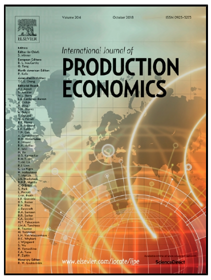
Accepted Manuscript



Pollution responsibility allocation in supply networks: A game-theoretic approach and a case study

F. Ciardiello, A. Genovese, A. Simpson

PII: S0925-5273(18)30419-5

DOI: 10.1016/j.ijpe.2018.10.006

Reference: PROECO 7195

To appear in: *International Journal of Production Economics*

Received Date: 05 June 2017

Accepted Date: 10 October 2018

Please cite this article as: F. Ciardiello, A. Genovese, A. Simpson, Pollution responsibility allocation in supply networks: A game-theoretic approach and a case study, *International Journal of Production Economics* (2018), doi: 10.1016/j.ijpe.2018.10.006

Pollution responsibility allocation in supply networks:

A game-theoretic approach and a case study

F. Ciardiello*, A. Genovese*, A. Simpson*

*Management School, University of Sheffield
Conduit Road, Sheffield S10 1FL (UK)
{f.ciardiello, a.genovese, andrew.simpson}@sheffield.ac.uk

Abstract

This study introduces a cooperative game theory approach aimed at addressing the problem of allocating pollution responsibility across partners collaborating in supply networks. The proposed framework includes three different allocation rules through which companies can share pollution responsibility across complex supply networks. A case study in the context of a supply network for the manufacturing of construction materials is illustrated for demonstrating the real-world applicability of the approach.

Keywords: Supply Networks, Multi-Tier, Pollution Responsibility Allocation, Game Theory, Shapley Value

Pollution responsibility allocation in supply networks: A game-theoretic approach and a case study

Abstract

This study introduces a cooperative game theory approach aimed at addressing the problem of allocating pollution responsibility across partners collaborating in supply networks. The proposed framework includes three different allocation rules through which companies can share pollution responsibility across complex supply networks. A case study in the context of a supply network for the manufacturing of construction materials is illustrated for demonstrating the real-world applicability of the approach.

Keywords: Supply Networks, Multi-Tier, Pollution Responsibility Allocation, Cooperative Game Theory, Shapley Value

1. Introduction

Environmental consciousness plays a pivotal role in contemporary global supply networks (Allaoui et al., 2018). Newly introduced regulations, especially in the European Union (EU), require robust sustainability certifications for companies participating in public procurement exercises (UN Global, 2011). Also, in the private sector, large multi-national enterprises are adopting tighter requirements for their suppliers, which also involve small and medium-sized enterprises (SMEs) (UN Global, 2011).

Such stringent environmental performance standards also encourage the implementation of benchmarking approaches; for instance, Life Cycle Assessment (LCA) methods allow estimating environmental impacts of supply networks against a wide set of indicators.

While LCA methods are gaining popularity, they should be enhanced by considering the concept of pollution *responsibility*. Allocating environmental impacts (including carbon emissions, land use, waste generation) to actors in the supply network is a fundamental issue if proper mitigation, abatement and remedial actions need to be implemented. This debate is very relevant to policy-making; for instance, currently, the European Union and national governments are promoting directives and legal requirements for maximising the proportion of marketed products which are recovered and recycled (European Commission, 2014). Such directives extend the producer *responsibility*, forcing them to have adequate plans (and adequate financial commitments) for managing the materials in their products at the end of their life. Policies can also involve incentives for producers to design their products taking into account environmental considerations (European Commission, 2014; Gui et al., 2018). Similar obligations currently cover producers of packaging, batteries, vehicles, tyres and electrical goods, with calls for these obligations to be extended to other consumer goods, with the objective of achieving a reduction in the environmental impact of products, throughout their lifespan, from production through end-of-life.

Scientific interest in the pollution responsibility issue started with the aim of suggesting pollution burden sharing mechanisms across countries (see, for instance: Leontief and Ford, 1970; Wyckoff and Roop, 1994; Bastianoni et al., 2004; Lenzen and Murray, 2010). While an abundant stream of literature has been developed in order to tackle allocation problems within different contexts, the vast majority of the current methods analyze these problems at a macro-level (Zhou and Wang, 2016). The application of pollution responsibilities approaches to contemporary multi-tier and multi-stakeholders supply networks is often overlooked.

In order to bridge this literature gap, this study provides a normative framework (based on cooperative game theory) for pollution responsibility allocation across multi-tier supply networks. After the formal identification of literature gaps through an appropriate review (Section 2), the paper presents the mentioned framework from a general point of view (Section 3). In Section 4, such framework is adapted to a generic supply network, by developing appropriate pollution responsibility allocation rules. Section 5 develops a practical application of the introduced cost allocation rules, with the reference to a case study from the construction materials supply network; results, along with some managerial implications are also discussed. Conclusions and avenues for future research are then drawn.

2. Environmental Pollution Responsibility: a Literature Review

Based on the review by Zhou and Wang (2016), pollution responsibility allocation methods can be classified into several categories, which are discussed in details in the following of this section.

2.1 Indicator-based approaches

One of the most popular methods for determining environmental pollution targets or permits is the one based on the development of specific indicators (Zhou and Wang, 2016). Methods based on single-indicator approaches employ an individual indicator for allocating emission permits or reduction targets among a set of actors (Rose and Stevens, 1993). Single indicators that have been used for this purpose include Population, GDP, Emissions and Energy Usage, Emission Intensity. Also, composite indicator approaches have been developed in order to develop multi-criteria tools incorporating multiple perspectives for conducting the allocation exercise (Ringius et al., 1998; Vaillancourt and Waaub, 2004).

Notably, the work of Gallego and Manfred (2005) and Lenzen et al. (2007) illustrated approaches for pollution responsibility allocation based on an Input-Output (I/O) analysis framework. Through a Multi-Regional I/O framework, Zhang et al. (2015) proposed mechanisms (based on both production and consumption perspectives) for allocating carbon emissions at a provincial level in China. Llop and Ponce-Alifonso (2015) proposed a structural path method for allocating responsibilities related to water ecosystems degradation.

2.2 Optimization approaches

Optimization approaches (based on mathematical programming framework) can successfully be employed for dealing with pollution allocation problems. Efficiency perspectives (i.e., minimizing the cost of pollution abatement measures) mainly characterize these studies. According to Zhou and Wang (2016), Data Envelopment Analysis (DEA) is a very popular approach for solving this sort of problems. Färe et al. (2012) proposed a DEA model for evaluating pollution abatement strategies in different countries over a multi-year time horizon. Several authors have proposed DEA for examining emissions allocation across Chinese provinces (e.g. Wei et al., 2012; Wang et al., 2013; Zhou et al., 2014). Lozano et al. (2009) and Sun et al. (2014) provide applications to the micro-level (i.e., single firm).

