2009), and in more general areas such as trade modelling (Peters and Hertwich, 2006b; Peters and Hertwich, 2006a; Lenzen et al., 2007) and in trophic systems (Suh, 2005; Lenzen, 2006b).

The basic idea behind a SPA is the unravelling of the Leontief inverse by means of a series expansion of the direct requirements matrix (Waugh, 1950). This allows the analyst to investigate impacts that are caused directly by final consumption (such as emissions from gas cooking) to those caused in the first order away from the consumer (such as emissions in electricity generated for the consumer) to those in higher orders (for example, emissions in electricity for steel for a train for a train journey taken by the consumer).

The use of SPA has only been applied statically—often for extracting the main upstream impacts of products or organisations. In this paper, by applying SDA techniques, we seek to a) investigate the effects of changes within the production chain over time and b) decompose production chains to a level of interest for analysis of change.

1.3. This work: Structural Path Decomposition (SPD)

This paper proceeds with a mathematical description of the method in Section 2. The dual benefits of the methodology is shown, by a) decomposing SDA into ranked production chains in a case study in Section 3, and by b) providing a temporal aspect to SPA through a case study in Section 4. Application notes are briefly discussed in Section 5 before conclusions are brought in Section 6.

2. Mathematical description

In this section, we derive the mathematical basis for the combination of SDA and SPA. We start from the basic Leontief production function, and derive the SDA equations before applying the decomposition into structural paths (SPA).

2.1. Structural Decomposition Analysis

Beginning from the basic Leontief model, total output can be expressed as:

$$\mathbf{x} = \mathbf{L}\mathbf{y}, \tag{1}$$

where $\boldsymbol{x}$ is a vector of total output, $\boldsymbol{L}$ is the Leontief inverse $(\boldsymbol{I}\text{-}\boldsymbol{A})^{-1}$ of the direct requirements matrix $\boldsymbol{A}$, and $\boldsymbol{y}$ is a vector of final demand (Leontief (1966) or comparable). Whilst decomposition can be applied to this purely monetary equation, it is often performed for a physical production factor such as greenhouse gas emissions or energy consumption. Hence, as an example, we expand Eq. (1) to:

$$C = \mathbf{cLy} = \mathbf{cL}\boldsymbol{\psi}\delta\mathrm{YP} = \mathbf{c}(\mathrm{I}-\mathrm{A})^{-1}\boldsymbol{\psi}\delta\mathrm{YP} \tag{1a}$$

where:

C	Total CO_2-eq emissions (1×1)
$\mathbf{c}$	Greenhouse gas intensity of production n sectors $(f\times n)$
$\boldsymbol{L}$	Leontief inverse $(n\times n)$
$\boldsymbol{I}$	Unity matrix $(n\times n)$
$\boldsymbol{A}$	Direct requirements matrix $(n\times n)$
ψ	Commodity structure of final demand $(n\times \mathrm{d})$
δ	Destination structure of final demand $(d\times1)$
Y	Per-capita final demand (1×1)
P	Population (1×1)

The decomposition of Eq. (1a) then becomes (compare Proops et al., 1993)

$$\begin{aligned} \mathrm{d}C = {} & \mathrm{d}\mathbf{c}\;\mathbf{L}\,\boldsymbol{\psi}\delta\mathrm{YP} + \mathbf{c}\;\mathrm{d}\mathbf{L}\;\boldsymbol{\psi}\delta\mathrm{YP} \\ & + \mathbf{cL}\;\mathrm{d}\boldsymbol{\psi}\;\delta\mathrm{YP} + \mathbf{cL}\,\boldsymbol{\psi}\;\mathrm{d}\delta\;\mathrm{YP} + \mathbf{cL}\,\boldsymbol{\psi}\delta\;\mathrm{d}Y\;P + \mathbf{cL}\,\boldsymbol{\psi}\delta Y\;\mathrm{d}P \end{aligned} \tag{1b}$$

Eq. (1b) represents a typical SDA of macro-variables, here for seven components (change in emissions due to: change in greenhouse gas intensity of production d**c**; change in industrial structure d**L**; change in commodity structure of final demand d$\boldsymbol{\psi}$; change in destination of final demand, dδ; change in expenditure dY; and change in population dP).

