Allocation of Greenhouse Gas Emissions in Supply Chains

Greys Sošić
University of Southern California

Joint work with: **Sanjith Gopalakrishnan**, **Daniel Granot** and **Frieda Granot**,
University of British Columbia
Hailong Cui, University of Southern California

USC Marshall SCHOOL OF BUSINESS

Zagreb, 2015

Carbon footprint is the total amount of greenhouse gas (GHG) emissions over a given period of time associated with an organization, product, or service

Organizational carbon footprint

- measures the GHG emissions from all the activities across the organization, including energy used in buildings, industrial processes and company vehicles.

Product carbon footprint

- measures the GHG emissions over the whole life of a product (goods or services), from the extraction of raw materials and manufacturing right through to its use and final re-use, recycling or disposal.

Greenhouse gases are gases that absorb infrared radiation in the atmosphere

Carbon dioxide (CO_2)

- Fossil fuel, deforestation.

Methane (CH_4)

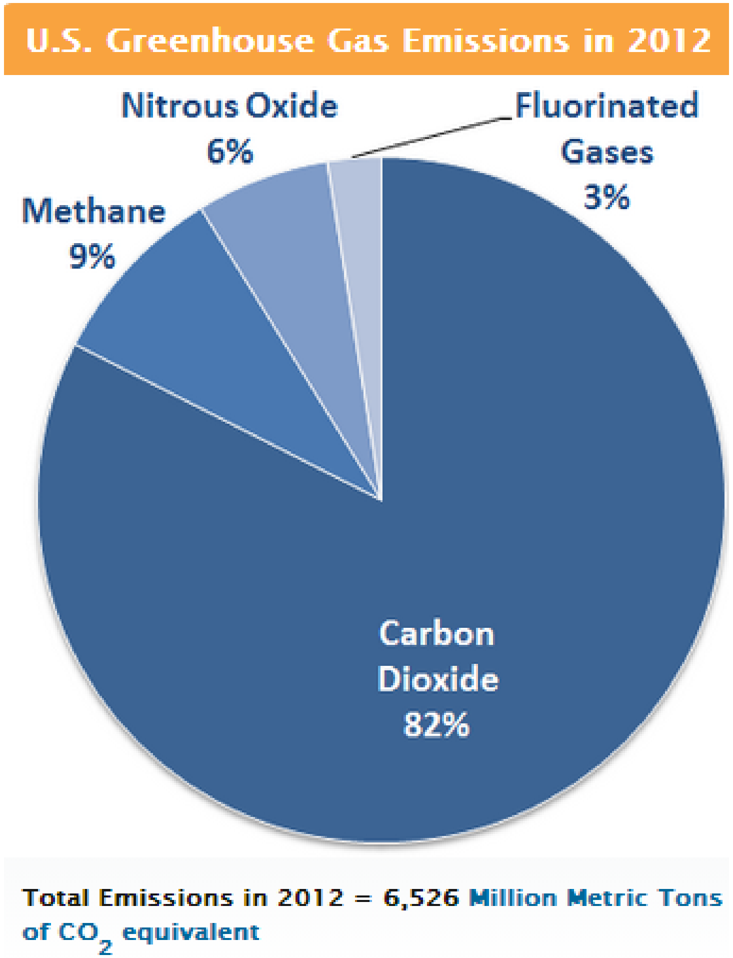
- Agricultural activities, waste management, energy use

Nitrous oxide (N_2O)

- Agricultural activities (fertilizer use)

Fluorinated gases (F-gases)

- Industrial processes, refrigeration, and the use of a variety of consumer products. Include hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6).

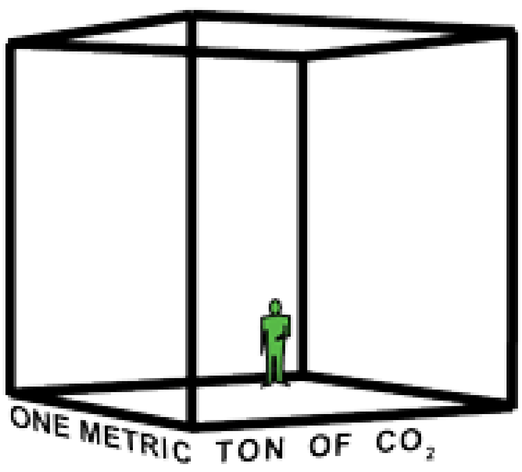


Global warming potential (GWP) of the indicated non-CO_2 gases relative to CO_2

	Formula	Lifetime	GWP (20-yr)	GWP (100-yr)
Methane	CH_4	12.4	84	28
Nitrous oxide	N_2O	121.0	264	265
HFC-134a	CH_2FCF_3	13.4	3,710	1,300
CFC-11 (freon)	CCl_3F	45.0	6,900	4,660
Tetrafluoromethane	CF_4	50,000.0	4,880	6,630

Intergovernmental panel on climate change, Assessment report 5, November 2013

A metric ton equivalent of CO_2 is used to describe emissions. What does it mean?



A metric ton of CO_2 is like a 27' cube

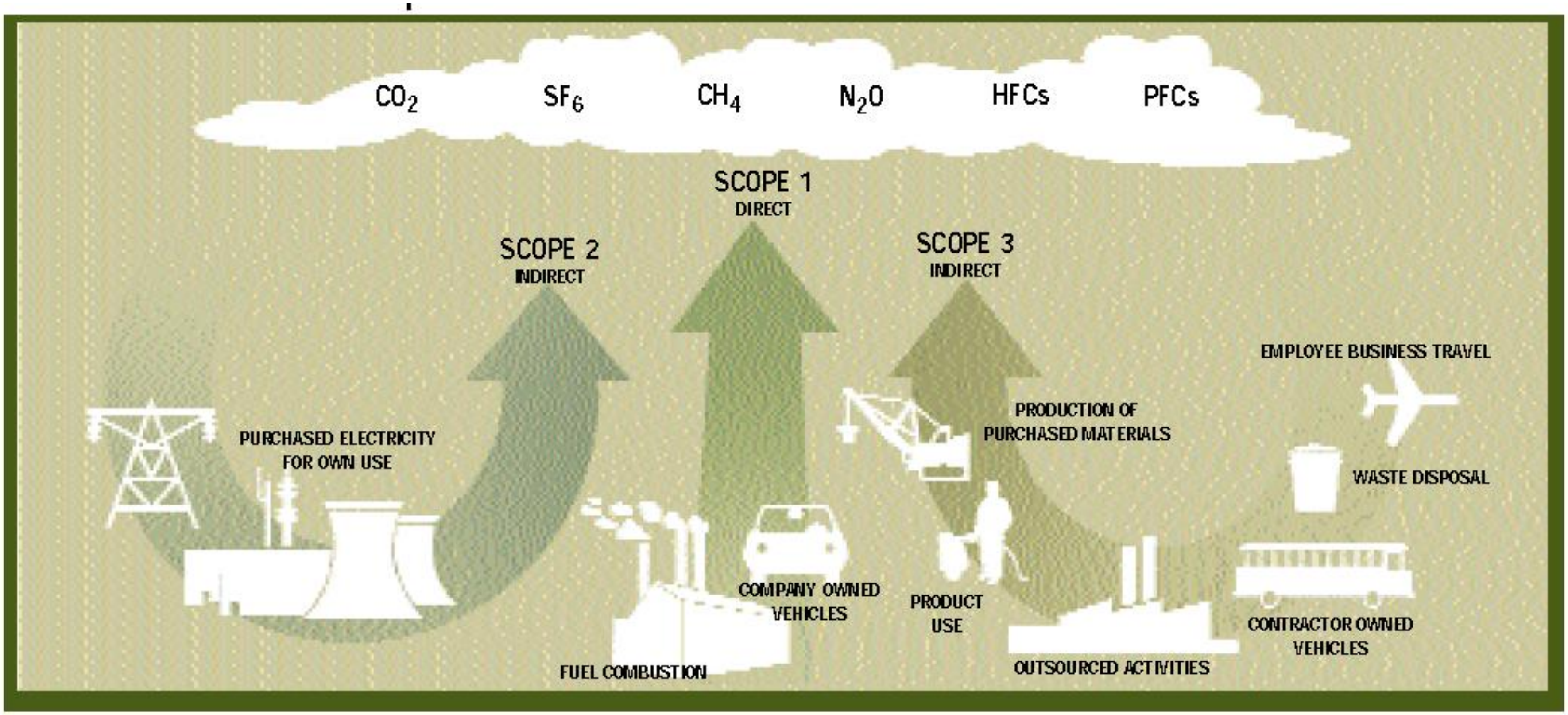
A metric ton of burned coal releases 2.1 metric tons of CO_2

A single tree sequesters about .277 metric tons of CO_2 over 40 years

A vehicle with fuel economy of a 20.3 MPG driven 12,000 miles per year emits about 5.5 metric tons of CO_2 per year

1 car ~ 20 trees

The Greenhouse Gas Protocol (GGP) introduces the concept of “scope” for organizational GHG accounting and reporting purposes



Adopted from NZBCSD, 2002

If the markets operate freely, GHG emissions will be excessive, since there is insufficient incentive to reduce emissions

Economists recommend applying the "polluter pay" principle and placing a price on GHGs

Carbon tax

- British Columbia, Colorado

Cap-and-trade

- Europe, Shenzhen, California

A carbon tax imposes a tax on each unit of GHG emissions

firms have an incentive to reduce pollution whenever this costs less than paying the tax

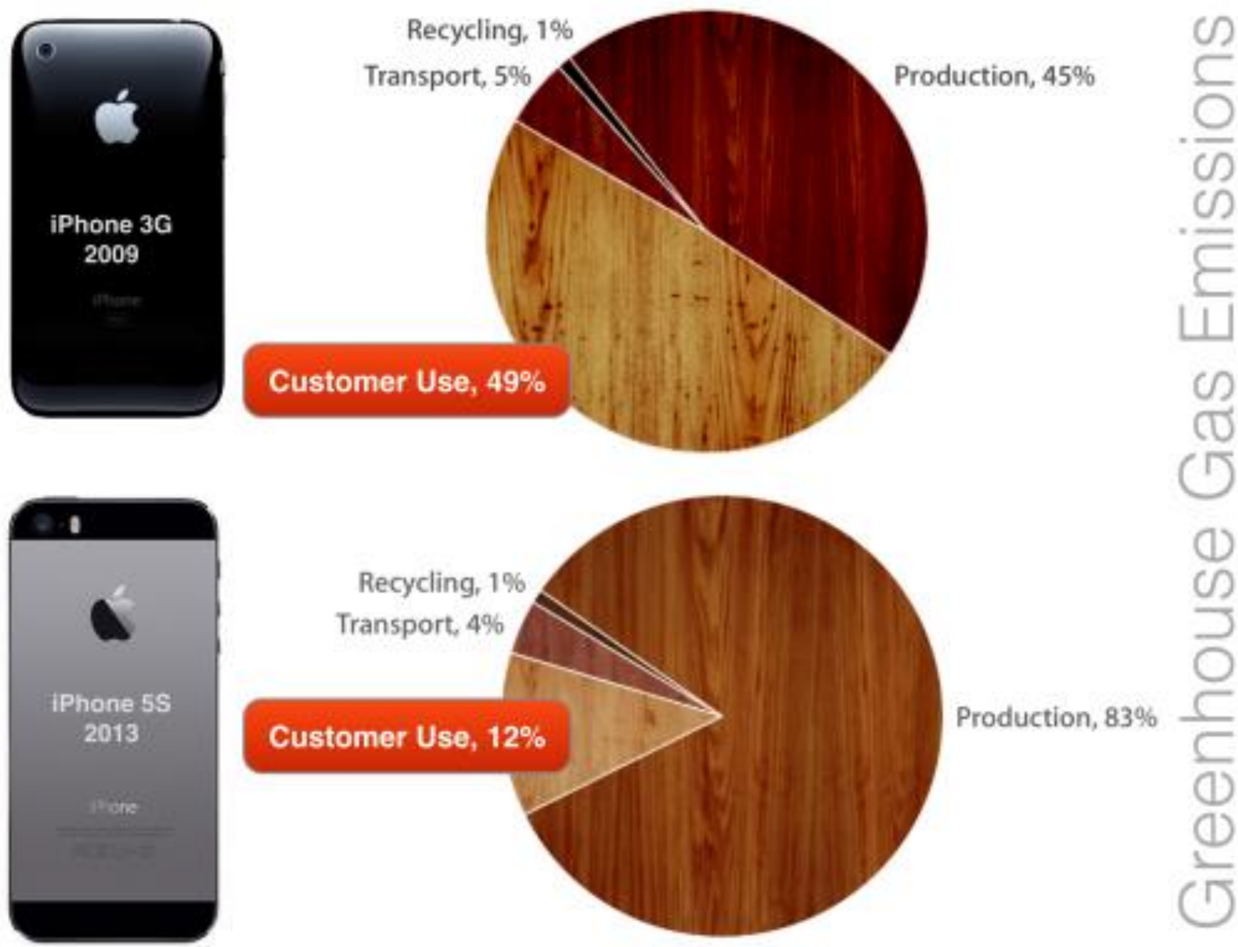
the quantity of pollution reduced depends on the chosen level of the tax