2.3 Game Theoretic approaches

Pollution allocation mechanisms often include negotiation and bargaining processes among multiple actors. As such, Game Theory might model these situations in a very effective way, with allocation results which could be seen as equilibrium solutions to games.

Chander and Tulkens (1995) and Filar and Gaertner (1997) provided seminal contributions employing Game Theory for studying the allocation emission reduction quotas among countries; classical cooperative game theory concepts (including the Shapley value method) have been utilized for this purpose, with the aim of achieving fair and equitable distributions (Rose, 1990).

Eyckmans and Tulkens (2003) developed a similar approach to the problem, while Germain and Steenberghe (2003) adopted a dynamic game framework. In order to solve a similar allocation problem, Viguier et al. (2006) deployed a two-level game. At a regional level, Shi et al. (2017) test multiple game-theoretic approaches (i.e., the nucleolus, Nash-Harsanyi allocation solution, Shapley value and Separable Cost Remaining Benefit principle) for evaluating collaborative and cost-effective SO_2 reduction strategies in three cities of Hunan province in China. Similarly, Huang et al. (2018) developed a game-theoretic model based on the formation of fuzzy coalitions in order to deal with pollution discharge rights.

At a company unit of analysis, MacKenzie et al. (2008) utilized rank-order contests for allocating pollution perits; MacKenzie et al. (2009) developed a further application to the same problem by employing incomplete information games. Chung et al. (2013) deployed dynamic games to evaluate companies' responses to environmental pollution taxes in a spatially distributed supply chain. Liao et al. (2015) applied a Shapley value framework for working out a fair allocation of emission allowances across energy producers in Shanghai. A Stackelberg game is constructed by Ren et al. (2015) for studying CO_2 reduction targets in a buyer-supplier interaction. Compared to the other methods, the game theoretic approach might seem less straigthforward. However, such methods have the advantage of inherently incorporating the implicit negotiations between different stakeholders about environmental pollution responsibility allocation. The use of these approaches, however, is underexploited, especially when dealing with complex and multi-tier supply networks which can represent real-world production systems.

2.4 Hybrid Approaches

Hybrid approaches combine multiple methods from the above-mentioned categories. For example, Ridgley (1996) integrated composite indicators with an optimization method for producing suitable pollution responsibility allocations at a country level. Gomes and Lins (2008) combined Data Envelopment Analysis and Game Theory for solving the problem at the same level; Sun et al. (2017) employed a similar combination in order to deal with emission permits allocation across competing companies. Similar frameworks have also been employed by Pang et al. (2015) for permit allocation across countries. Yu et al. (2014) addressed the problem from a regional perspective in China by combining a particle swarm optimization algorithm, fuzzy c-means clustering algorithm, and game-theory approaches based on Shapley decomposition.

Hybrid approaches have generally a higher level of complexity; therefore, allocation results might lack transparency. Nevertheless, the combination of multiple methods can allow the simultaneous consideration of different fairness and efficiency criteria.

2.5 Research Gaps and Contribution of the Paper

The proposed overview of the literature, coherently with findings from the extensive review from Zhou and Wang (2016), allows the identification of the following gaps:

- Most of the literature is concerned with pollution responsibility at a macro-level, dealing with allocation problems from a national or regional perspective.
- Despite the existence of firm-level approaches, the supply chain perspective has been, so far, largely overlooked. Also, the few approaches which are available in this domain are characterized by very simple buyer-supplier dyadic relationships.

- Multi-tier perspectives and multi-stakeholder views, which are intrinsic to contemporary supply networks, involving multiple companies at each tier, are rarely incorporated.

In order to bridge these gaps, the main contribution of this paper focuses on the development of a pollution responsibility allocation framework for a generic multi-tier and multi-stakeholder supply network (characterized by the presence of multiple companies at each tier). A game theoretic approach, based on the recent work from Ciardiello et al. (2018), will be developed, given the suitability of such methods for dealing with these problems (Zhou and Wang, 2016; Ciardiello et al., 2018).

3. A general game theoretic responsibility framework for supply networks

We recall the game theoretic responsibility framework, which has been introduced in Ciardiello et al. (2018). A supply network consists of companies ($i = 1 \ldots |N|$). A generic process (i, j) represents the production of goods by company i to be supplied to company j. A set of processes P_i (with $|P_i| \leq |N|$) is associated with each company. For a generic representation of such supply network, see Figure 1. The set P is equal to $\cup_{i=1 \ldots n} P_i$. Furthermore, each process is characterized by an environmental cost (indicated as c_{ij}, with the generic c_{ij} belonging to a generic set C).

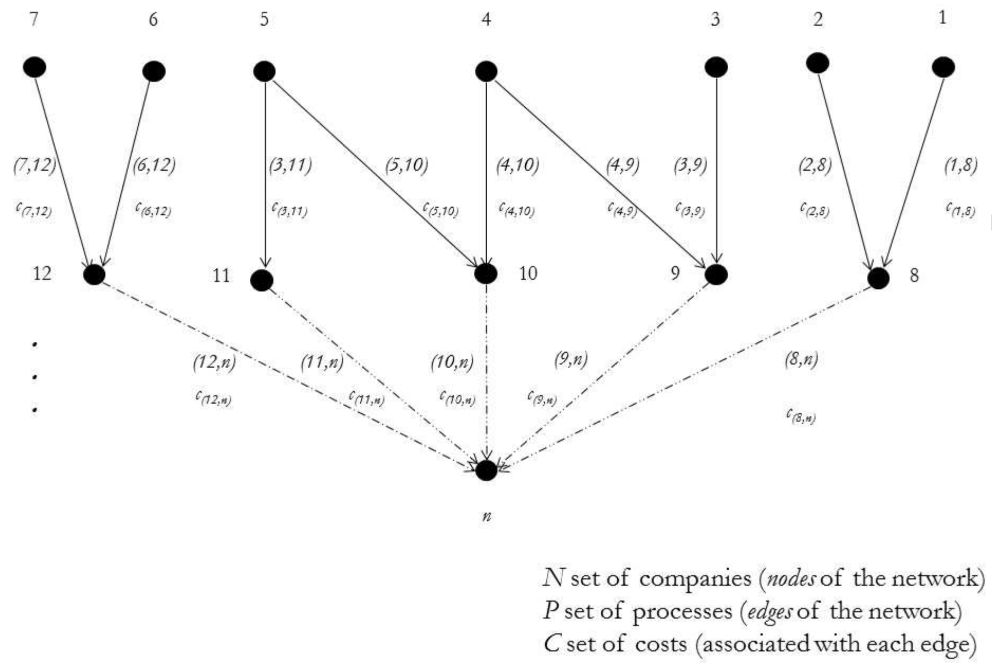


Figure 1 – Generic supply network representation

A generic mathematical framework can be constructed as follows:

$$(N, P, C) \qquad (1)$$

A $|N| \times |P|$ responsibility matrix $B = (B_{i,p})$ can be introduced, where the row index i represents companies and the column index p represents processes; $b_{ip} = 1$ if company i is responsible for process p, $b_{ip} = 0$ otherwise. Let B_i be the set of the processes for which company i is environmentally responsible, that is $B_i = \{p \in P \mid b_{ip} = 1\}$. It is remarkable to outline that b_{ip} may be equal to 1 even if process does not involve company i. Therefore, the framework (1) can be rewritten as (N, P, B, C), where B is the responsibility matrix. A coalition responsibility set can be defined as $B_S = \cup_{i \in S} B_i$; then, the social cost function for each coalition of companies $S \subseteq N$ can be defined as follows:

$$v(S) = \sum_{p \in B_s} c_p \qquad (2)$$

The last quantity is the environmental cost of all the processes for which at least one company, which belongs to the coalition S, is responsible. Moreover, each cost is enumerated only once even if more than one company may be responsible for the same process.