As a continuous time series of data is often not available, in order to apply Eq. (3), differences ΔC, are obtained by integrating changes in dC over discrete time intervals (corresponding to years of IO data). As the integral path within each interval is not known, it is approximated using a form of indexing. In this paper, we use the logarithmic mean divisia index (LMDI), the mathematics of which are explained elsewhere (Ang and Lee, 1994; Ang et al., 2003; Wood and Lenzen, 2006) For choice of index and uniqueness issues, we refer the reader to (Dietzenbacher and Los, 1998; Ang, 2004, Lenzen, 2006a).

The result of the interval approximation and indexing gives us a series of equations:

$$\begin{aligned} \Delta C &= \Delta\mathbf{c} + \Delta\mathrm{L} + \Delta\boldsymbol{\psi} + \Delta\delta + \Delta Y + \Delta P \\ \Delta\mathbf{c} &= \mathrm{d}\mathbf{c}\,\mathrm{L}\,\boldsymbol{\psi}\delta YP \\ \Delta\mathrm{L} &= \mathbf{c}\,\mathrm{dL}\;\boldsymbol{\psi}\delta YP \\ \Delta\boldsymbol{\psi} &= \mathbf{c}\mathrm{L}\;\mathrm{d}\boldsymbol{\psi}\;\delta YP \\ \Delta\delta &= \mathbf{c}\mathrm{L}\,\boldsymbol{\psi}\;\mathrm{d}\delta\;YP \\ \Delta Y &= \mathbf{c}\mathrm{L}\,\boldsymbol{\psi}\delta\;\mathrm{d}Y\;P \\ \Delta P &= \mathbf{c}\mathrm{L}\,\boldsymbol{\psi}\delta Y\;\mathrm{d}P \end{aligned} \tag{2}$$

where the differential is calculated (d**c** for example) according to the LMDI:

$$\mathrm{dc} = \left(\frac{C_2 - C_1}{\log(C_2\,/\,C_1)}\right) {*}\log\left(\frac{\mathrm{c}_2}{\mathrm{c}_1}\right) \tag{2b}$$

Subscripts refer to Year 1 and Year 2—the endpoints of the analysis period. C and $\boldsymbol{c}$ are calculated as per Eq. (1a).

2.2. Applying Structural Path Analysis

From Eq. (1)b, using the Taylor series expansion familiar to SPA,

$$\mathrm{L} = \mathrm{I} + \mathrm{A} + \mathrm{A}^2 + \mathrm{A}^3 + \ldots$$

greenhouse content can be expressed along the actual production pathway:

$$C = \mathbf{c}\left(\mathrm{I} + \mathrm{A} + \mathrm{A}^2 + \mathrm{A}^3 + \mathrm{A}^4 + \ldots\right)\boldsymbol{\psi}\delta YP \tag{3}$$

Such that Eq. (1b) can be summarised as:

$$\mathrm{d}C = \mathrm{d}(\mathbf{c}\boldsymbol{\psi}\delta YP) + \mathrm{d}(\mathbf{c}\,\mathrm{A}\,\boldsymbol{\psi}\delta YP) + \mathrm{d}\left(\mathbf{c}\mathrm{A}^2\boldsymbol{\psi}\delta YP\right) + \mathrm{d}\left(\mathbf{c}\mathrm{A}^3\boldsymbol{\psi}\delta YP\right) + \ldots. \tag{4}$$

or in expanded form:

$$\begin{aligned} \mathrm{d}C = {} & \mathrm{dc}\;\;\boldsymbol{\psi}\delta YP + \mathrm{cd}\boldsymbol{\psi}\delta YP + \mathrm{c}\boldsymbol{\psi}\mathrm{d}\delta YP + \mathrm{c}\boldsymbol{\psi}\delta\mathrm{d}YP \\ & + \mathrm{c}\boldsymbol{\psi}\delta Y\mathrm{d}P + \mathrm{dc}\mathrm{A}\;\;\boldsymbol{\psi}\delta YP + \mathrm{cd}\boldsymbol{A}\delta YP + \mathrm{cAd}\boldsymbol{\psi}\delta YP \\ & + \mathrm{c}\boldsymbol{A\psi}\mathrm{d}\delta YP + \mathrm{c}\boldsymbol{A\psi}\delta\mathrm{d}YP + \mathrm{c}\boldsymbol{A\psi}\delta Y\mathrm{d}P + \mathrm{dc}\boldsymbol{AA\psi}\delta YP \\ & + \mathrm{cd}\boldsymbol{AA\psi}\delta YP + \mathrm{cAd}\boldsymbol{A\psi}\delta YP + \mathrm{c}\boldsymbol{AA}\mathrm{d}\boldsymbol{\psi}\delta YP \\ & + \mathrm{c}\boldsymbol{AA\psi}\mathrm{d}\delta YP + \mathrm{ce}\boldsymbol{AA\psi}\delta\mathrm{d}YP + \mathrm{ce}\boldsymbol{AA\psi}\delta Y\mathrm{d}P + \ldots \end{aligned} \tag{5}$$

Where the first line of Eq. (5) is the decomposition of first order impacts, the second line is the decomposition of second order impacts and the third and fourth line are the decompositions of third order impacts. Fourth and above orders follow the same form.

Some examples for single-path structures of the first four orders are:

1st-order: $dc_j\psi_{jk}\delta_k YP$, or $c_j\psi_{jk}\delta_k Y dP$;
2nd-order: $dc_j A_{jk}\psi_{kl}\delta_l YP$, or $c_j dA_{jk}\psi_{kl}\delta_l YP$;
3rd-order: $dc_j A_{jm}A_{mk}\psi_{kl}\delta_l YP$, or $c_j A_{jm}\, dA_{mk}\, \psi_{kl}\delta_l YP$;
4th-order: $dc_j A_{jm}A_{mn}A_{nk}\psi_{kl}\delta_l YP$, or $c_j A_{jm} dA_{mn}A_{nk}\psi_{kl}\delta_l YP$,

The first example: $dc_j\psi_{jk}\delta_k YP$, is the change brought about by the change in greenhouse content (Δc) of sector j, for destination of final demand k, whereas the second 1st-order example, $c_j\psi_{jk}\delta_k Y dP$, is the change in the same production chain brought about by population change (ΔP). The higher order examples read the same, but with intermediate production steps shown through the introduction of the technical co-efficient matrix $\boldsymbol{A}$. In summary, our differential terms are (compare Eqs. (2) and (5)):

$$\Delta C = \Delta \mathbf{c} + (\Delta \mathbf{A1} + \Delta \mathbf{A1A2} + \mathbf{A1}\Delta \mathbf{A2} + \Delta \mathbf{A1A2A3} + \mathbf{A1}\Delta \mathbf{A2A3} + \mathbf{A1A2}\Delta \mathbf{A3} + \ldots..) + \Delta \boldsymbol{\psi} + \Delta \boldsymbol{\delta} + \Delta Y + \Delta P \quad (6)$$

3. Case study, Australia

In our case study, we use the Australian IO tables for 2 years—1995 and 2005 (Australian Bureau of Statistics, 1999; Australian Bureau of Statistics, 2008a) converted to constant prices using price indices and optimising the dataset against chain volume national account aggregates (Australian Bureau of Statistics, 2007; Australian Bureau of Statistics, 2008b; Australian Bureau of Statistics, 2008c). For the purpose of illustrating this method, we have aggregated the tables to 30 sectors. We use indirect allocation of imports to reflect the true technology of the economy. Greenhouse gas emissions are sourced from the National Greenhouse Gas Inventory (Australian Greenhouse Office, 2007).

The decomposition equation is:

$$C = \mathbf{c}(\mathbf{I} - \mathbf{A})^{-1}\boldsymbol{\psi}\boldsymbol{\delta}YP \quad (6)$$

Variables are per Eq. (2). Results presented in Table 1 are changes in total emissions (ΔC) due to changing greenhouse gas intensity $\Delta \mathbf{c}$, changes in technology $\Delta \mathbf{L}$, changes in type of final demand $\Delta \boldsymbol{\psi}$, changes in destination of final demand $\Delta \boldsymbol{\delta}$, changes in affluence ΔY and changes in population ΔP. Percentages are the change in each variable with respect to change in total emissions. Results are annualised.