the tax is set by assessing the cost associated with each unit of pollution and the costs associated with controlling that pollution

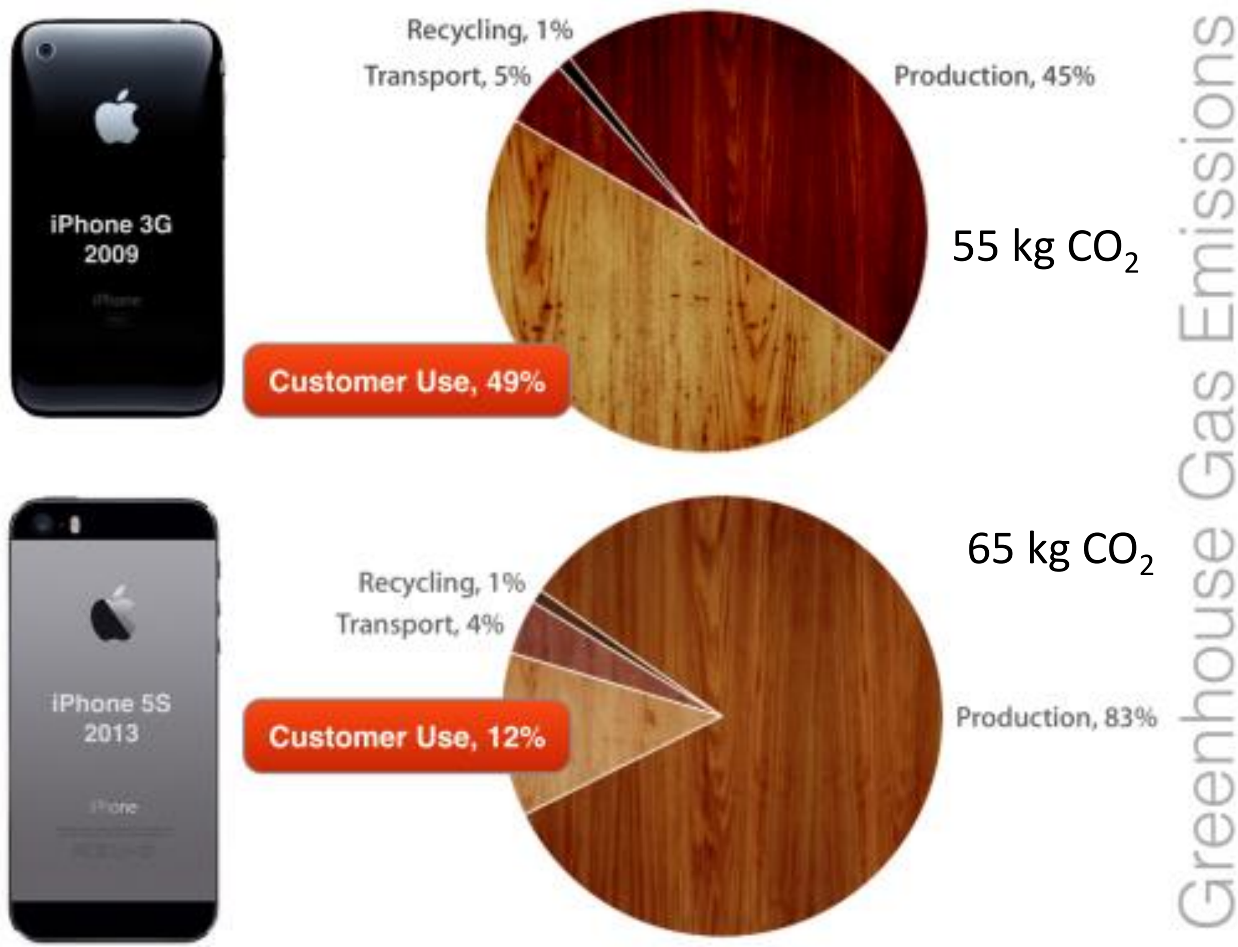
A cap-and-trade system sets a maximum level of pollution (a cap) and distributes emissions permits among firms that produce emissions

- Companies must have a permit to cover each unit of pollution they produce
- Permits are obtained either through an initial allocation or through trading with other firms
- While the maximum pollution quantity is set in advance, the trading price of permits fluctuates.
- A price on pollution is created as a result of setting a ceiling on the overall quantity of emissions.

