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Carbon mitigation in the built environment: an input-output analysis of building materials and components in the UK

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Abstract

The circular economy has set out a new paradigm for a much needed shift from eco-efficiency to eco-effectiveness. Buildings are top contributor globally for resource use and waste creation. Therefore, any improvement in an effective use of building materials would have significant effects when scaled up. However, some interventions are better than others; in the sense that they can maximize the reduction of negative environmental externalities with minimal impact on the economy. This paper investigates the most effective strategies for the reduction of environmental impacts from building material and components within the context of the UK. It uses the most recent input-output table to establish the link between the reduction of environmental externalities and the impact on the various economic sectors. In doing so, an informed trade-off is achieved and intervention strategies that would yield the most beneficial effect for the environment with minimal impact on economic growth are identified.

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1. Introduction

The construction sector is the world's largest consumer of raw materials, and accounts for 25-40% of global carbon dioxide emissions [1]. In the past decades there have been numerous initiatives to improve those figure, but with little success.

More recently, it was accepted that the sole focus on the operational stage of buildings would not help reduce the overall environmental impacts, and whole life approaches are becoming increasingly mainstream as the right path to sustainability [2].

However, life cycle assessment (LCA) of buildings is far more complex than that of standard manufactured products, because built assets are characterized by long life-spans and numerous components that interact both temporally and dynamically [3]. Due to this complexity the suitability of LCA to guide significant improvements in the building sector is being questioned [4], even if it remains the most comprehensive tool to evaluate the life cycle environmental impacts of buildings [5].

Meanwhile, the new paradigm of the circular economy is increasingly gaining momentum, as a means to overcome the traditional contradiction between environmental consciousness and economic growth [6]. A recent review of existing research on the circular economy in the built environment can be found in [2], which also provides a research framework for future works in the field. However, the uptake of circular economy thinking within the built environment is still in its infancy, and this is likely due to the same reasons that make LCA hard to apply consistently, transparently, and rigorously.

Notwithstanding the difficulty of the task, it is evident that enabling circular economy in the built environment is a very worthwhile aim to pursue, for even small interventions that

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improve the effectiveness of resource use in the building sector would have significant environmental benefits.

To this end, this paper sets out to investigate which interventions are better than others, i.e. the most effective strategies for the reduction of environmental impacts from building material and components within the context of the UK. This materializes in a two-part problem:

1. Which interventions maximize the reduction of negative environmental externalities with minimal impact on the economy; and,
2. Which interventions maximize the economic growth given a target of accepted negative environmental externalities.

The paper unfolds as follows. Section 2 presents the methodology developed for and adopted in this research, while Section 3 presents and discusses the results in two separate sub-sections. Section 4 concludes the article and highlights future research directions.

2. Methodology

Given the whole-economy coverage that input-output (IO) tables provide, they represent a useful tool for circular economy research.

IO tables map, and allow to analyze, the industrial structure of an economy and its intersectoral links [7]. Additionally, if the simplifying assumption that average relationships between inputs and outputs apply at the margin, IO multipliers can be "used to quantify the impact of economic change" [7].

Over the years, IO tables have been enriched with satellite accounts, which include the negative environmental externalities of each economic sector. As such, they are often used in an environment-economic input-output framework [e.g. 8], and the expectation for the future is of a steady significant growth of research in the area [9]. In fact, it was already Wassily Leontief – who invented IO tables and received for this reason the Nobel Prize in 1973 – to highlight the possibility to assess environmental repercussions from the analysis of the economic structure [10].

Traditionally, IO tables present two main limitations:

- Very different sub-sectors (e.g. wheat and rice grains) are aggregated into a single sector (e.g. agriculture) and sector-specific impacts can be lost
- Different countries develop IO tables with different levels of granularity (i.e. different number of sectors, and what they include), thus increasing the difficulty to account for international trade

However, both limitations have been overcome in recent years by international teams of researchers who developed harmonized databases of IO tables for the whole world, with high level of granularity. One such database is EORA World MRIO [11, 12], which has been used in this research. Specifically, the most recent IO table available for the UK was used (IO_GBR_2013_BasicPrice).

The EORA IO table includes all intersectoral links between all sectors of the UK economy, as well the transaction between each of those sectors with the other countries of the world. All such transactions are expressed in '000 US Dollars. In addition, for each sector of the economy another matrix called 'satellite account' is available, which shows – for instance – energy inputs [TJ] and GHG emissions [Gg of CO_2, CH_4, N_2O] among others [12]. Due to the length requirement of the paper, the focus of this research is limited to CO_2 emissions only.

The IO table used features 511 different sectors for the UK and therefore the first necessary task was to identify those sectors more directly related to buildings. Thirteen sectors were identified, and their description is given in Table 1.