Reasonably large increases in greenhouse efficiency occurred in Australia, with $\Delta \boldsymbol{c}$ being the one of the largest drivers of change across all variables Table 1. $\Delta \boldsymbol{L}$ and $\Delta \boldsymbol{\psi}$ show likewise decreasing effect on emissions. $\Delta \boldsymbol{L}$ represents the production recipes used within the economy—the flows between different industries in intermediate production. A decrease in $\Delta \boldsymbol{L}$ is often a result of shifts to using lesser quantities of emissions intensive industries such as electricity or transport, as will become clearer in our later analysis

Table 1
Summary of differentials of SPD.

ΔC	Change in total greenhouse gas emissions
$\Delta \boldsymbol{c}$	Change due to greenhouse intensity of production
$\Delta \boldsymbol{A1}$	Change due to first order technical co-efficient
$\Delta \boldsymbol{A2}$	Change due to second order technical co-efficient
$\Delta \boldsymbol{A3}$	Change due to third order technical co-efficient
…	So forth for higher orders of A
$\Delta \boldsymbol{\psi}$	Change due to type of final demand (product mix)
$\Delta \boldsymbol{\delta}$	Change due to destination of final demand (household, capital, export, etc)
ΔY	Change due to affluence
ΔP	Change due to population

(Table 2). $\Delta \boldsymbol{\psi}$ shows a diminishing effect on emissions due to relative changes in final demand categories. In essence, the results are showing consumption changing from products with high embodied carbon to products with low embodied carbon. Offsetting these improvements, were large changes in affluence ΔY, population ΔP, and to a lesser extent, final consumption destination $\Delta \boldsymbol{\delta}$. $\Delta \boldsymbol{\delta}$ reflects the changing importance of domestic, capital and exported consumption. Over the 10 year time period, the effect of $\Delta \boldsymbol{\delta}$ is minimal. Shorter time periods often show larger fluctuations due to changes in capital effects.

However, apart from the scalar effects of ΔY and ΔP, these changes are not consistent across all production chains within the economy. There are generally many competing sectoral trends within an economy, where improvements in emissions in some sectors are offset by deterioration in others. It is simply not possible to appreciate the scale of these competing trends, unless a more detailed breakdown is undertaken. Thus, in order to analyse those production chains driving the aggregate changes, the SPD formulation derived in Section 2 is applied to extract the production paths with the greatest impacts (Table 2).

To firstly explain these results, Table 2 presents the top 30 production chains that have contributed most to change in Australia's greenhouse gas emissions over the period 1995–2005. Results are annualised such that the kT CO2-eq figure is the average annual change from each production chain over the time period. The “order” of the path represents how many steps occur in the production chain. A path of order 1 shows a direct flow from production to consumption—for example electricity production to household consumption. A path of order 2 shows an intermediary step, for example, electricity production to trade to household consumption. Paths of order 0 (for example household combustion of gas) are not included in this analysis, as they are not strictly structural economic changes. The differential refers to the variable of change within the production chain (see Table 3). Sector 1, 2, 3, 4 refers to the agents in the production chain. Sector 1 will always be the source of emissions—the producing industry. Sector 2 will be the final sector of consumption in the case of a first order path, or in the case of higher order paths, will be an intermediary sector in the production chain. For example, path 21 shows emissions produced in the livestock industry, embodied in the inputs to the dairy and meat industry, which is subsequently required as an input into the trade sector, which is destined for household consumption. The final demand component is disaggregated into destination of final demand (see Eq. (1a)).

It is clear that the key drivers are mainly first or second order production chains, and that paths stemming from the electricity and livestock sectors are most important (Table 2). The top paths show an effect of up to 1.4 MT CO_2-eq, or 25% of the total annualised change in greenhouse gas emissions across the economy. The competing nature of these paths is evident, with the top 6 paths offsetting each other to have close to zero net impact. The first and third paths, show the changes that have occurred from the changing mix of products going to export ($\Delta \boldsymbol{\psi}$). These paths show reduced emissions from a reduction in the proportion of livestock and meat products (which both have high embodied greenhouse gas emissions) exported. This is mainly due to the contraction of the Australian sheep industry in the global marketplace. It should however be noted that in this small-scale example we present, sheep and beef cattle are aggregated, and hence share the same greenhouse gas intensity. This is not true in practice, as sheep and cattle have considerably different greenhouse gas emissions. Hence a more disaggregated model would need to be applied before policy is derived from the results we present.