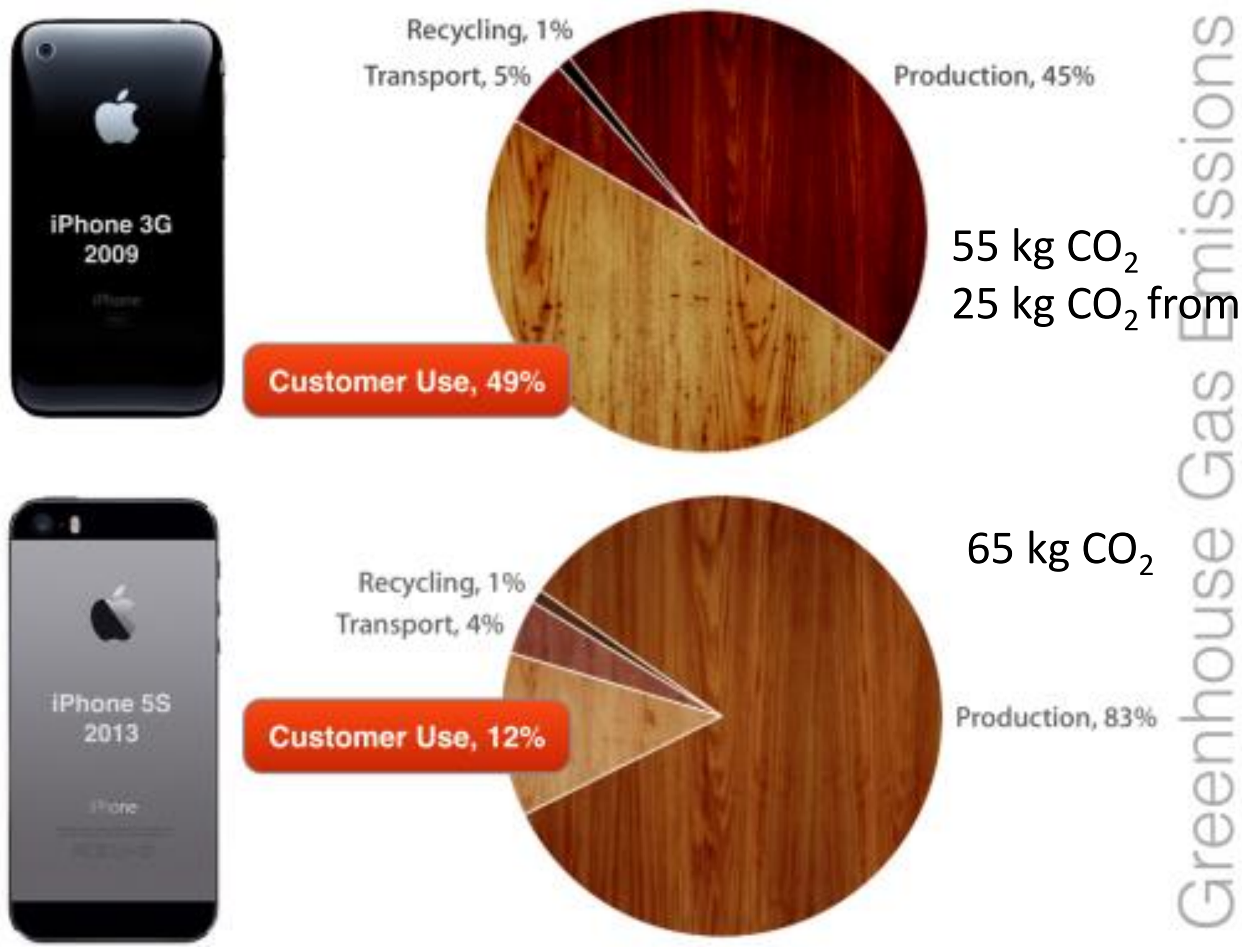
Product GHG emission example – iPhone



Product GHG emission example – iPhone



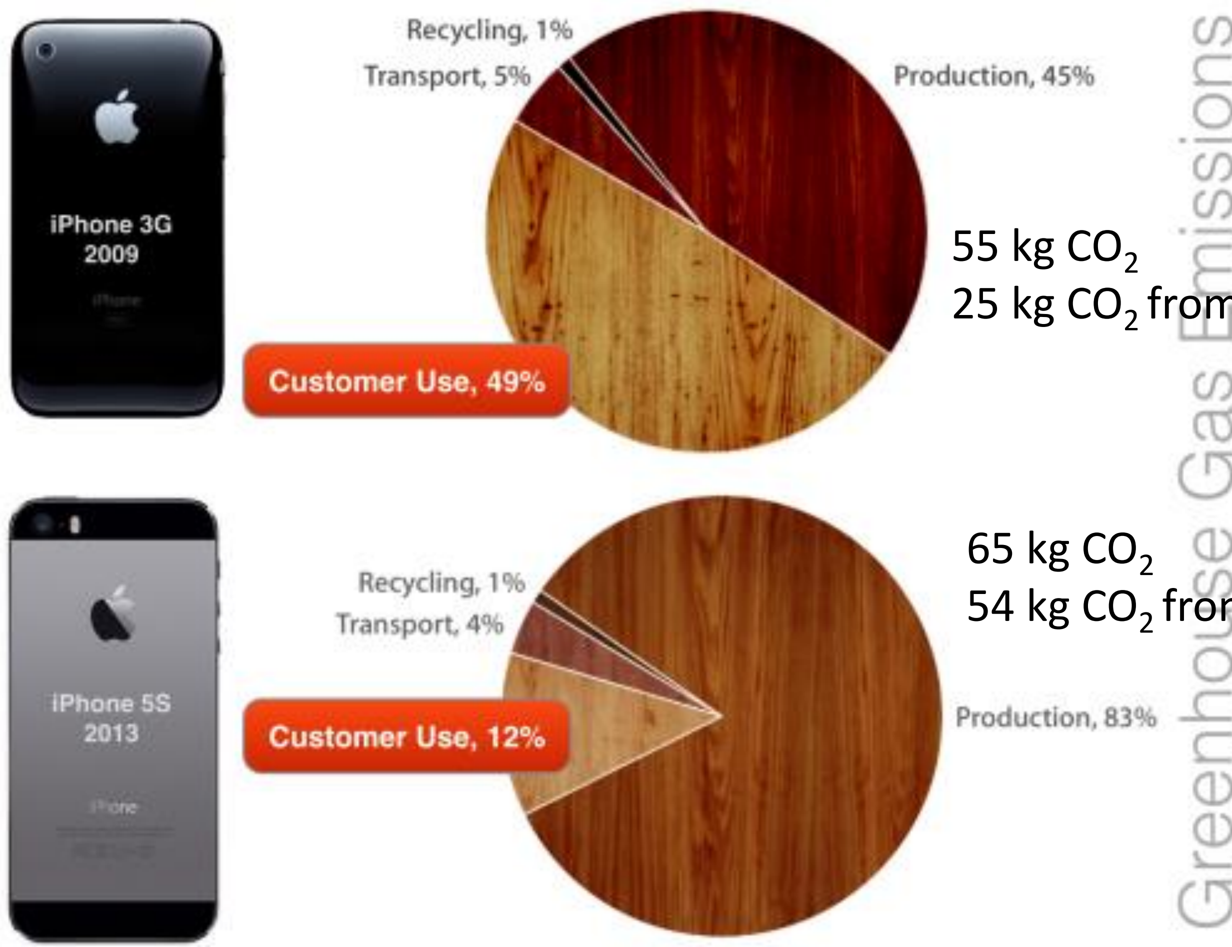
Product GHG emission example – iPhone



55 kg CO_2
25 kg CO_2 from production

65 kg CO_2

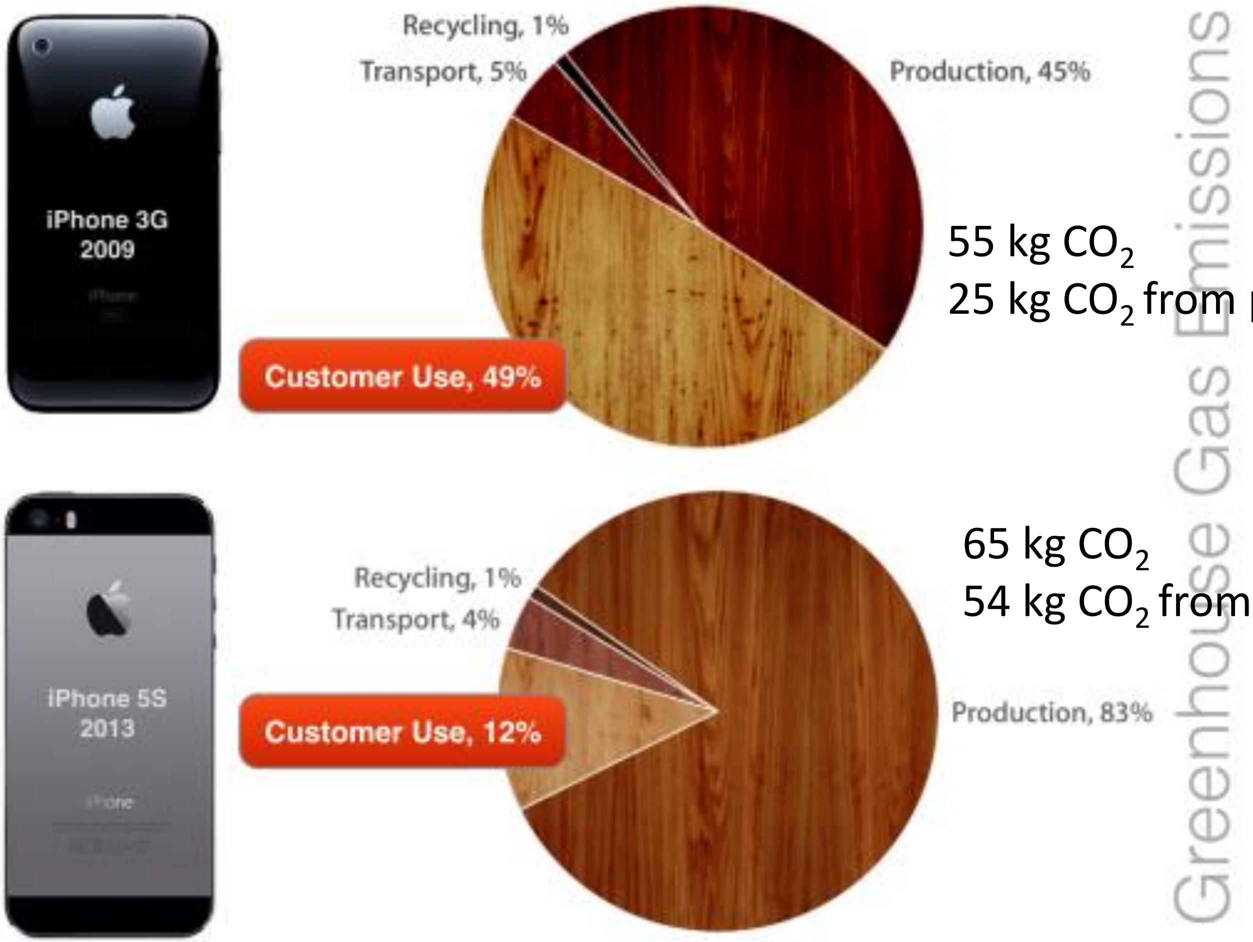
Product GHG emission example – iPhone



55 kg CO_2
25 kg CO_2 from production

65 kg CO_2
54 kg CO_2 from production

Product GHG emission example – iPhone

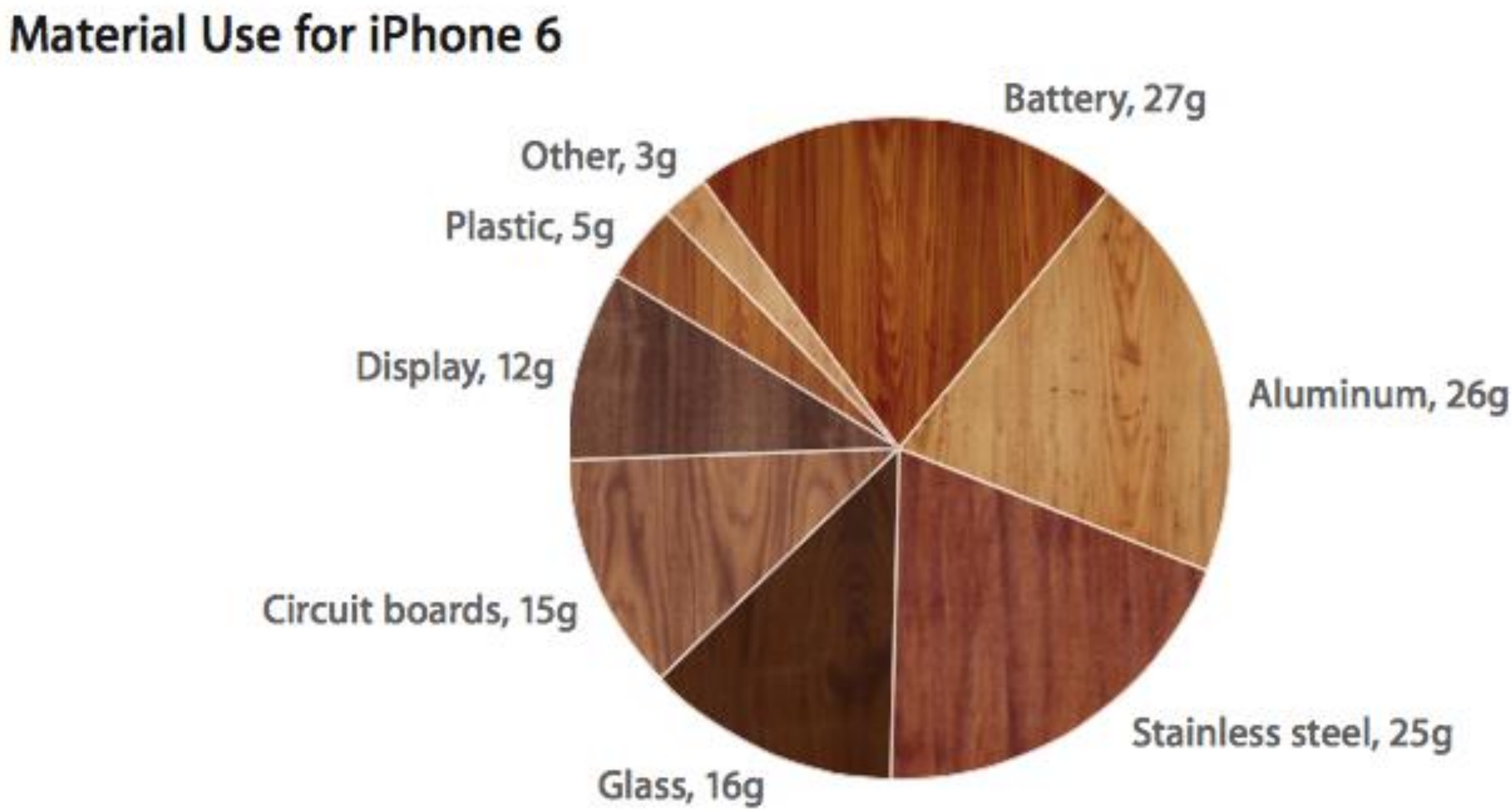


55 kg CO_2
25 kg CO_2 from production

iPhone 6
95 kg CO_2

65 kg CO_2
54 kg CO_2 from production

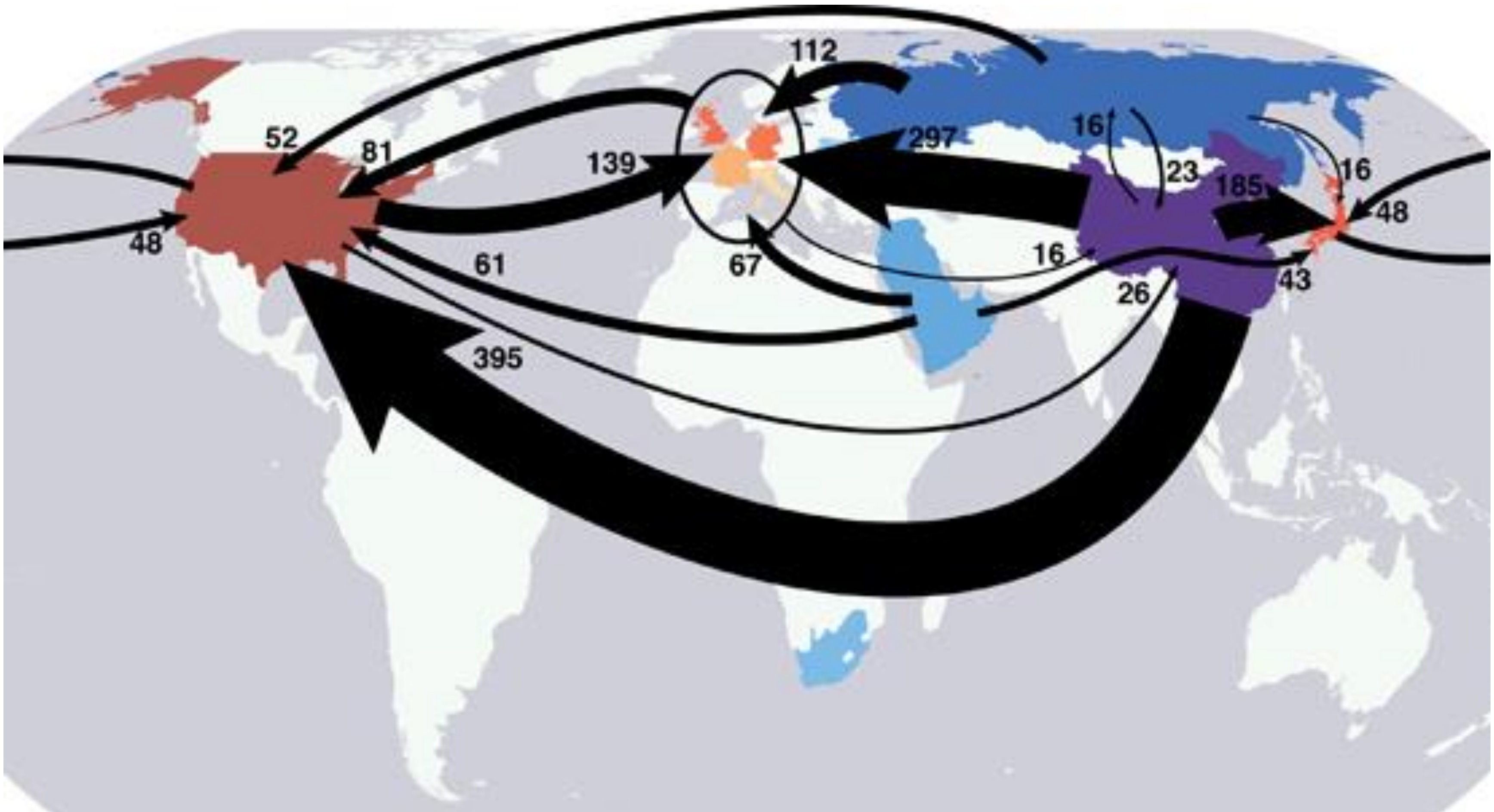
Who is responsible for the 95 kg CO_2 emissions for iPhone 6 ? How should the responsibility be allocated among supply chain members?

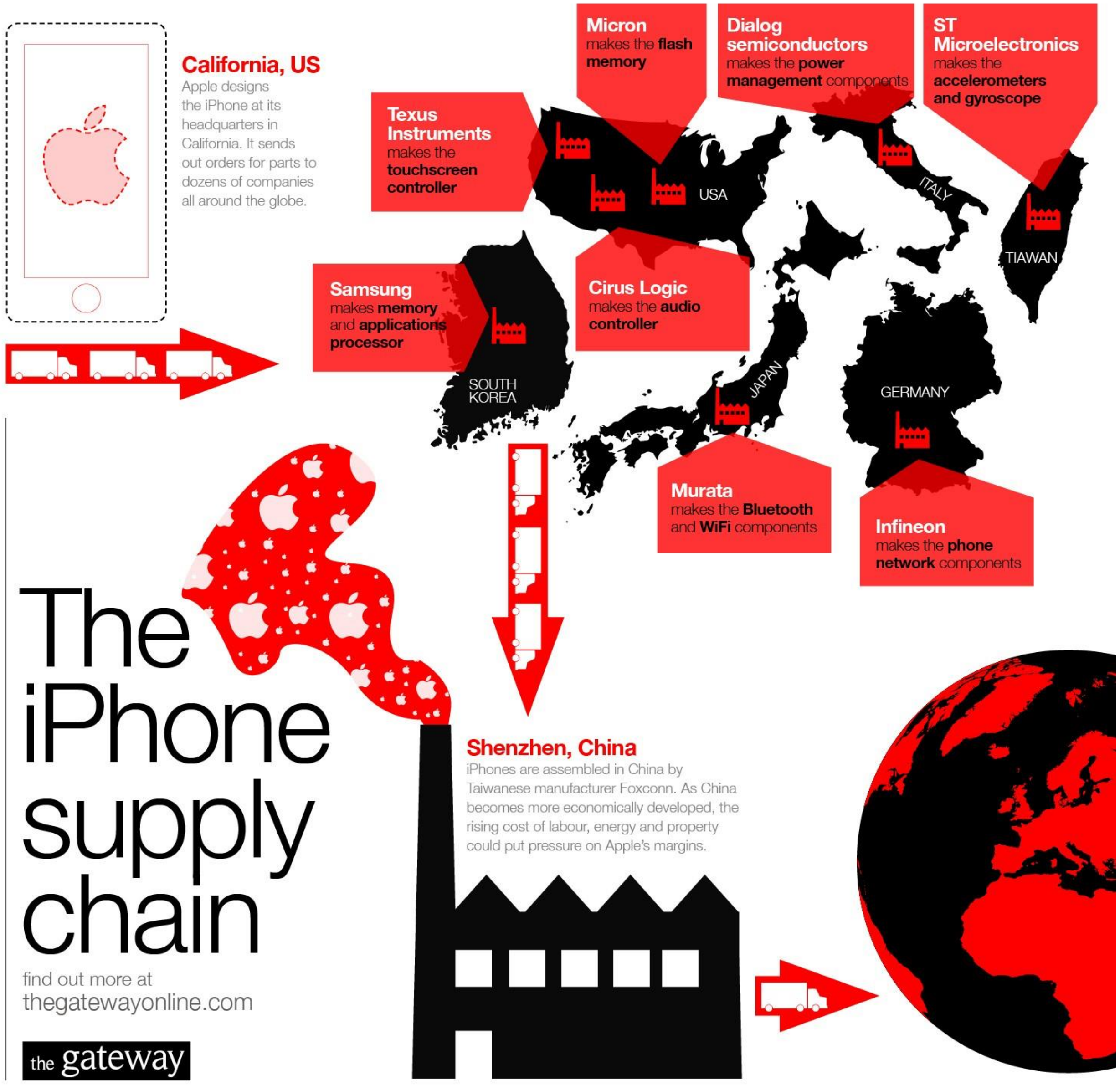


How to allocate GHG emissions among supply chain members?