Table 1: Industrial sectors analyzed in this research

Sector classification	Sector No.
Timber	1
Bricks	2
Concrete	3
Plaster products for construction purposes	4
Steel	5
Mining, quarrying, and construction	6
Construction of commercial buildings	7
Construction of domestic buildings	8
Construction of civil engineering constructions	9
Construction of motorways, roads, and airfields	10
Construction of water projects	11
Other construction work involving special trades	12
Other building completion and finishing	13

It should be noted that there were two sectors ('Renting of construction or demolition equipment' and 'Renting of construction and civil engineering machinery and equipment') that were excluded due to their service nature and the high dependency on the other sectors already identified above.

Transactions and satellite accounts are expressed in IO analysis in matrix form. The first one is called transaction matrix and is square by definition because rows and columns refer to the same elements (sectors and industries). This is then transformed into a matrix of technical coefficients by dividing each input to its output [13] and in IO LCA is generally referred to as matrix **A**. The second one is called the satellite matrix (**B**) and contains the environmental flows for each element of the transaction matrix [10]. The matrix **A** is linked to the final demand vector **y** and the total output vector **x** of an economy through the famous Wassily Leontief's equation:

$$x = (I - A)^{-1} y \tag{1}$$

where $\mathbf{I}$ is the identity matrix, and $(\mathbf{I} - \mathbf{A})^{-1}$ goes under the name of the Leontief inverse matrix [14].

The powerfulness of IO analysis lies with its capability to account for impacts occurring in upstream layers of the supply chain, thus ensuring the quantification of all indirect emissions as well as the direct ones. Mathematically, this is done through the composition of all CO_2 embodied emissions into an infinite series of production layers. In this case, let us assume we have a functional unit **f** which contains all zeroes other than the entry related to the sector being analysed (e.g. Sector 1 in Table 1), and that entry is 1 (which corresponds to 1000 $). The expansion into an infinite series to calculate the carbon emissions **C** works as follows:

$$C = B(I + A + A^2 + \cdots)f = Bf + BAf + BA^2 f + \cdots \quad (2)$$

It should be noted that the more we expand the series the smaller the terms gets as they are powers of a matrix with values smaller than 1. Of course, an infinite series is not possible to calculate but research has shown that there is a clear plateau after the analysis of about 8 upstream production layers and stability is reached [15, 16]. This approach can then be repeated for all 13 sectors of Table 1 to assess the carbon intensity of each sector and its upstream supply chain.

To address the second part of this research, a different approach had to be developed. Specifically, a target increase in negative environmental externalities (e.g. **ΔC** = 1 tonne CO_2) was established and an iterative algorithm was designed to find, for each of the thirteen sectors, the new value of **f** that would produce that **ΔC**. In pseudo-code, this can be expressed as:

```
for $i$ = 1 : $N_{sec}$
    find $f_{(i)}$ subject to $\Delta C = 1000 kg_{CO_2}$        (3)
```

All calculations have been performed in MATLAB R2015b ©. Results are shown and discussed in the next section.

3. Results and discussion

Results are presented in separate sub-sections for the two parts of the research addressed in this paper.

3.1. Carbon intensity of building-related industrial sectors

Figure 1 shows the direct and indirect emissions for all 13 sectors analyzed in this research.

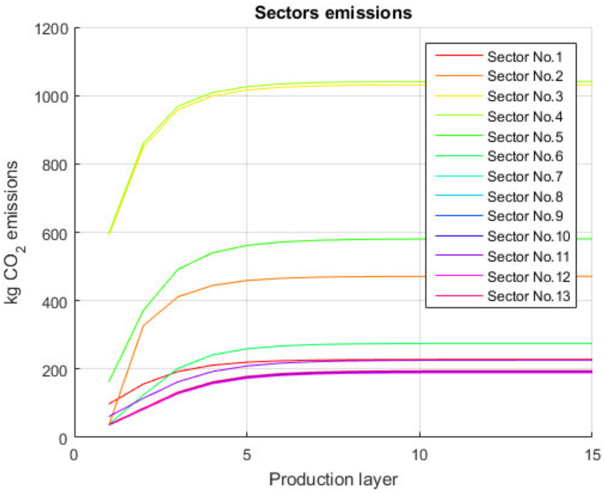

Figure 1 - Direct and indirect emissions of building-related industrial sectors

It can be seen that different sectors have very different emissions intensity, and there is also difference in how steep the curves are towards the final value of emission intensity for the whole supply chain related to each of the sectors.

Figure 2 shows the convergence to system's completeness for all 13 sectors.