Shifts in the structure of final demand ($\Delta \boldsymbol{\psi}$) are responsible for many of the top paths. From the analysis, we can see that household demand is having an increasing impact on emissions through household consumption habits incorporating a greater relative reliance on transport (path 4), and a decreasing impact through lower relative electricity consumption (path 7; −896 kT CO_2-eq) and meat and dairy (a second order path, path 9). Overall, however, impacts from

Table 2
SPD of carbon emissions in Australia, 1995–2005.

Rank	kT CO2-e	Order	Differential	Sector 1	Sector 2	Sector 3	Sector 4
1	−1,374	1	$\Delta\psi$	Livestock	Exports		
2	1,370	1	ΔY	Electricity	Household demand		
3	−1,154	2	$\Delta\psi$	Livestock	Meat and dairy	Exports	
4	1,139	1	$\Delta\psi$	Transport	Household demand		
5	−1,078	2	Δc	Livestock	Meat and dairy	Household demand	
6	911	2	ΔY	Livestock	Meat and dairy	Household demand	
7	−896	1	$\Delta\psi$	Electricity	Household demand		
8	−888	2	Δc	Livestock	Meat and dairy	Exports	
9	−862	2	$\Delta\psi$	Livestock	Meat and dairy	Household demand	
10	806	1	$\Delta\psi$	Livestock	Changes in inventories		
11	751	2	ΔY	Livestock	Meat and dairy	Exports	
12	−704	1	Δc	Livestock	Exports		
13	−642	1	$\Delta\psi$	Transport	Private capital		
14	596	1	ΔY	Livestock	Exports		
15	555	1	ΔP	Electricity	Household demand		
16	−511	1	Δc	Grains	Exports		
17	−500	1	$\Delta\psi$	Electricity	Public enterprise capital		
18	−495	1	$\Delta\delta$	Electricity	Public enterprise capital		
19	478	2	$\Delta A1$	Livestock	Trade	Household demand	
20	468	1	Δc	Electricity	Household demand		
21	414	3	$\Delta A2$	Livestock	Meat and dairy	Trade	Household demand
22	−404	1	Δc	Livestock	Private capital		
23	387	2	$\Delta A1$	Livestock	Meat and dairy	Household demand	
24	378	1	ΔY	Metals	Exports		
25	373	1	$\Delta\psi$	Livestock	Private capital		
26	369	2	ΔP	Livestock	Meat and dairy	Household demand	
27	−366	1	Δc	Govt, public services	Government demand		
28	365	1	ΔY	Coal and minerals	Exports		
29	342	1	ΔY	Livestock	Private capital		
30	319	2	$\Delta A1$	Livestock	Meat and dairy	Exports	
TOTAL	5,663						

Top 30 ranked paths, "Differential" refers to the variable of change (refer Eq. (2)), "Order" refers to the length of the production chain.

household electricity consumption are responsible for increasing emissions, with the decrease in relative household consumption offset by the affluence effect (path 2—representing overall increased expenditure on this path), the population effect (path 15) and the intensity effect (path 20; $\Delta\boldsymbol{c}$; 468 kT CO_2-eq—representing decreases in greenhouse efficiency within the electricity sector).

Significant change has occurred in livestock practices in Australia over the 1995–2005 period, both in the changing quantities of demand for exports as previously mentioned, and for domestic use. Due to reductions in direct land clearing by the industry (decreasing $\Delta\boldsymbol{c}$), path 5 and 8 show the implications of this for household and export demand for meat products, with an annual saving of close to 1 MT CO_2-eq each. Unfortunately this saving has been offset by the increase in overall demand of meat products due to affluence and population effects (paths 6 and 26). Similar to Electricity consumption, we are at least seeing a decrease in the relative consumption of meat products in a household basket of goods (path 9; $\Delta\boldsymbol{\psi} = -862$ kT CO_2-eq).