Net flow of emissions among the major exporting and importing countries: Arrows indicate direction and magnitude of flow; numbers are megatons

Credit: Steven Davis/Carnegie Institution for Science





Sources: Apple, IHS iSuppli, IDC Worldwide

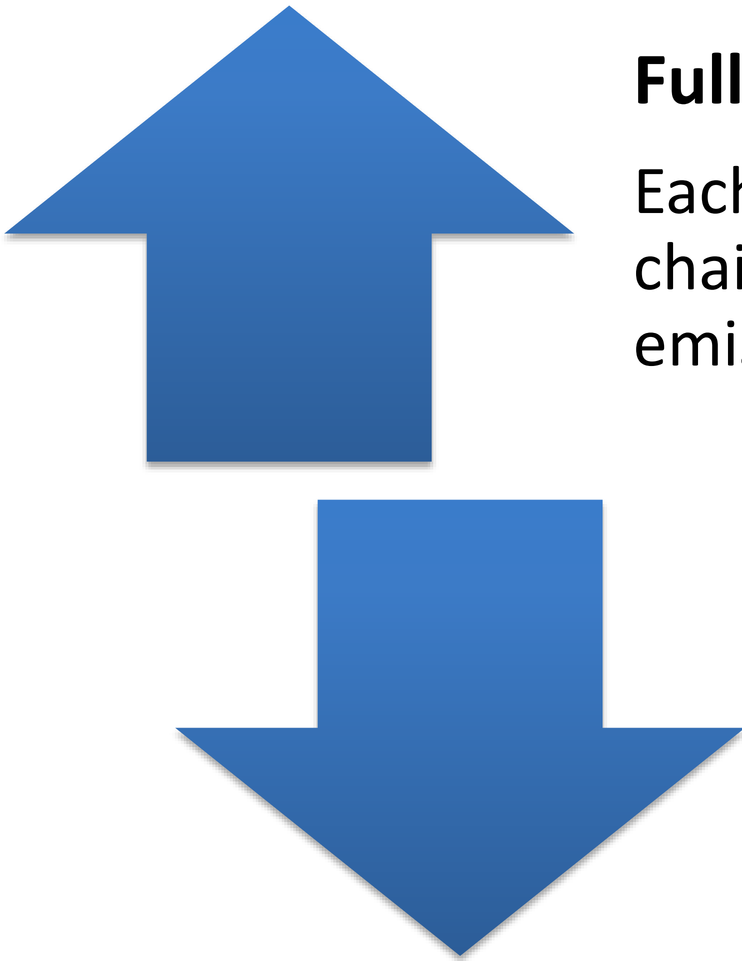
Desirable features for allocation rules that we want to achieve

It allocates responsibilities for all GHG emitted by the supply chain members and avoids double counting.

It is easy to compute.

It is fair and transparent.

Two simple (and extreme) allocations:



Full Producer Responsibility

Each member in the supply chain is responsible for the emission she directly creates.

Two simple (and extreme) allocations:

Full Producer Responsibility

Each member in the supply chain is responsible for the emission she directly creates.

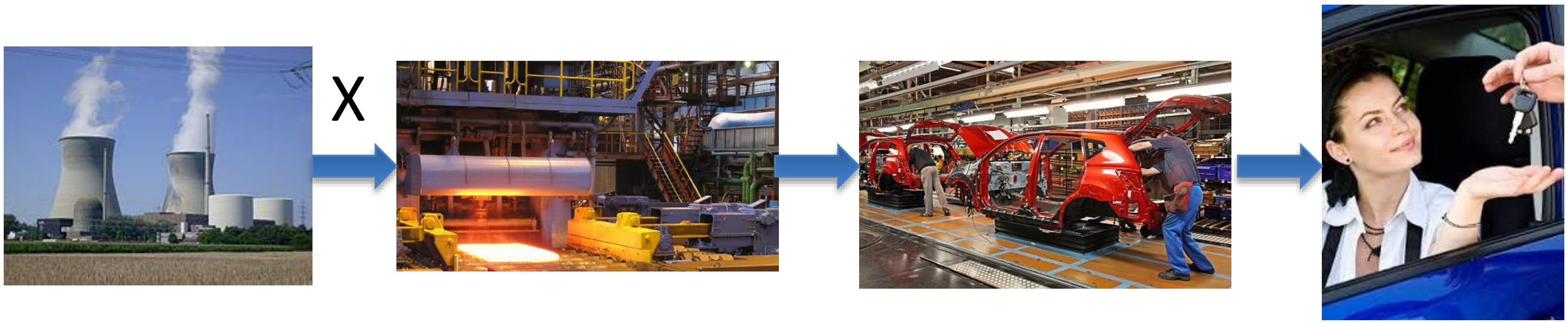
Full Consumer Responsibility

The most downstream manufacturer is responsible for all the pollution created by the supply chain.