Being N a finite set, $v: 2^N \rightarrow R$ is a function which associates a real value with each subset of N. Following a classical definition, (N, v) represents a cooperative game with a characteristic function. In addition, the elements in N are called players; v represents the characteristic function of the game. By construction, the characteristic function v is defined through P, B and C, therefore leading to the following primitive model:

$$G = (N,P,B,C,v) \qquad (3)$$

Such cooperative games are defined in terms of a characteristic function, which specifies the utility that each coalition can achieve. By assuming the formation of a *grand coalition*, the main aim of such games is the definition of a solution concept, which allocates utility (or, alternatively, costs) among each player in N. In a supply network context, it can be assumed that companies form binding agreements for coordinating production activities. Cooperative game theory can provide solutions by allowing transferable payments among companies. Therefore, the cost allocation becomes a vector $x = (x_i) \in R_+^{|N|}$ taking into account transferable payments. Such redistribution is efficient in our settings. To be more precise, an allocation is efficient if the sum of all cost-allocations, that is $\sum_{i=1}^{|N|} x_i$, is equal to the sum of all costs, i.e. $\sum_{i=1}^{|N|} \sum_{j=1}^{|N|} c_{ij}$.

Among efficient allocations, the Shapley value (Shapley, 1953) represents an allocation rule, which has gained a relevant normative reputation because of its distributive justice. Following this fair approach to cost allocations, we claim that allocations satisfy the following property: if B_i is empty implies that x_i is null. Throughout the current, paper we will always refer to allocations satisfying the responsibility-compatibility principle.

4. Responsibility rules for Supply Networks

The set of processes P can be seen as a mathematical relation defined on the set of companies N. We define $\mathrm{P}(i) := \{j \in N \,|\, (i, j) \in P\}$ as the section of the relation $P \subseteq N \times N$ for the element $i \in N$. The subset $\mathrm{P}(i) \subseteq N$ can be interpreted as the set of companies, which are supplied by company i. Similarly we define the inverse relation of P, that is P^{-1}. We say that $(i, j) \in P^{-1}$ if and only if $(j, i) \in P$, namely if the company j supplies the company i. It follows that $(i, j) \in P^{-1}$ means that the company i is supplied by the company j. Similarly we define the section of P^{-1} for i in the following way: $P^{-1}(i) = \{j \in N \,|\, P^{-1}(i) = j\}$.

We also define the transitive closure of the relation P, and we denote it by $\grave{P}$. By definition, $(\mathrm{i}, j) \in \grave{P}$ if and only if there exists a chain of firms $h_s = j$ such that $(h_s, h_{s+1}) \in \mathrm{P}$ with $s = 1 \ldots \mathrm{m}$ where $h_1 = i$ and $h_{m+1} = j$. Similarly, we define the transitive closure of the relation P^{-1}, denoted by $\grave{P}^{-1}$. Therefore, we have that $j \in \grave{P}^{-1}(i)$ if and only if there exists a chain of firms h_s such that $h_{s+1} \in P^{-1}(s)$ and $h_s = j$ with $s = 1 \ldots m$.

We define the following set of firms on the supply network structure:

- $\sigma(i) = \{i\} \cup \grave{P}^{-1}(i)$. Such a subset contains all the firms, which are located downstream with respect to i; for each s in $\sigma(i)$ there exists a path composed of processes which start form the product supplied by the company i and, at the end, becomes a product which is supplied to the company s.

- $\alpha(i) = \{i\} \cup \grave{P}(i)$. Similarly, this represents the set of firms located upstream in the supply network with respect to i.

In this section, we assume that each company can act as a supplier for a single company within the supply network of a given product. By assuming this, the supply network assumes a tree-structure (see Figure 2). As such, since $\mathrm{P}(i)$ is a singleton, there is one and only one process starting from i; the cost attached to this process can be identified as c_i.

Let us call $|N| = n + 1$. In this context, we can assume that existence of a *final* company $n + 1$; such a company is characterized by the following assumption: $P_{n+1} = \emptyset$. We further assume that the final company has no environmental responsibility, which is characterized by the assumption $B_{n+1} = \emptyset$. If straightforwardly follows that the responsibility matrix is a $(n + 1) \times n$ matrix, where $(n + 1)$ is the number of firms and n is the number of processes. From the company n, a single process starts, and it supplies the final company $n + 1$. Because we focus on responsible-compatible allocation, we can say that $x_{n+1} = 0$. Therefore, we disregard the final company $n + 1$ because of its always null cost allocation. Therefore the number of *significant* firms becomes equal to the number of processes n.