Changes in the production structure of the economy, represented by paths with differential $\Delta\boldsymbol{A}$, show the effects of changes of inter-relationships of industries in the economy. Path 19 and 21 are the highest ranked paths, and they show that for the given household consumption of trade (which refers to retail and wholesale trade, and incorporate hospitality) there have been higher requirements directly from livestock (path 19, $\Delta\boldsymbol{A}1$) and also via the meat and dairy industry ($\Delta\boldsymbol{A}2$ indicates the second linkage in the production chain). Hence, comparing to path 9, we are seeing a decrease in the household consumption of meat and dairy, but an increase in livestock and meat utilised in the trade industry. In simple terms, there is a greenhouse saving due to the population eating less meat at home, but this is offset by more meat purchases at restaurants.

Other important structural changes within the economy are shown by path 23 and 30, the increase in livestock required for the average meat and dairy product. Lower rankings (not shown in Table 2) include the reduction in animal inputs into clothing manufacture, which saves almost 289 kT CO_2-eq a year; and the increasing requirements of electricity of the trade sector for household demand, most probably due to the increased uptake of air-conditioning systems, producing 173 kT CO_2-eq more a year.

Other interesting paths in the top 30 include several effects stemming from improvements in the greenhouse gas intensity of production ($\Delta\boldsymbol{c}$). Apart from those already identified, we are seeing improvements in efficiency in paths stemming from the grains sector (path 16), and government and business services (path 27). Paths 17 and 18 show the decreased emissions stemming from reduced relative electricity needs of public enterprise capital, and a shift away from public enterprise capital relative to total final demand. Finally, the overall expenditure/affluence effects ($\Delta\boldsymbol{Y}$) show strongly for key export sectors of metals (path 24) and coal and minerals (path 28).

In summary, this case study has been selected to illustrate the application of SPD to an SDA study. The analysis of an SDA is broken down to look at the competing forces underlying the aggregate results. Unlike a traditional SDA undertaken at the sector-level, this allows a true consumption/life-cycle viewpoint to be used, and enriches the detail extracted, particularly when analysing production chains within the Leontief production structure of the economy.

4. Case study, SPD of wood products IO-LCA

We now turn to applying SPD in a more conventional Life-Cycle context. In this case study, we utilise the same methodology and

Table 3
SDA of carbon emissions in Australia kT CO_2-eq, 1995–2005.

Δc	ΔL	$\Delta\psi$	$\Delta\delta$	ΔY	ΔP	ΔC
−7,544	−982	−6,539	110	14,675	5,944	5,663
−133%	−17%	−115%	2%	259%	105%	100%

Table 4
SPA of wood products in the Australia, 2005.

Rank	kT CO2	Order	%	Sector 1	Sector 2	Sector 3
1	137	1	38.6%	Wood products		
2	73	2	20.6%	Electricity	Wood products	
3	18	2	5.2%	Transport	Wood products	
4	15	2	4.2%	Forestry	Wood products	
5	11	2	3.1%	Wood products	Wood products	
6	10	3	2.8%	Electricity	Electricity	Wood products
7	6	3	1.7%	Electricity	Wood products	Wood products
8	4	3	1.2%	Electricity	Transport	Wood products
9	3	2	0.8%	Chemicals, plastics	Wood products	
10	3	3	0.8%	Electricity	Chemicals, plastics	Wood products
11	3	3	0.8%	Electricity	Trade	Wood products
12	2	2	0.7%	Metals	Wood products	
13	2	2	0.6%	Mineral products nec	Wood products	
14	2	3	0.6%	Forestry	Forestry	Wood products
15	2	3	0.4%	Electricity	Business and finance	Wood products
TOTAL	355					

Top 15 ranked paths.

context for the analysis of the environmental impact of timber products as done by (Lenzen and Treloar, 2002). We analyse only fuel combustion related emissions, as per the energy analysis of Lenzen and Treloar. This case study is designed to show the application of the SPD methodology to Life-Cycle Assessment, where temporal factors within the production process are sought.