Gallego, Lenzen: **A consistent input-output formulation of shared consumer and producer responsibility**, *Economic Systems Research* 2005

- GHG emission responsibilities should be shared among all supply chain members who have directly or indirectly created these emissions
- ***the parties further away from the source have to bear a proportionally smaller share of responsibility for emissions***

Gallego and Lenzen (2005)



Gallego and Lenzen (2005)

X

(1-α)X

Gallego and Lenzen (2005)

X

$(1-\alpha)X$ $\alpha(1-\alpha)X$

Gallego and Lenzen (2005)

X

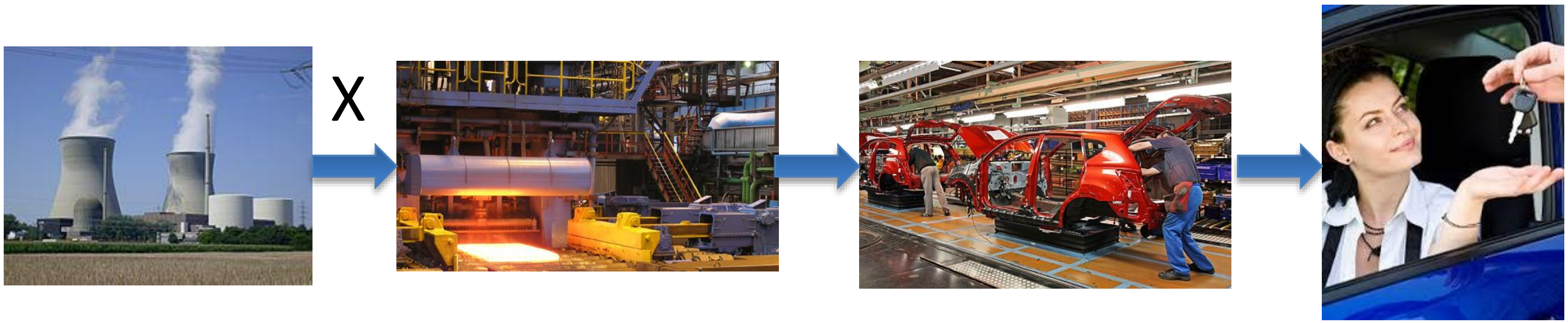
$(1-\alpha)X$

$\alpha(1-\alpha)X$

$\alpha^2(1-\beta)X$

$\alpha^2\beta X$

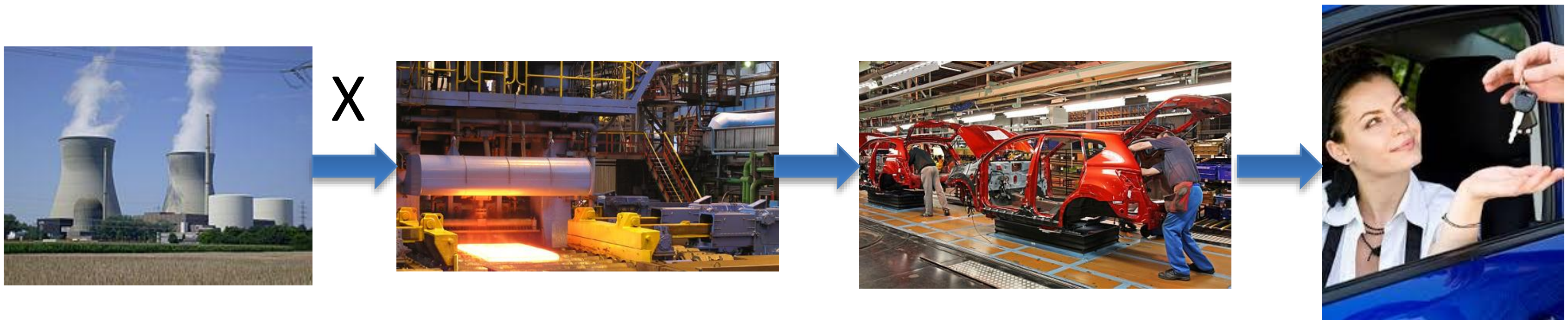
Gallego and Lenzen (2005)



$(1-\alpha)X$ $\alpha(1-\alpha)X$ $\alpha^2(1-\beta)X$ $\alpha^2\beta X$

$\alpha=0$ ➔ full producer responsibility

Gallego and Lenzen (2005)



$(1-\alpha)X$ $\alpha(1-\alpha)X$ $\alpha^2(1-\beta)X$ $\alpha^2\beta X$

$\alpha=0$ ➔ full producer responsibility

$\alpha=1$, $\beta=1$ ➔ full consumer responsibility

Gallego and Lenzen (2005)

X

$(1-\alpha)X$ $\alpha(1-\alpha)X$ $\alpha^2(1-\beta)X$ $\alpha^2\beta X$

$\alpha=0$ ➔ full producer responsibility

$\alpha=1$, $\beta=1$ ➔ full consumer responsibility

$\alpha=0.5$, $\beta=0.5$ ➔ X/2; X/4; X/8; X/8

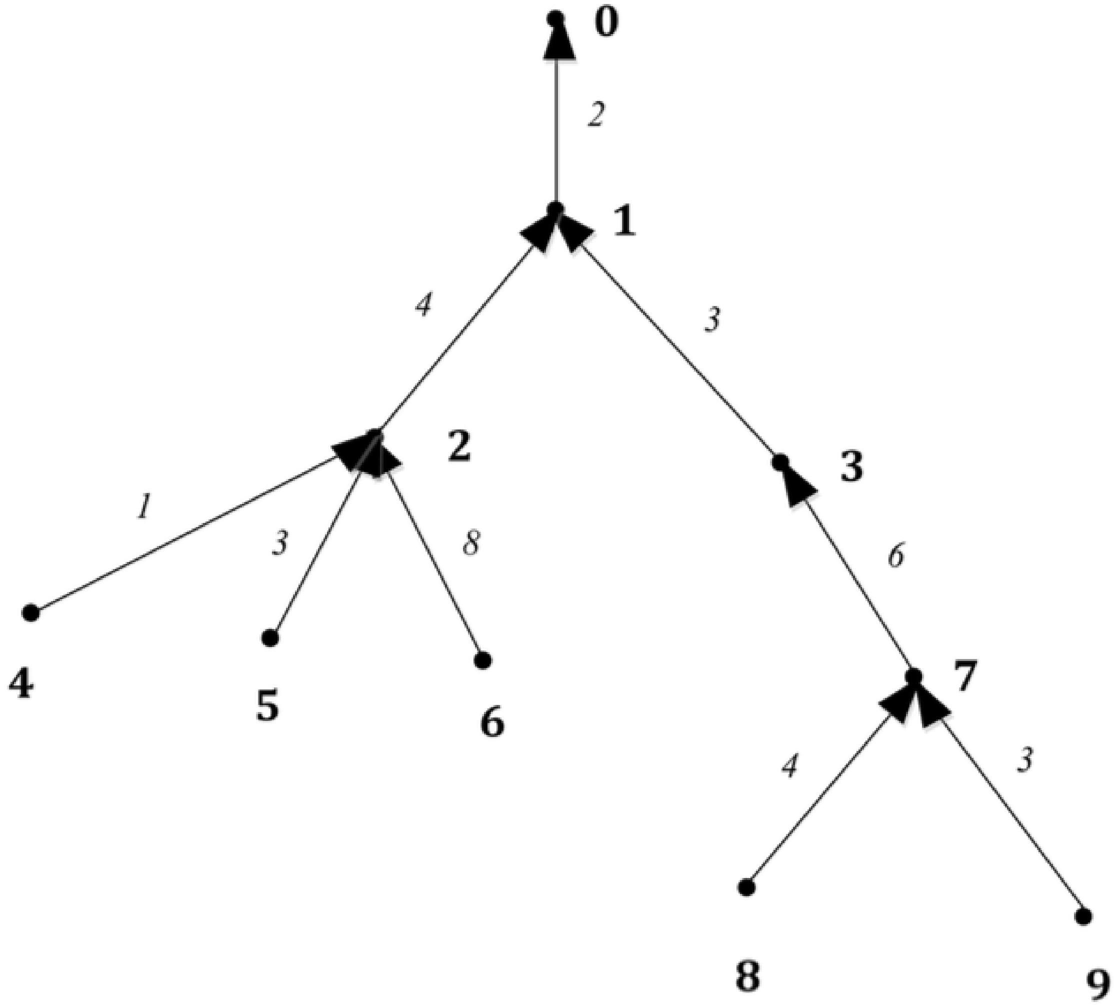
Gallego, Lenzen: **A consistent input-output formulation of shared consumer and producer responsibility**, *Economic Systems Research* 2005

- GHG emission responsibilities should be shared among all supply chain members who have directly or indirectly created these emissions
- ***the parties further away from the source have to bear a proportionally smaller share of responsibility for emissions***
- allocations might be complex to compute and can be a bit arbitrary
- no double counting

Our model – **G**HG **R**esponsibility – **E**missions and **EN**vironment (GREEN) game

- Supply chain is represented by a directed graph
- Each node represents a player/supply chain member
- The weight, a_i, of an arc, e_i, emanating from node *i* represents GHG emissions generated directly by player *i*
- ***Each player is associated with the set of arcs whose associated pollution is his direct or indirect responsibility***

Supply chain with tree structure



Game theoretical concepts

Some terminology

- A **coalition structure** is a partition of the set of all players, N
- The **grand coalition** is the alliance of all players

- Cost game (N,c), $c{:}2^N \rightarrow R$
  - GREEN game: $c(S) = \Sigma\, a_i$: there is j *in* $S \subseteq N$ responsible for a_i

Core allocations for cooperative games

- An allocation φ belongs to the **core** of a cost game if
  - It allocates the entire cost generated by all players
  - It allocates to each coalition S at most the amount that the coalition generates by itself

- A cost game is **convex** if a player's cost contribution to a coalition never exceeds his contribution to its subcoalition

$$c(S \cup \{i\}) - c(S) \geq c(T \cup \{i\}) - c(T), i \notin T, S \subset T$$

In general, the core can be empty!

- Example:

  $N = \{1, 2, 3\}$

  $c(N) = 4$, $c(S) = 2.5$ for $|S| = 2$, $c(S) = 1.5$ for $|S| = 1$

  $\varphi_1 + \varphi_2 + \varphi_3 = 4,$

  $\varphi_1 + \varphi_2 \leq 2.5, \varphi_2 + \varphi_3 \leq 2.5, \varphi_1 + \varphi_3 \leq 2.5$