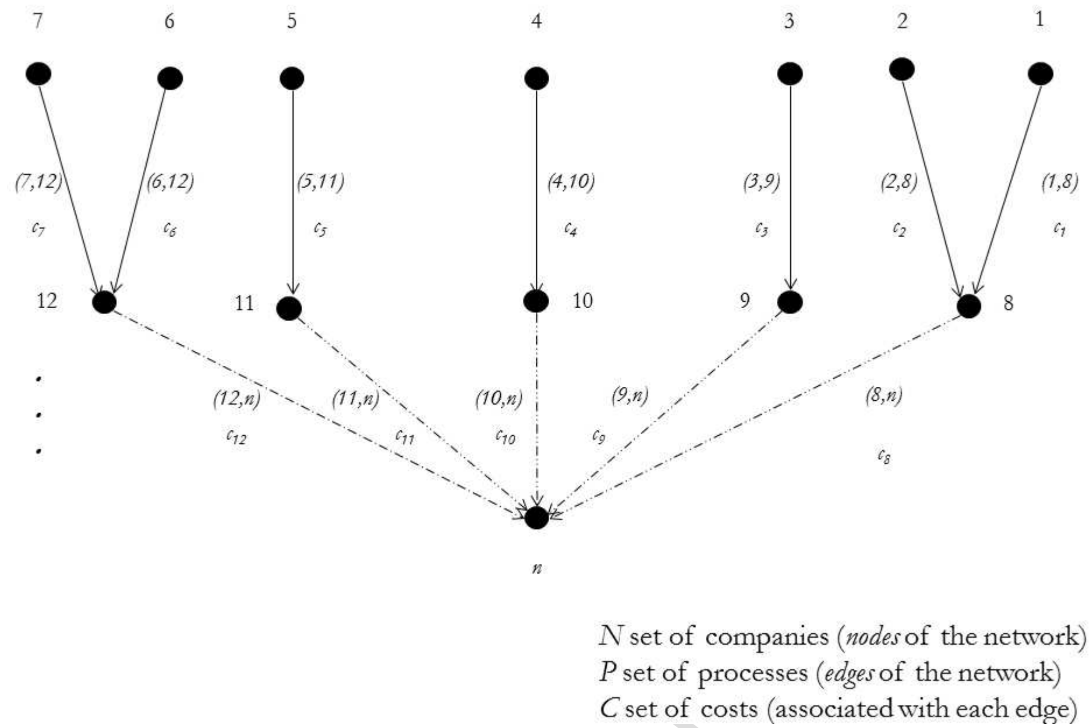


Figure 2 – Tree-type supply network representation

The responsibility matrix B can be defined according to three different responsibility allocation principles, introduced as follows:

- A Local Responsibility principle (LR), according to which each company i is strictly responsible for the pollution costs, related to the production activities strictly happening at its premises. Then we may formalize $B_i = (i, j)$ where j is the only company supplied by firm i.
- An Upstream Responsibility principle (UR), stating that upstream suppliers (dealing with raw material extraction, sub-component manufacturing and other energy intensive activities) are responsible not only for pollution happening at their premises, but can also influence the environmental performance of downstream

partners. This can be formalized, for a generic company i, as: $B_i = \{(h,k) \in P \mid h \in \sigma(i), \mathrm{k} \in N\}$.

- A Downstream Responsibility principle (DR), stating that downstream partners in the supply network are responsible of the polluting activities happening at upstream suppliers' premises. This can be formalized, for a generic company i, as: $B_i = \{(h,k) \in P \mid h \in \alpha(i), \mathrm{k} \in N\}$.

In the previous Section 3, we introduced the model $G = (N,P,B,C,v)$ where the responsibility matrix was generic. Here we adopt the three above responsibility matrices and, then, we obtain three different cooperative models. We say that G becomes:

- A *stand-alone game* if the LR principle is adopted.
- An *upstream-oriented game* if UR principle is adopted.
- A *downstream-oriented game* if DR principle is adopted.

It can be noted that the mathematical formulation of our model in (3), when LR or UR or DR responsibility principles are adopted, becomes equivalent to the river network problem introduced by Dong et al. (2012). In this problem, a river network is polluted by agents agents (e.g., firms, villages, municipalities, or countries) which are located upstream and downstream. Agents must deal with pollution by implementing some mitigation actions, whose costs must be distributed among the agents themselves. Dong et al. (2012) model this problem as a cost sharing problem on a tree network. Interestingly, (Dong et al., 2012) find a solution to the river network problem by using LR, UR and DR principles. They allocate cleaning costs to the different municipalities and the government by using the Shapley value allocation method (which provides a responsible-compatible cost allocation)[1].

.Given the fact that the mathematical formulation of the model presented in (3) is equivalent to the one from Dong et al. (2012), it can be deduced that Shapley value allocations for such a model are equivalent to the ones provided by Dong et al. (2012) for the river network problem (by taking into account that the company $(n+1)$ has always a null cost allocation). As such, the following allocation rules from Dong et al. (2012) can be adapted to our case (refer to the original paper for the proof of the related theorems).

Allocation Rule 1 - LRS

Local Responsibility Sharing cost allocation rules can be defined as:

$$x_i^{\mathrm{LRS}} = \mathrm{c_i} \qquad (4)$$

Furthermore, as shown by Dong et al. (2012), x_i^{LRS} is the Shapley value of the stand-alone game (N,P,B,C,v).

Allocation Rule 2 - DES

The Downstream Equal Sharing cost allocation rule can be defined as:

$$x_i^{\mathrm{DES}} = \sum_{\mathrm{j} \in \alpha(\mathrm{i})} \frac{\mathrm{c_j}}{|\sigma(\mathrm{j})|} \qquad (5)$$

[1] The compatible-responsible nature of the Shapley value allocation can be shown with the following simple proof. Let us assume that a firm i is endowed with an empty subset $\mathrm{B_i}$. Given the coalition responsibility set and the mathematical formulation of (2), it is straightforward to see that firm i does not increase pollution costs of any group of companies. The latter means that company i, according to a classical property of the Shapley value, can be regarded as a *dummy* player; as such, the Shapley value of firm i is null. Therefore, the Shapley value is a responsible-compatible cost allocation.

Furthermore, as shown by Dong et al. (2012), x_i^{DES} is the Shapley value of the upstream oriented game (N,P,B,C,v).

Allocation Rule 3 - UES

The Upstream Equal Sharing cost allocation rule can be defined as:

$$x_i^{UES} = \sum_{j \in \sigma(i)} \frac{c_j}{|\alpha(j)|} \qquad (6)$$

Furthermore, as shown by Dong et al. (2012), x_i^{UES} is the Shapley value of the downstream oriented game (N,P,B,C,v).

5. A Case Study

The developed approach has been tested on a real-world case study related to the supply network for the manufacturing of thermal and insulation materials. Insulation materials (for thermal and acoustic purposes) represent one of the crucial components in the construction of new buildings and in renovation projects. In the United Kingdom (UK), insulation products contribute largely to construction materials markets. Also, with the growing emphasis placed on the energy performance of buildings, such materials play a pivotal role in improving environmental credential of construction projects, through prevention of heat loss in buildings.

Stone wool (a furnace product of molten rock) represents one of the main insulation materials based in the construction industry (Väntsi and Kärki, 2013).

This case study focuses on the supply network associated with the production of stone wool. Primary data from one of the leading producer for this material (which is here anonymised for confidentiality purposes), along with Ecoinvent (2018) database were utilized to extract data related to the "cradle-to-grave" part of the supply network of the product. This includes raw material inputs, energy inputs (assuming medium voltage electricity for industrial use in the UK), production process, distribution processes up to the retail store; emissions associated with the installation of product, its usage and disposal are not included.

In a typical supply network, carbon equivalent emissions (expressed in Kg CO_2-eq per Kg) can be utilized as a proxy indicator for a wide range of environmental impacts (Genovese et al., 2017). Based on multiple sources (Nasir et al., 2017; Ecoinvent et al., 2018), CO_2-eq emissions (per kilogram of product) happening at each stage of the supply network can be reported as shown in Figure 3. Pollution abatement costs can be assumed proportional to such environmental impacts.