As such, we investigate the principal causes in the changes in the production process for a unit of timber products in Australia between 1995 and 2005. As we are applying our analysis on a single unit of final demand, Eq. (5) becomes,

$$dC = d(\mathbf{c}\,\boldsymbol{\gamma}) + d(\mathbf{c}\,\mathbf{A}\,\boldsymbol{\gamma}) + d\left(\mathbf{c}\,\mathbf{A}^2\,\boldsymbol{\gamma}\right) + d\left(\mathbf{c}\,\mathbf{A}^3\,\boldsymbol{\gamma}\right) + ... \quad (7)$$

Where $\boldsymbol{\gamma}$ is the final demand vector with unitary demand (AUD \$1 million) for timber products and zero demand for other product categories, i.e.:

$$\gamma_{i=\text{timber}} = 1,$$
$$\gamma_{\forall i,i \neq \text{timber}} = 0$$

A standard SPA for wood products is presented in Table 4, with the top 15 paths ranked.The standard SPA allows us to investigate the principle areas of impact within the manufacture of wood products. The top 4 paths are straightforward, with the first path showing direct (first order) emissions from fuel combustion in the wood products industry. The second, third and fourth paths show second order production paths for the supply of electricity, transport and forestry respectively. These are thus emissions caused in the direct suppliers to the wood products industry. Overall, these top 4 paths account for 69% of the total emissions. Path 5 wood products embodied in wood products shows the intra-sector purchases between different establishments. For example, within the wood products sector, goods such as joinery products have inputs from other establishments, such as those producing undressed timber. This intra-sector circulatory is also evident in the electricity and forestry sectors (paths 6 and 14) and is manifested more in aggregated data sets such as in use here. The existence of these paths, particularly in the third order paths reflects both the importance of the key sectors of electricity, forestry and wood products, as well as the diverse manufacturing base (large numbers of establishments) within the sectors. Other production chains of note are second and third order chemical paths (paths 9 and 10), metals and minerals (paths 12 and 13), and finally, the significance of the impact of electricity used in the business and finance sector servicing wood products (rank 15).

Such an analysis as this can be extremely important in identifying carbon bottlenecks in the supply chain of a product. However, often we are not only interested in this static analysis, but we would like to know how things are changing over time, and whether there is any improvement in the processes under study, especially if some kind of policy has been or can be applied. In order to do this, we apply the decomposition to the 1995 and 2005 results with SPD.

By applying the SPD method (Table 5), we see that the top path from the SPA in Table 4 (forestry inputs into wood products) is undergoing significant change over time. Decreases in efficiency of the

Table 5
SPD of wood products in Australia, 1995–2005.

Rank	kT CO2-e	Order	Differential	Sector 1	Sector 2	Sector 3
1	2.7	1	Δc	Wood products		
2	−1.4	2	$\Delta A1$	Electricity	Wood products	
3	−1.0	2	$\Delta A1$	Wood products	Wood products	
4	0.8	2	Δc	Electricity	Wood products	
5	−0.7	2	$\Delta A1$	Transport	Wood products	
6	−0.6	3	$\Delta A2$	Electricity	Wood products	Wood products
7	−0.5	2	Δc	Forestry	Wood products	
8	−0.5	2	Δc	Transport	Wood products	
9	0.4	3	$\Delta A1$	Electricity	Electricity	Wood products
10	0.3	2	Δc	Wood products	Wood products	
11	−0.2	3	$\Delta A2$	Transport	Wood products	Wood products
12	0.2	2	$\Delta A1$	Chemicals, plastics	Wood products	
13	−0.2	3	$\Delta A2$	Electricity	Trade	Wood products
14	−0.2	3	$\Delta A1$	Electricity	Wood products	Wood products
15	−0.2	2	Δc	Chemicals, plastics	Wood products	
TOTAL	−3.3					

Top 15 ranked paths.

sector ($\Delta \boldsymbol{c}$—path rank 1) have increased emissions by about 2.7 kT CO_2-eq/year. This is equivalent to over 80% of the total change (−3.3 kT CO_2-eq). Structural changes are next most important in the ranking, with changes in the inter-sector flow between electricity and wood products (path 2) and the intra-sectoral flows of wood products (path 3) both reducing emissions in the order of 1 kT CO_2-eq. The second path is showing that the production chain is becoming less electricity intensive ($\Delta \boldsymbol{A}$—path rank 2), meaning that a lesser proportion of electricity is required in producing the wood products. The results for the structural change differentials thus imply that the manufacturing process has increased direct fuel use (path 1), whilst reducing the need for other inputs (paths 2,3,5,6,11,13,14).