  $\Rightarrow 2(\varphi_1 + \varphi_2 + \varphi_3) \leq 7.5$

- **Convex cost games gave a nonempty core!**

The **Shapley value** of a cooperative game

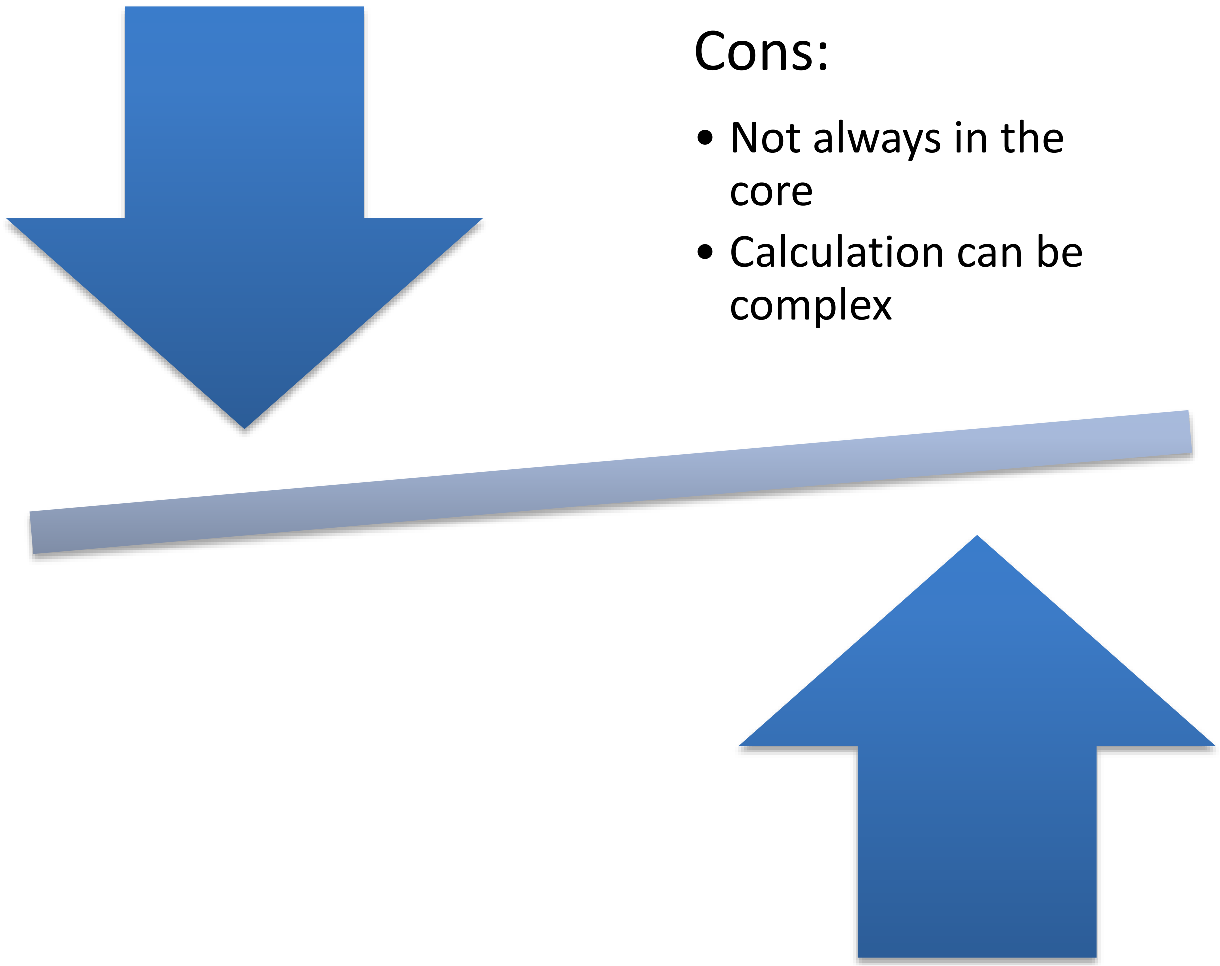
- Unique allocation that satisfies four axioms:
  - symmetry,
  - null-player,
  - efficiency,
  - additivity

The **Shapley value** of a cooperative game

- Unique allocation that satisfies four axioms:
  - symmetry,
  - null-player,
  - efficiency,
  - additivity
- For a game (N, c) and coalition $S \subseteq N$, Shapley value allocation is given by

$$\varphi_i(c) = \sum_{\{S: i \in S\}} \frac{(|S|-1)!(n-|S|)!}{n!} \left(c(S) - c\left(S \setminus \{i\}\right) \right)$$

More from cooperative game theory – the Shapley value



Cons:

- Not always in the core
- Calculation can be complex

More from cooperative game theory – the Shapley value

Cons:

- Not always in the core
- Calculation can be complex

Pros

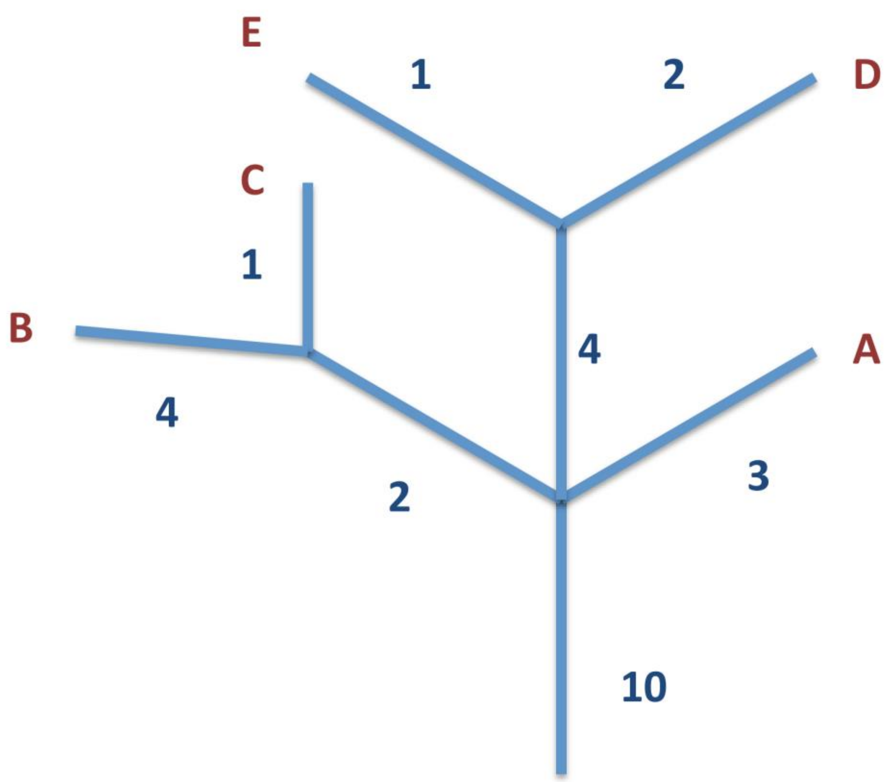
- Used in cost allocation because of perceived fairness
- Belongs to the core of convex games

GREEN game and emission allocations

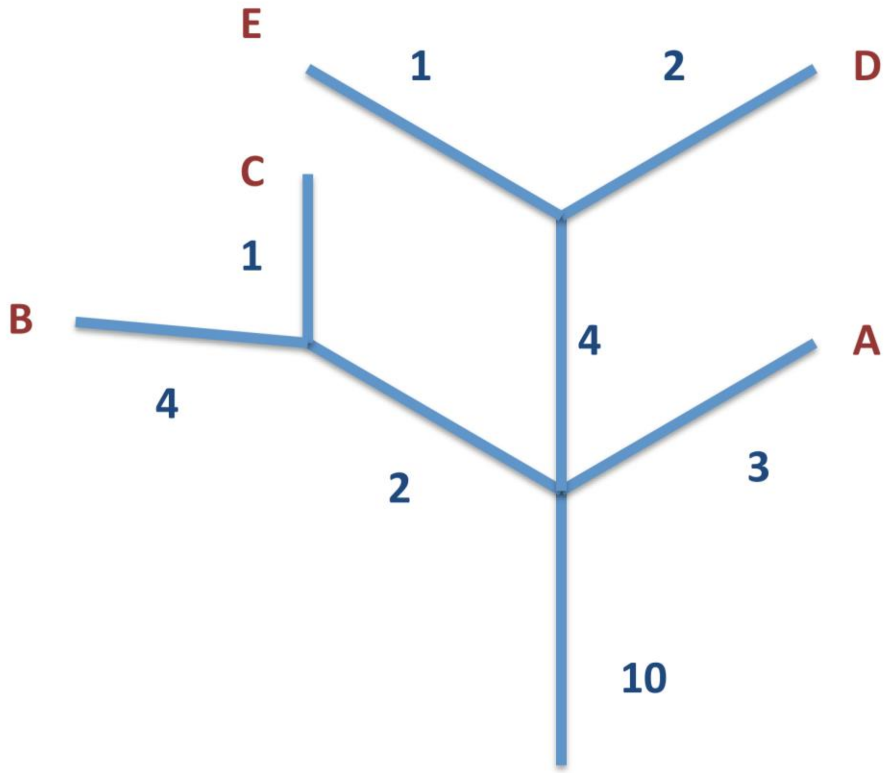
The GREEN game is convex, and thus has a nonempty core

- Core allocations avoid double counting and allocate all GHG emissions
- They are usually perceived as “fair”
- They are not always easy to compute
- **Full producer** responsibility and **full consumer** responsibility belong to the core and are easy to compute, but are somewhat extreme

Supply chain with tree graph resembles the **airport game** (Littlechild and Owen, 1973), for which calculation of the Shapley value is easy



Supply chain with tree graph resembles the **airport game** (Littlechild and Owen, 1973), for which calculation of the Shapley value is easy



A: 10/5+3=5

B: 10/5+2/2+4=7

C: 10/5+2/2+1=4

D: 10/5+4/2+2=6

E: 10/5+4/2+1=5

Shapley value for GREEN game with tree structure

- **The emissions on each arc are equally allocated among all players who are directly or indirectly responsible for them**
  - Easy to calculate
  - It belongs to the core

Some intuitive fairness properties that any rule should possess in the context of pollution allocation:

Equal sharing of extra pollution

- if the pollution at some arc increases and all the others remain the same, then any two firms which are held responsible for the pollution of that arc should bear the extra burden equally

Cross-subsidy free

- if the total pollution increases, but for some firm, the pollution of the processes it is responsible for are unchanged, then the firm's allocation remains the same

Firm equivalence

- if two firms are equivalent in that they are responsible for the exact same set of polluting processes, then they must be allocated an equal share of the total responsibility

Firm nullity

- if a firm is not responsible for any polluting process, then it is allocated zero responsibility

Some intuitive fairness properties that any rule should possess in the context of pollution allocation:

Equal sharing of extra pollution

- if the pollution at some arc increases and all the others remain the same, then any two firms which are held responsible for the pollution of that arc should bear the extra burden equally

Cross-subsidy free

- if the total pollution increases, but for some firm, the pollution of the processes it is responsible for are unchanged, then the firm's allocation remains the same

Firm equivalence

- if two firms are equivalent in that they are responsible for the exact same set of polluting processes, then they must be allocated an equal share of the total responsibility

Firm nullity

- if a firm is not responsible for any polluting process, then it is allocated zero responsibility

Some intuitive fairness properties that any rule should possess in the context of pollution allocation:

Equal sharing of extra pollution

- if the pollution at some arc increases and all the others remain the same, then any two firms which are held responsible for the pollution of that arc should bear the extra burden equally

Cross-subsidy free

- if the total pollution increases, but for some firm, the pollution of the processes it is responsible for are unchanged, then the firm's allocation remains the same

Firm equivalence

- if two firms are equivalent in that they are responsible for the exact same set of polluting processes, then they must be allocated an equal share of the total responsibility

Firm nullity

- if a firm is not responsible for any polluting process, then it is allocated zero responsibility

Some intuitive fairness properties that any rule should possess in the context of pollution allocation:

Equal sharing of extra pollution

- if the pollution at some arc increases and all the others remain the same, then any two firms which are held responsible for the pollution of that arc should bear the extra burden equally

Cross-subsidy free

- if the total pollution increases, but for some firm, the pollution of the processes it is responsible for are unchanged, then the firm's allocation remains the same

Firm equivalence

- if two firms are equivalent in that they are responsible for the exact same set of polluting processes, then they must be allocated an equal share of the total responsibility

Firm nullity

- if a firm is not responsible for any polluting process, then it is allocated zero responsibility

Some additional intuitive properties in the context of pollution allocation:

Process independence

- the change in responsibilities of the firms due to a change in pollution of any process is independent of the pollution levels of other processes

Disaggregation invariance

- if a manufacturer instead of selling directly, decides to disaggregate and sell via a distributor who creates no additional pollution, it should not change the pollution allocations to the firm

Some additional intuitive properties in the context of pollution allocation:

Process independence

- the change in responsibilities of the firms due to a change in pollution of any process is independent of the pollution levels of other processes

Disaggregation invariance

- if a manufacturer instead of selling directly, decides to disaggregate and sell via a distributor who creates no additional pollution, it should not change the pollution allocations to the firm

The Shapley pollution allocation is uniquely characterized by each of the following sets of independent properties:

Equal sharing of extra pollution and cross-subsidy free

- characterization is based on fairness considerations

Firm equivalence, firm nullity and process independence.