The results of the three allocation principles shown in Section 4 (LRS, UES, DES) to the considered supply network are shown in the following Figures 4, 5 and 6; calculations were performed in the *Mathematica 10* computing environment through the code provided in the Appendix.

As expected, the three proposed allocation principles provide very different results, allocating different shares of the total environmental impacts to different supply network partners. By employing the LRS rule, the highest proportion of environmental impacts (and, therefore, of associated mitigation costs) is assigned to the actual stone wool producer, respecting a simple proportionality mechanism. UES and DES rules produce more complex allocations. Interestingly, the DES rule strongly penalizes the Retailer (who is seen as responsible for demanding the activation of the whole supply network for the manufacturing of the products that are going to be sold at its premises), while the UES one penalizes the raw material suppliers (which are seen as responsible for extracting and employing virgin resources). It must be highlighted that such rules reproduce respectively the concepts of consumer and producer responsibility (as defined by Rodrigues and Domingos, 2008).

The three allocation rules must not be seen as mutually exclusive; indeed, convex combinations of these rules might be developed. Table 1, as an example, illustrates the results deriving from a combination of the LRS and DES rules. This could be done for introducing, within a prevailing LRS framework, elements of downstream responsibility.

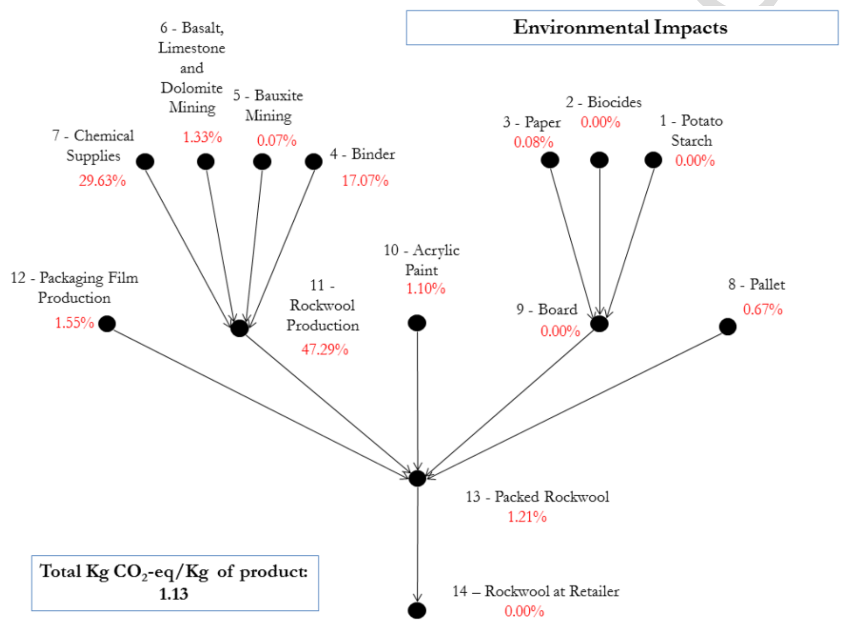


Figure 3 – Environmental Impacts (in Kg CO_2-eq/Kg

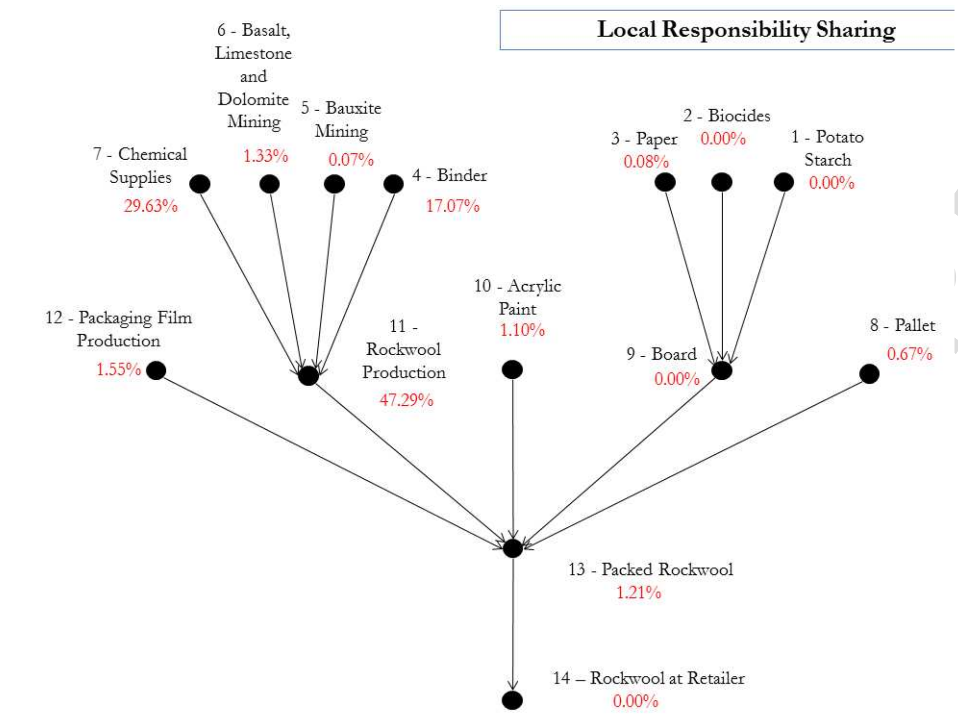


Figure 4 – Local Responsibility Sharing Allocation Results

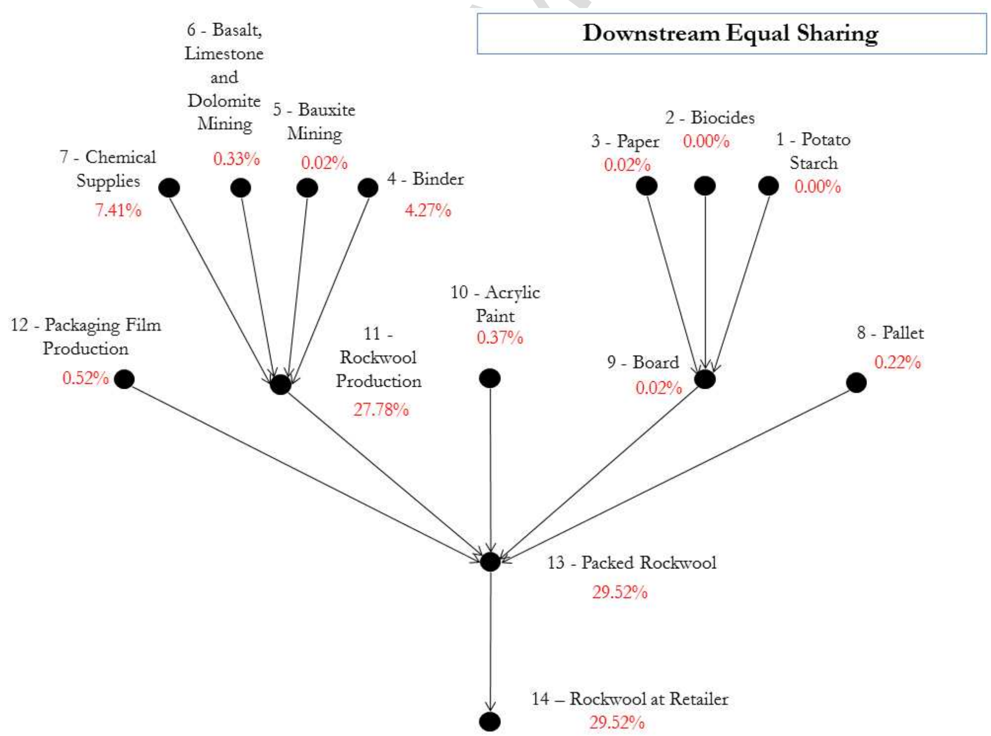


Figure 5 – Downstream Equal Sharing allocation results

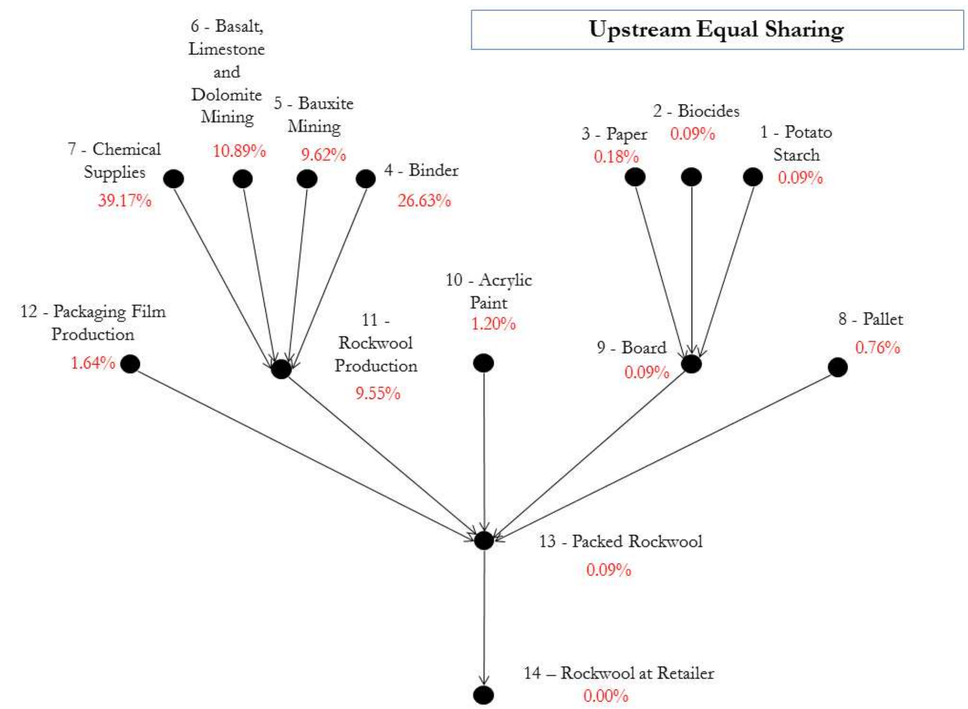


Figure 6 – Upstream Equal Sharing allocation results

#	Supply Network Stage	Emissions Share	LRS + DES (50-50)	LRS + DES (80-20)
1	Potato Starch	0.00%	0.00%	0.00%
2	Biocides	0.00%	0.00%	0.00%
3	Paper	0.08%	0.05%	0.07%
4	Binder	17.07%	10.67%	14.51%
5	Bauxite Mining	0.07%	0.05%	0.06%
6	Basalt, Limestone and Dolomite Mining	1.33%	0.83%	1.13%
7	Chemical Supplies	29.63%	18.52%	25.19%
8	Pallet	0.67%	0.45%	0.58%
9	Board	0.00%	0.01%	0.00%
10	Acrylic Paint	1.10%	0.74%	0.95%
11	Rockwool Production	47.29%	37.54%	43.39%
12	Packaging Film Production	1.55%	1.04%	1.34%
13	Packed Rockwool	1.21%	15.37%	6.87%
14	Rockwool at Retailer	0.00%	14.76%	5.90%

Table 1 - Hybrid Allocation Rules

6.1 Implications and Remarks

The illustrated model, together with the described allocation rules, could be utilized by governmental and environmental agencies in order to allocate pollution responsibilities (and associated costs), especially in centrally planned economic systems.