Two other structural changes show increased impact on emissions—that of chemicals (second order, path 12) and the upstream requirements of electricity supply (third order, with change occurring in the intra-sector electricity flows—path 9). This means that even whilst the wood products sector is reducing emissions through reduced electricity demand (path 2), the benefit is being reduced by the higher upstream requirements of the electricity sector itself (path 9). The SPD also allows us to observe the decreasing efficiency of electricity supply ($+\Delta \boldsymbol{c}$) flowing into wood products (path 4), and the converse increases in efficiency ($-\Delta \boldsymbol{c}$) of the second order paths forestry, transport and chemicals into wood products (paths 7,8 and 15). The chemicals path is a good example of no net effect of increased chemical use ($\Delta \boldsymbol{A}=0.2$ kT CO_2-eq, path 12) due to savings in efficiency of the sector ($\Delta \boldsymbol{c}=-0.2$ kT CO_2-eq, path 15).

5. Application notes

We found the most useful approach was to begin with an SPA algorithm in order to trace the branches of the production tree, with ranked sectors and higher orders only being traced when they are greater than a threshold. For a system of 30 sectors, it is feasible to cover all production chains and up to 10 orders, however, for larger models, thresholds and rankings are recommended to reduce computational time. For the application in SPD, three concurrent SPAs are performed—one for the initial year, one for the final year, and one for the index term. Instead of calculating the value of the path as per normal SPA, the differential of the path is calculated for the n variables, as per the examples in Section 2.2.

6. Conclusions and discussion

6.1. Summary

In this paper we have elucidated a means for investigating the temporal changes in production chains by combining the two techniques of Structural Path Analysis and Structural Decomposition Analysis. The amalgamation of the two techniques enables a bi-fold advantage to be gained–firstly such that SPA and its application in LCA can be employed in a temporal setting giving insight into changes and trends occurring within a production chain–and secondly by allowing the SDA analyst the ability to derive more policy applicable results, extricating the production pathways (and in particular the changes in the Leontief production structure) from the aggregate results where competing forces often subsume the changes occurring on the ground.

To illustrate the method, two case studies were undertaken—firstly for an SDA of Australia between 1995 and 2005, and secondly for an IO-LCA of wood products. Key results show strong competing forces in the top ranked paths, with shifts in demand structure being highly significant. There was a general decrease in the greenhouse gas intensity across the economy, and some key shifts in the production paths of intermediate demand. The analysis provided particularly for wood products highlighted these results, with generally lower greenhouse gas requirements from intermediate production paths offset by higher source emissions.

6.2. Discussion

Knowledge of the carbon liability of products and within countries is becoming increasingly important in a carbon constrained world. Identifying the evolution of production practices in a country can significantly help in the development of policy to curb rampant growth in consumption or production behaviour inducing high levels of emissions. Whilst the methods introduced in this paper do not further the benchmarking of environmental impact, they do help us to measure whether progress is being made on the way to sustainability. As almost all climate policy has been developed around relative reductions in carbon emissions, rather than absolute goals, these measures on progress within an economy are essential to sound out the areas in most need of address.

One of the weaknesses of conventional SDA, in the authors' opinion, is the difficulty of interpreting the changes in the Leontief production structure for meaningful policy. Previous analysis would be able to decipher that overall production recipes of a sector were getting better or worse, but had no convenient means to explain why. The advantage of the method introduced in this paper, is the ability to breakdown the Leontief production structure into individual production chains. This then allows the extraction of the links in the chain which are most important in the evolution of a country's emissions.

The development of policy based on the aggregate indicators of an SDA can miss significant opportunities, when, as identified in Section 3, there are competing forces in different production chains counterbalancing each other at an industry level. The study of Australia found exactly this—with significant changes occurring both in the type of consumption and the technology of production overshadowed in the aggregate analysis.

In an LCA context, the method adds to the practitioner's ability to identify trends in the sustainability of products–whether- and which–practices are moving towards low emissions, and which practices are potentially blowing out carbon or other environmental liabilities.

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