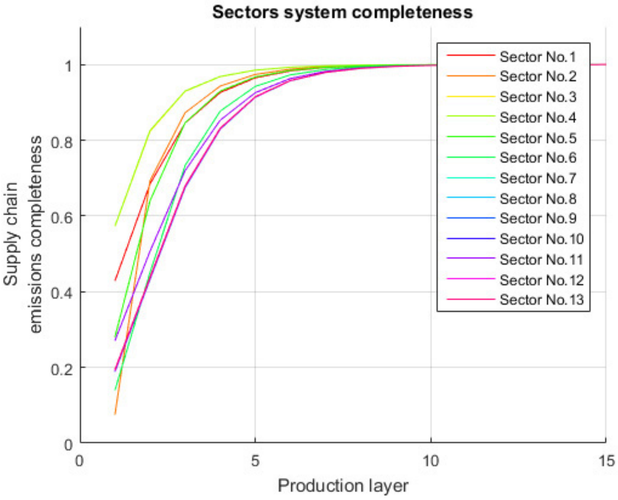

Figure 2 - Analysis of system completeness for all 13 sectors investigated

It can be seen that several of the curves cross one another, thus meaning that some sectors achieve most of the indirect emissions in the first upstream layers of the supply chain, while others show a more regular and steady increase.

Figure 2 also confirms that an infinite series expansion is not necessary as a clear plateau is reached after around 7-8 upstream production layers [15, 16]. The influence of direct vs. indirect figures on results and consequential decision-making can be more clearly seen in Table 2.

Table 2: Emission intensity ranking of building-related industrial sectors for both direct and indirect emissions

Sectors	**Rank (direct emissions)**	**Rank (+ indirect emissions)**
(1) Timber	4	6
(2) Bricks	13	4
(3) Concrete	2	2
(4) Plaster products for construction purposes	1	1
(5) Steel	3	3
(6) Mining, quarrying, and construction	6	5
(7) Construction of commercial buildings	11	12
(8) Construction of domestic buildings	12	11
(9) Construction of civil engineering constructions	10	10
(10) Construction of motorways, roads, and airfields	8	9
(11) Construction of water projects	5	7
(12) Other construction work involving special trades	9	13
(13) Other building completion and finishing	7	8

The three sectors which scored the highest in terms of direct emissions are also the three with highest overall emission figures. However, apart from those all other sectors have shifted – and in some cases significantly – their position in the rank. For example, bricks as a structural material (Sector 2) would seem a very advantageous option (lowest rank in direct emissions) but it skyrockets to fourth position when the whole supply chain is considered. If only partial (direct emissions) information were available, a policy maker could think that to achieve circularity in the built environment investing heavily in the bricks industry would be one of the best options to effectively use resources, minimize environmental externalities, and promote economic growth. However, the whole system analysis shows that the result of such decision would be rather the opposite, given the high-polluting upstream supply chain linked to the brick industry.

Conversely, timber appears to be a very viable structural material for the UK as it drops from 4th to 6th position when the analysis switches from direct emissions to the whole supply chain. The usual suspects (i.e. concrete and steel) are the structural materials with the highest emission intensity and, as such, their use should be progressively reduced and targeted mitigation efforts should be aimed at those sectors.

It is remarkable to see that the sector 'plaster products for construction purposes' (Sector 4) has higher impacts than any of the structural materials, despite the widespread belief that building structures account for the most carbon emissions in buildings. Of course, this is also due to all refurbishment activities, which do require plaster products without the need of a new structure. However, this finding challenges a false myth in the LCA of buildings, whereby impacts occurring in the use stage (i.e. precisely those related to maintenance, repair, and refurbishment) are often neglected under the belief that their contribution is not significant. These results prove quite the opposite in fact, and circular economy policies should unreservedly take into account the fit-out cycles of domestic and non-domestic buildings as well as the materials used in maintaining, repairing, and refurbishing the existing building stock.

3.2. Economic profitability of building-related industrial sectors

A main component of the circular economy paradigm is a more effective use of resources that does not translate into a halt to economic growth. As explained in Section 2, IO tables represent an excellent tool for such kind of investigation—which falls under the name of multiplier analysis—providing the simplifying assumptions explained in the methodology are understood and accounted for [7].

In this particular case, multiplier analysis will be used to decompose the effects of change according to the "the initial output effect", which allows to investigate the change of an industry required to supply an additional unit of final output of that industry [7].

The novel approach proposed here, however, lies with linking the additional output supply to a given target value of increase in negative environmental externalities, which is represented in the case of this research by 1 tonne of CO_2.

Figure 3 shows the resulting emissions across all sectors for such analysis. It can be seen that the emissions for the complete system (direct + indirect) are 1000kgCO_2 greater than those shown in Figure 1.