In free-market scenarios, focal firms still need to co-operate with partners from their supply networks in order to measure and manage environmental impacts, according to self-regulatory mechanisms (Sundarakani et al., 2010). Within these contexts, the mentioned responsibility rules could be seen as representative of different supply chain leadership styles (Gosling et al., 2016) adopted by the focal firm. In particular, the Local Responsibility principle (stating that each company is just responsible for activities strictly happening at its premises) can be related to a *lasseiz-faire* leadership style. According to this style, the focal company of the supply chain is not taking much action in terms of mitigation of environmental impacts, letting individual companies dealing with the problem.

The Downstream Responsibility principle (stating that downstream actors in the supply chain – such as retailers- will take the burden of some of the pollution costs incurred by upstream suppliers) can be seen as related to a *transformational* leadership style, in which the focal firm takes responsibility for enhancing the performance of the whole supply chain; indeed, downstream actors (that, in many cases, constitute the most powerful entities of the supply chain) have all the interest to improve the environmental performance of their suppliers, as this will result in lower environmental impacts (and related costs) being allocated to themselves as well.

The Upstream Responsibility principle, stating that upstream suppliers (typically involved in energy intensive activities, such as raw material extraction) are responsible not only for pollution happening at their premises, but will be also allocated shares of the environmental performance of downstream partners (who will be purchasing and utilizing these goods) can be seen as related to a transactional leadership style, in which the focal firm (usually involved in the final stages of the supply chain) will have a great amount of power towards upstream suppliers.

6. Conclusions

This study has provided a normative framework based on a cooperative game theory responsibility model for pollution allocation; the paper has detailed the generic model in the case of a complex real-world supply network, by selecting three different responsibility principles (namely: Upstream, Downstream and Local Responsibility) and developing some associated pollution responsibility allocation rules; results, along with some managerial implications have been discussed.

The presented work could be extended in future researches, in order to address some of the limitations that characterize the current approaches. First of all, different supply network structures, including, for instance, reverse and circular elements could be studied (see, for instance: Choudhary et al., 2015; Battini et al., 2017). Also, different pollution responsibility schemes might incorporated in the model (similarly to the work proposed by Jacobs and Subramanian, 2012). Furthermore, a new set of normative properties could be defined, aimed at specifically addressing the stability of transnational supply networks operating across different environments characterized by different environmental legislations. Finally, further industrial case studies could be developed, in order to investigate the suitability of game-theoretic approaches to real-world pollution responsibility allocation problems.