Firm equivalence, cross-subsidy free, and disaggregation invariance

The Shapley pollution allocation is uniquely characterized by each of the following sets of independent properties:

Equal sharing of extra pollution and cross-subsidy free

- characterization is based on fairness considerations

Firm equivalence, firm nullity and process independence.

- milder fairness properties of firm equivalence and firm nullity, and the process independence property that emphasizes the ease of interpreting the effect of a change in pollution of a process on the allocation of responsibilities.

Firm equivalence, cross-subsidy free, and disaggregation invariance

The Shapley pollution allocation is uniquely characterized by each of the following sets of independent properties:

Equal sharing of extra pollution and cross-subsidy free

- characterization is based on fairness considerations

Firm equivalence, firm nullity and process independence.

- milder fairness properties of firm equivalence and firm nullity, and the process independence property that emphasizes the ease of interpreting the effect of a change in pollution of a process on the allocation of responsibilities.

Firm equivalence, cross-subsidy free, and disaggregation invariance

- subject to certain natural fairness properties, the Shapley allocation rule is the unique pollution allocation rule that is disaggregation invariant and is thus strategy proof

Gallego and Lenzen (2005)

X

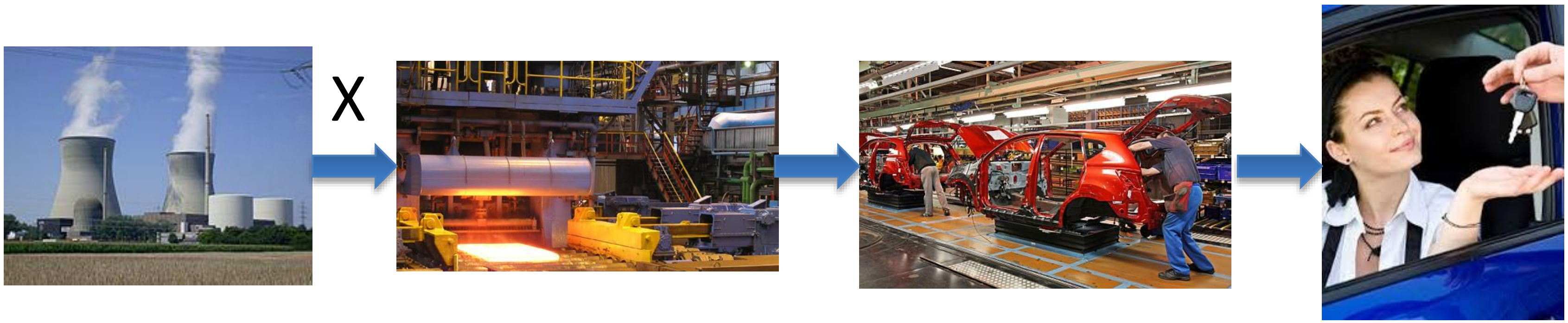
$(1-\alpha)X$ $\alpha(1-\alpha)X$ $\alpha^2(1-\beta)X$ $\alpha^2\beta X$

$\alpha=0$ ➔ full producer responsibility

$\alpha=1$, $\beta=1$ ➔ full consumer responsibility

$\alpha=0.5$, $\beta=0.5$ ➔ $X/2$; $X/4$; $X/8$; $X/8$

Gallego and Lenzen (2005)



$(1-\alpha)X$ $\alpha(1-\alpha)X$ $\alpha^2(1-\beta)X$ $\alpha^2\beta X$

$\alpha=0$ ➔ full producer responsibility

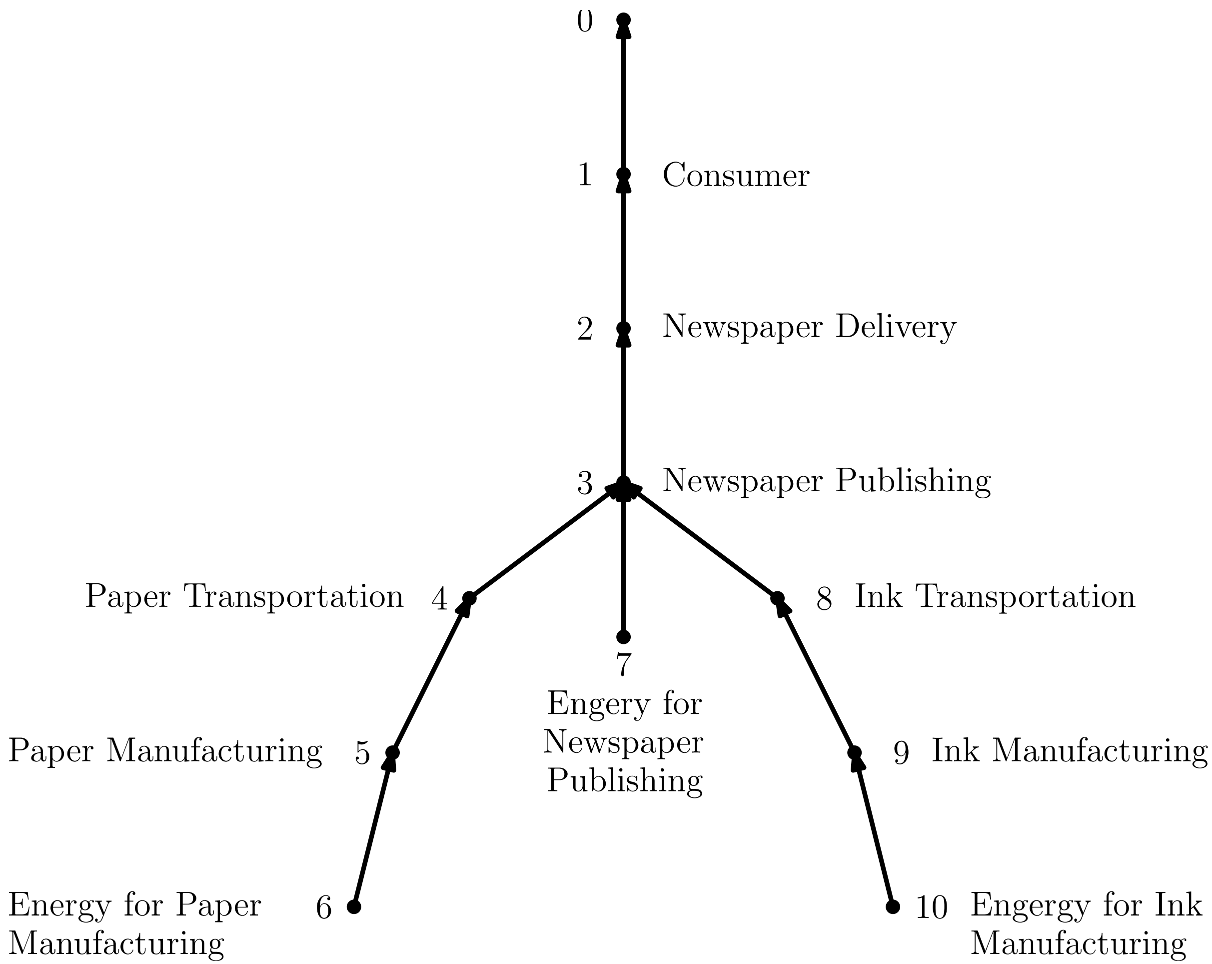
$\alpha=1$, $\beta=1$ ➔ full consumer responsibility

$\alpha=0.5$, $\beta=0.5$ ➔ X/2; X/4; X/8; X/8

Shapley value ➔ X/4; X/4; X/4; X/4

Illustrative example—newspaper publishing emissions

A newspaper supply chain



Paper manufacturing and transportation emissions (kg CO_2Eq) – LAT vs NYT

- Assume 100% virgin paper
- Environment Paper Network: GHG emissions factor of 2.8 kg CO_2Eq per kg of paper
- Distribution of emissions (Ford, 2012): 35% manufacturing, 35.3% energy, 15% transportation

	LAT	NYT
Pages/week	483	507
Weight/year	96.7 kg	101.5 kg
Paper manufacturing	94.80	99.51
Paper transportation	40.24	42.24
Energy for manufacturing	95.55	100.30

Newspaper publishing and delivery emissions (kg CO_2Eq) – LAT vs NYT

- CMU Green Design Institute – 317 kg CO_2Eq per $1,000 of newspaper publishing, which includes paper, ink, and energy emissions
- 30% of cost is attributed to delivery (Toffel and Sice 2011); GHG emissions factors from Greenhouse Gas Conversion Factor Repository by the UK Department for Environment Food & Rural Affairs

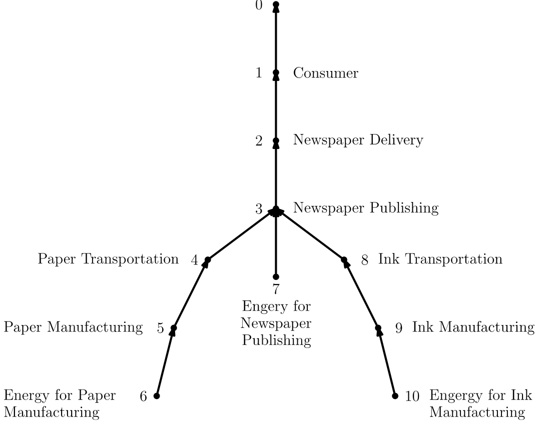
	LAT	NYT
Subscription cost	$572	$1,092
Newspaper publishing	50.82	97.02
Energy	51.25	97.84
Delivery distance (miles)	20	32
Newspaper delivery	1.08	1.69

Ink manufacturing and transportation emissions (kg CO_2Eq) – LAT vs NYT

- Environment Paper Network: GHG emissions factor of 0.015 kg CO_2Eq per $1,000 of newspaper publishing
- CMU Green Design Institute: 20% energy, 4% transportation

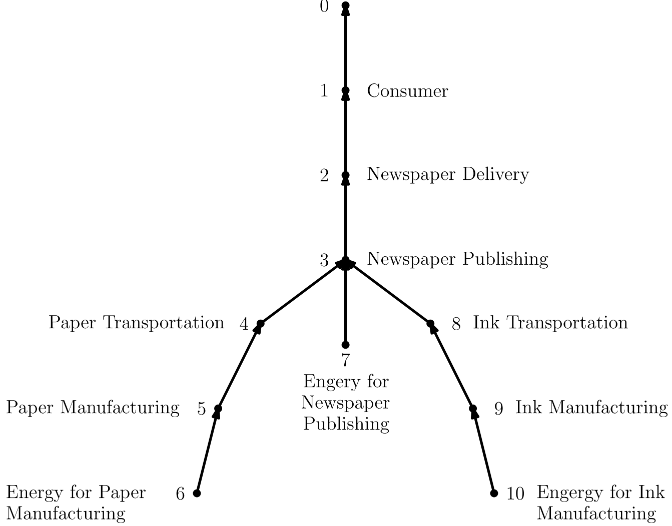
	LAT	NYT
Ink manufacturing	0.0060	0.0115
Energy for mfg	0.0012	0.0023
Inktransportation	0.0002	0.0005