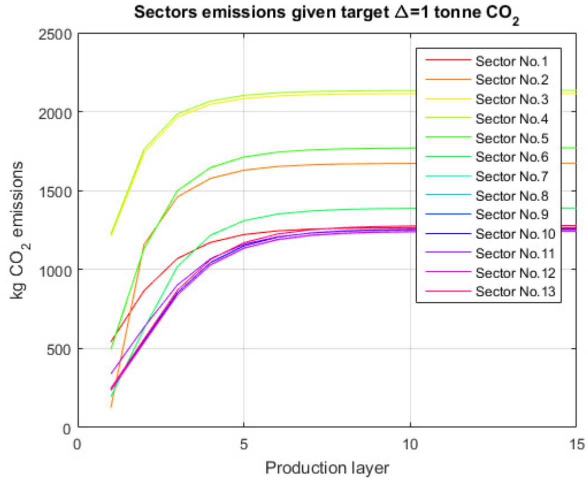

Figure 3 - Sectors' emissions given a target value of CO_2 increase

Table 3 shows how the functional unit **f** changed for all 13 sectors when the same target of increase in carbon emissions (**ΔC** = 1 tonne CO_2) was given. It should be noted that some numbers appear identical (e.g. Sector 3 and Sector 4 have the same value of 2.1). This is due to the incremental step used in the algorithm to search for **f**, which has been set to 0.1 (=100 USD). In reality, with smaller incremental steps, different numbers would be obtained but the significance to the results is negligible.

Table 3: Analysis of economic growth for building-related sectors given a target value of increase in CO_2 emissions

Sector No.	Old functional unit f (Figure 1) ['000 USD]	New functional unit f (Figure 3) ['000 USD]	Rank (from the most to the least profitable)
1	1	5.5	8
2	1	3.3	10
3	1	2.1	12
4	1	2.1	12
5	1	2.9	11
6	1	4.8	9
7	1	6.4	1
8	1	6.4	1
9	1	6.4	1
10	1	6.4	1
11	1	5.6	7
12	1	6.4	1
13	1	6.3	6

Results show very well the different emission intensities across the 13 sectors. This enables to understand which sectors would yield the highest economic growth for a given amount of negative environmental externalities that the society is willing to pay.

It can be seen that the sectors in which the government should invest are the *'Constructions'* sectors (with the exception of Sector 11 'Construction of water projects')—namely Sectors 7, 8, 9, 10, and 12. The reason is to be found in the very own nature of those sectors, for they are highly labor-intensive, and human labor has a lower emission intensity than, say, manufacturing activities. Within the bigger picture of a whole economy, investing in those sectors might promote employment while keeping carbon emissions at bay.

In terms of building materials timber seems, also from this perspective, a worthwhile sector to invest in. Specifically, 1 additional tonne of CO_2 in the timber is linked to an increase of 5,500$ which is more than twice as much as the increase in concrete and plaster sectors (2,100$), 90% more than the increase for steel (2,900$), and 67% more than that for bricks (3,300$). These numbers show that, while fully decoupling economic growth from environmental costs might still be quite far ahead, it is already possible to develop conscious policies aimed at minimizing environmental costs to promote economic growth.

4. Conclusions and future work

This paper has investigated, through an environmentally extended input-output analysis, the results of applying circular economy thinking to building-related industrial sectors in the UK. In total, 13 sectors have been identified, which are primarily linked to the manufacturing of structural and building materials, and the construction of buildings and built assets. Circular economy aims at fully decoupling economic growth from negative environmental externalities. While this is only likely to be achieved in the mid-to-long term, results from this research have shown that it is possible to develop environmentally conscious policies to mitigate environmental impacts from buildings and the construction sector.

Results from this research addressed a two-part problem. Firstly, they allowed to identify which interventions maximize the reduction of negative environmental externalities with minimal impact on the economy. One such example is reducing the use of plaster products in the fit-out cycles of buildings while promoting the development and adoption of reusable materials with lower environmental impacts.

Secondly, the results allowed to evaluate which interventions would yield maximum economic growth given a target of accepted negative environmental externalities. One example in this respect is represented by higher investments in, and a wider use of, timber which appears to be the structural material characterised by a lower carbon emission intensity. However, the sole focus on carbon emissions represents one of the limitations of this work. A wider use of timber would likely have repercussion across other environmental impact categories, such as deforestation and land use change.

While tackling global warming and climate change is of the utmost importance, it also crucial to avoid shifting environmental burdens from one impact category to the others [17] if the circular economy is to achieve environmental sustainability holistically. For this reason, future works should carry out a broader assessment which includes all negative environmental externalities available in the satellite accounts of IO tables, such as water and land use, and air quality indicators – for instance.

Additionally, calculating emission intensities with IO has a limitation, in the sense that results are significantly influenced by the price of products. Future work should use a physical reference investigate the results without the influence of prices. Additionally, a broader approach that considers IO data from the last decade would certainly strengthen the reliability of the findings and the confidence in the directions towards which they seem to point.

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