Acknowledgments

This research was partially supported by the project "*Promoting Sustainable Freight Transport in Urban Contexts: Policy and Decision-Making Approaches* (ProSFeT)", funded by the H2020-MSCA-RISE-2016 programme (Grant Number: 734909).

The authors are extremely grateful to the three anonymous referees; their very useful observations helped us lifting the quality of our paper in a very significant way.

References

Allaoui, H., Guo, Y., Choudhary, A. and Bloemhof, J., 2018. Sustainable agro-food supply chain design using two-stage hybrid multi-objective decision-making approach. *Computers & Operations Research*, *89*, 369-384.

Bastianoni S., Pulselli F.M., Tiezzi E., (2004). The problem of assigning responsibility for greenhouse gas emissions. *Ecological Economics*, 49 (3), 253-257.

Battini, D., Bogataj, M., Choudhary, A. (2017). Closed loop supply chain (CLSC): economics, modelling, management and control. *International Journal of Production Economics*, 183(B), 319-321.

Ciardiello, F., Genovese, A., & Simpson, A. (2018). A unified cooperative model for environmental costs in supply chains: the Shapley value for the linear case. *Annals of Operations Research*, forthcoming. DOI: 10.1007/s10479-018-3028-3

Chander, P., Tulkens, H. (1995). A core-theoretic solution for the design of cooperative agreements on transfrontier pollution. *International Tax and Public Finance*, 2 (2), 279–293.

Choudhary, A., Sarkar, S., Settur, S., Tiwari, M.K. (2015). A carbon market sensitive optimization model for integrated forward–reverse logistics. *International Journal of Production Economics*, *164*, pp.433-444.

Chung, S. H., Weaver, R. D., Friesz, T. L. (2013). Strategic response to pollution taxes in supply chain networks: Dynamic, spatial, and organizational dimensions. *European Journal of Operational Research*, 231 (2), 314–327.

Dong, B., Ni, D., Wang, Y., 2012. Sharing a polluted river network. *Environmental and Resource Economics*, 53 (3), 367–387.

Ecoinvent (2018). Ecoinvent Database, Version 3. Available online at www.ecoinvent.ch [Last Accessed on 1 July 2018]

Eyckmans, J., Tulkens, H., 2003. Simulating coalitionally stable burden sharing agreements for the climate change problem agreements for the climate change problem. *Resources and Energy Economics*, 25, 299–327.

European Commission (2014). Development of guidance on Extended Producer Responsibility (EPR). Available online at: http://ec.europa.eu/environment/archives/waste/eu_guidance/introduction.html [Last accessed on 30 September 2018]

Färe, R., Grosskopf, S., Margaritis, D., Weber, W.L. (2012). Technological change and timing reductions in greenhouse gas emissions. *Journal of Productivity Analysis*, 37(3), 205–216.

Filar, J.A., Gaertner, P.S. (1997). A regional allocation of world CO2 emission reductions. *Mathematical and Computer Simulation*, 43, 269–275.

Gallego, B., Manfred, L. (2005). A Consistent Input-Output Formulation of Shared Producer and Consumer Responsibility. *Economic System Research*, 17(4), 365-391.

Genovese, A., Morris, J., Piccolo, C., & Koh, S. L. (2017). Assessing redundancies in environmental performance measures for supply chains. *Journal of Cleaner Production*, *167*, 1290-1302.

Germain, M., Steenberghe, V.V. (2003). Constraining equitable allocations of tradable CO2 emission quotas by acceptability. Environmental and Resources Economics, 26, 469–492.

Gomes, E.G., Lins, M.P.E. (2008). Modelling undesirable outputs with zero sum gains data envelopment analysis models. *Journal of the Operational Research Society*, 59(5), 616–623.

Gosling, J., Jia, F., Gong, Y., & Brown, S. (2016). The role of supply chain leadership in the learning of sustainable practice: toward an integrated framework. *Journal of Cleaner Production*, *137*, 1458-1469.

Gui, L., Atasu, A., Ergun, Ö., & Toktay, L. B. (2018). Design incentives under collective extended producer responsibility: A network perspective. *Management Science*.

Huang, X., Chen, X. and Huang, P. (2018). Research on Fuzzy Cooperative Game Model of Allocation of Pollution Discharge Rights. *Water*, *10*(5), p.662.

Jacobs, B. W., Subramanian, R. (2012). Sharing responsibility for product recovery across the supply chain. *Production and Operations Management*, 21 (1), 85–100.

Lenzen, M., Murray, J., Sack, F., Wiedmann, T., 2007. Shared producer and consumer responsibility — Theory and practice. *Ecological Economics* 61(1), 27-42.

Lenzen M., Murray J., 2010. Conceptualising environmental responsibility, *Ecological Economics*, 70 (2), 261-270.

Leontief, W., Ford, D. (1970). Environmental repercussions and the economic structure: an input-output approach, *Review of Economics and Statistics,* 52, pp. 262-271.

Liao, Z.L., Zhu, X.L., Shi, J.O. (2015). Case study on initial allocation of Shanghai carbon emission trading based on Shapley value. *Journal of Cleaner Production*, 103 (15), 338–344.

Llop, M., Ponce-Alifonso X. (2015). Identifying the role of final consumption in structural path analysis: An application to water uses *Ecological Economics*, 109, 203-210.

Lozano, S., Villa, G., Brannlund, R. (2009). Centralised reallocation of emission permits using DEA. *European Journal of Operational Research*, 193, 752–760.

MacKenzie, I.A., Hanley, N., Kornienko, T. (2008). The optimal initial allocation of pollution permits: a relative performance approach. *Environmental Resources and Economics*, 39, 265–282.

MacKenzie, I.A., Hanley, N., Kornienko, T. (2009). Using contests to allocate pollution rights. *Energy Policy*, 37, 2798–2806.

Nasir, M.H.A., Genovese, A., Acquaye, A.A., Koh, S.C.L., Yamoah, F. (2017). Comparing linear and circular supply chains: A case study from the construction industry. *International Journal of Production Economics*, *183*, pp.443-457.

Pang, R.Z., Deng, Z.Q., Chiu, Y.H. (2015). Pareto improvement through a reallocation of carbon emission quotas. *Renewable and Sustainable Energy Reviews*, 50, 419–430.

Ren, J., Bian, Y.W., Xu, X.Y., He, P. (2015). Allocation of product-related carbon emission abatement target in a make-to-order supply chain. Computers and Industrial Engineering, 80, 181–194.

Ridgley, M.A. (1996). Fair sharing of greenhouse gas burdens. *Energy Policy*, 24 (6), 517–529.