GHG emissions in newspaper supply chain (kg CO_2Eq)



Supply chain member	Arc e_j	Emission on arc e_j LAT	Emission on arc e_j NYT
Consumer (1)	(1,0)	0	0
Newspaper delivery (2)	(2,1)	1.08	1.69
Newspaper publishing (3)	(3,2)	50.82	97.02
Paper transportation (4)	(4,3)	40.24	42.24
Paper manufacturing (5)	(5,4)	94.80	99.51
Energy for paper mfg (6)	(6,5)	0.0002	0.0005
Energy for publishing (7)	(7,3)	0.0060	0.0115
Ink transportation (8)	(8,3)	95.55	100.30
Ink manufacturing (9)	(9,8)	51.25	97.84
Energy for ink mfg (10)	(10,9)	0.0012	0.0023

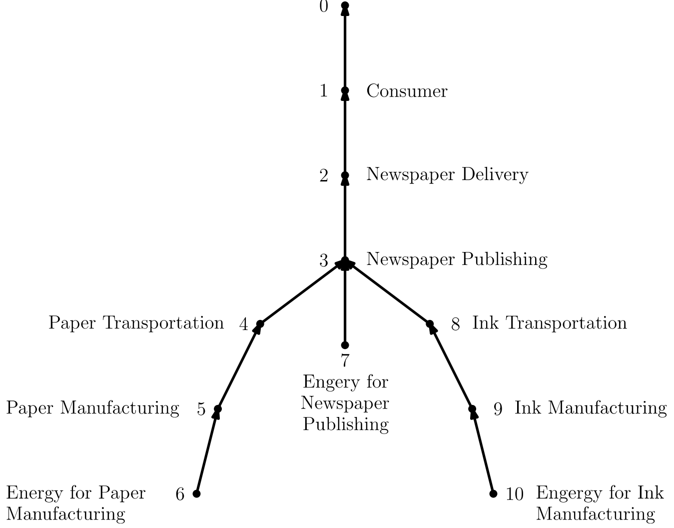
GHG responsibility for all nodes



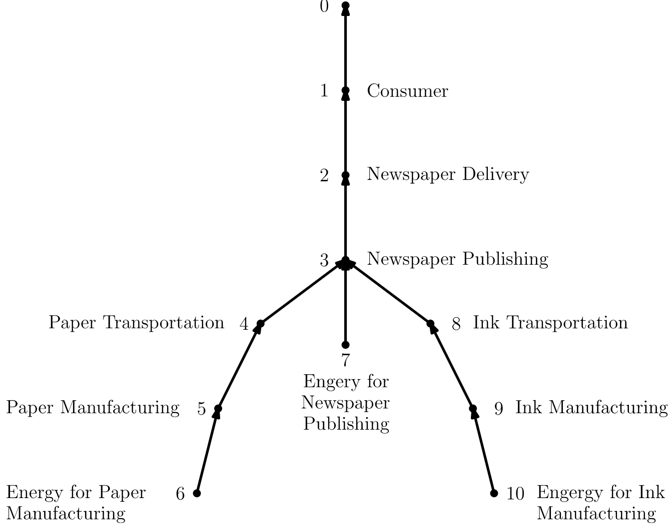
Supply chain member	Direct and indirect responsibility
Consumer	(1,0), (2,1), (3,2), (4,3), (5,4), (6,5), (7,3), (8,3), (9,8), (10,9)
Newspaper delivery	(2,1)
Newspaper publishing	(3,2), (4,3), (5,4), (6,5),(7,3), (8,3), (9,8), (10,9)
Paper transportation	(4,3)
Paper manufacturing	(5,4), (6,5)
Energy for paper mfg	(6,5)
Energy for publishing	(7,3)
Ink transportation	(8,3)
Ink manufacturing	(9,8),(10,9)
Energy for ink mfg	(10,9)

GHG emission responsibility for all arcs

Arc e_j	Nodes
(1,0)	1
(2,1)	1,2
(3,2)	1,3
(4,3)	1,3,4
(5,4)	1,3,5
(6,5)	1,3,5,6
(7,3)	1,3,7
(8,3)	1,3,8
(9,8)	1,3,9
(10,9)	1,3,9,10



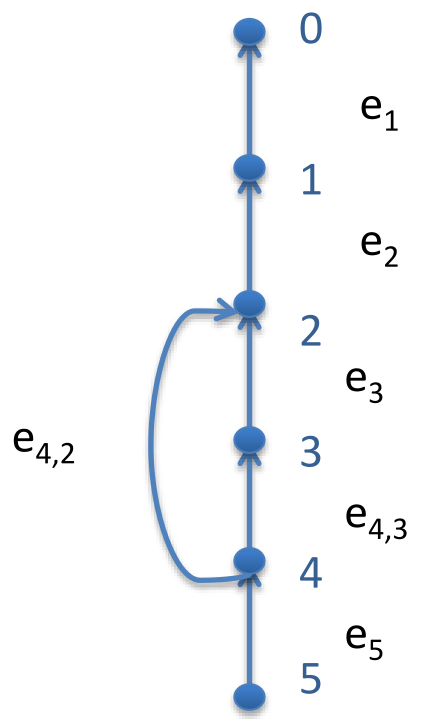
GHG emissions allocated to each supply chain member (kg CO_2Eq)



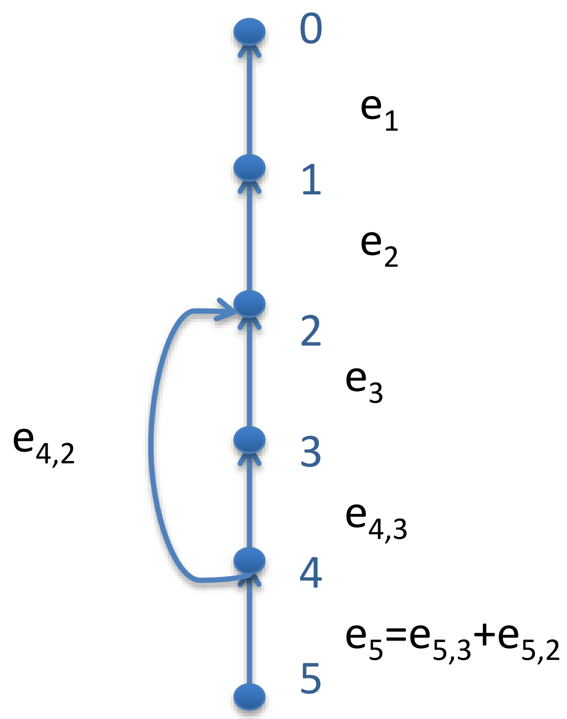
Supply chain member	Node	Emission allocation LAT	Emission allocation NYT
Consumer	1	111.9370	154.3028
Newspaper delivery	2	0.5378	0.8467
Newspaper publishing	3	111.3992	153.4561
Paper transportation	4	13.4140	14.0805
Paper manufacturing	5	55.4887	58.2459
Energy for paper mfg	6	23.8884	25.0754
Energy for publishing	7	17.0837	32.6144
Ink transportation	8	0.0001	0.0002
Ink manufacturing	9	0.0023	0.0044
Energy for ink mfg	10	0.0003	0.0006

What about more general supply chains?

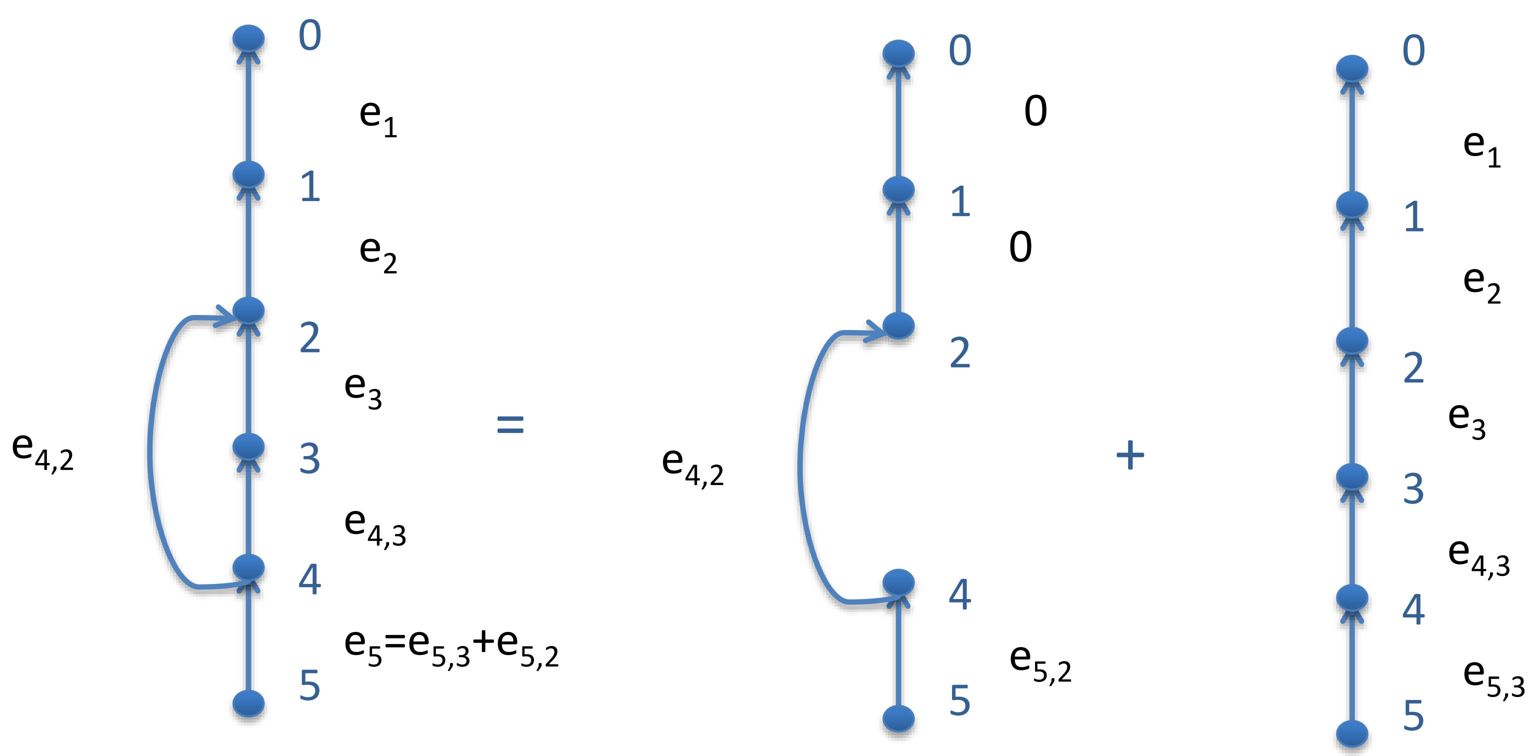
How to allocate emission on a general supply chain structure?



How to allocate emission on a general supply chain structure? **We use additivity of the Shapley value!**



How to allocate emission on a general supply chain structure? **We use additivity of the Shapley value!**



Conclusions

- Focus on GHG allocations that are fair and transparent, are easy to compute, avoid double counting
- GREEN game is convex and has a nonempty core
- Full producer responsibility and full consumer responsibility belong to the core, but are rather extreme
- Shapley value allocates emissions equally among all the responsible parties and meets all desired criteria
- Shapley value is the unique pollution allocation rule satisfying natural and intuitive properties