Ringius, L., Torvanger, A., Holtsmark, B. (1998). Can multi-criteria rules fairly distribute climate burdens? OECD results from three burden sharing rules. *Energy Policy*, 26(10), 777–793.

Rodrigues, J., Domingos T. (2008). Consumer and producer environmental responsibility: Comparing two approaches. *Ecological Economics,* 66, 533-546.

Rose, A. (1990). Reducing conflict in global warming policy: the potential of equity as a unifying principle. *Energy Policy*, 18, 927–935.

Rose, A., Stevens, B. (1993). The efficiency and equity of marketable permits for CO_2 emissions. *Resources and Energy Economics*, 15, 117–146.

Shapley, L.S. (1953). A value for n-person games. *Contributions to the Theory of Games*, 2, 28, 307-317.

Shi, G. M., Wang, J. N., Fu, F., Xue, W. B. (2017). A study on transboundary air pollution based on a game theory model: Cases of SO2 emission reductions in the cities of Changsha, Zhuzhou and Xiangtan in China. *Atmospheric Pollution Research*, *8*(2), 244-252.

Sun, J., Wu, J., Liang, L., Zhong, R.Y., Huang, G.Q. (2014). Allocation of emission permits using DEA: centralised and individual points of view. *International Journal of Production Research*, 52(2), 419–435.

Sun, J., Fu, Y., Ji, X., Zhong, R.Y., 2017. Allocation of emission permits using DEA-game-theoretic model. *Operational Research*, *17*(3), pp.867-884.

Sundarakani, B., De Souza, R., Goh, M., Wagner, S. M., Manikandan, S. (2010). Modeling carbon footprints across the supply chain. *International Journal of Production Economics*, 128(1), 43–50.

UN Global (2011). *The ten principles*. United Nations Global Compact (Available online at: http://www.soprahr.com/docs/default-source/D%C3%A9veloppement-durable_PacteMondial/attestation_sopra_en.pdf).

Vaillancourt, K., Waaub, J.P. (2004). Equity in international greenhouse gases abatement scenarios: a multicriteria approach. *European Journal of Operational Research*, 153, 489–505.

Viguier, L., Vielle, M., Haurie, A., Bernard, A. (2006). A two-level computable equilibrium model to assess the strategic allocation of emission allowances within the European Union. Computers & Operations Research, 3, 369–385.

Yu, S.W., Wei, Y.M., Wang, K. (2014). Provincial allocation of carbon emission reduction targets in China: an approach based on improved fuzzy cluster and Shapley value decomposition. *Energy Policy*, 66, 630–644.

Wang, K., Wei, Y.M., Zhang, X., Yu, S. (2013). Regional allocation of CO2 emissions allowance over provinces in China by 2020. *Energy Policy*, 54, 214–229

Wei, C., Ni, J.L., Du, L.M. (2012). Regional allocation of carbon dioxide abatement in China. *China Economic Review*, 23(3), 552–565

Wyckoff, A. W. & Roop, J. M. (1994). The embodiment of carbon in imports of manufactured products - Implications for international agreements on greenhouse gas emissions, *Energy Policy,* 22, 187-194.

Zhang Y., Zheng H., Yang Z., Su M., Liu G., Li Y. (2015). Multi-regional input–output model and ecological network analysis for regional embodied energy accounting in China, *Energy Policy*, 86, 651-663.

Zhou, P., Sun, Z.R., Zhou, D.Q. (2014). Optimal path for controlling CO2 emissions in China: a perspective of efficiency analysis. *Energy Economics*, 45, 99–110.

Zhou, P. & Wang M. (2016). Carbon dioxide emissions allocation: A review. *Ecological Economics*, 125, 47-59.

Appendix

The aim of this section is to provide a heuristic algorithm to compute allocations for a generic supply network. In the following, the algorithm and its implementation (by utilising the syntax provided by the modelling environment *Wolfram Mathematica 10*) will be shown.

Input data

A graph g=(N,P) can be built for describing the supply network by employing the dedicated *Mathematica 10* function. The attribute *EdgeWeight* defines the costs c_j associated with each edge.

Basic functions

The two following fundamental functions can be defined for the development of the algorithm.

We consider the list of companies, which are part of at least one directed path starting from company **x_**, including company **x_**. The previous list is composed by the companies which are downstream to company i, i.e. σ(**x_**). The function **f[x_]**, defined as follows, finds the length of such a list.

f[x_] := Length[Sort[VertexOutComponent[g, {x}]]]

Similarly, we consider the list of companies, which are part of at least one directed path ending at company **x_**, including company **x_**. The previous list is composed by the companies which are upstream to company i, i.e. α(**x_**). The function **t[x_]**, defined as follows, finds the length of such a list of companies.

t[x_] := Length[Sort[VertexInComponent[g, {x}]]]

In general these two lists are different because *g* is a directed graph.

Allocation Rule 2 – DES

We compute the DES allocation for a generic company m (with m ranging between 1 and n *-1*). The list of costs related to companies which are upstream to company *m* including m, i.e. companies in $\alpha\ (m)$, can be defined through the following code:

Total [PropertyValue [{g,#},EdgeWeight]&/@Sort[EdgeList[g,DirectedEdge[Alternatives@@VertexInComponent[g,{m}],_]

The selection **VertexInComponent[g,{m}]** selects the list of companies which are upstream to company m including m. For each of these companies, let's say s, we compute the length of the list of companies which are downstream to each company s. In doing this we utilize the function **f[x_]**. The length of the previous list is:

Map[f,Sort[VertexInComponent[g,{m}]]]]]

The two above-mentioned lists (which have the same dimension) can be employed to compute the ratios contained in the allocation formula (5). All these contributions are summed up (as per Equation (4)) thanks to the function **Total**. Similarly, company n has the following allocation:

Total[Append[PropertyValue[{g,#},EdgeWeight]&/@Sort[EdgeList[g,DirectedEdge[Alternatives@@VertexInComponent[g,{VertexCount[g]}],_]]],0]/Map[f,Sort[VertexInComponent[g,{VertexCount[g]}]]]]

Allocation Rule 3 –UES

For UES allocations, the nature of the algorithm is the same with some modifications. The role of **VertexInComponent[g,{m}]** is replaced by **VertexOutComponent[g, {m}].** The role of function **f[x_]** is replaced by the function **t[x_]. VertexOutComponent[g, {m}]** finds the list of companies, which belong to any path starting from the node m, i.e. the companies which belong to $\sigma(m)$. The UES allocation formula (6) can be computed as:

```
Do[
Print[
Total[
Append[PropertyValue[{g, #}, EdgeWeight] & /@
Sort[EdgeList[g,
DirectedEdge[Alternatives @@ VertexOutComponent[g, {m}], _]]],      0]
/
Map[t, Sort[VertexOutComponent[g, {m}]]]]]],
{m, 1,    VertexCount[g]}]
```