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ENVIRONMENTAL ECONOMICS MODELS FOR EFFICIENT AND SUSTAINABLE LOGISTICS SYSTEMS

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Summary

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Ilaria

1 INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC) reports that global warming poses a grave threat to the world's ecological system and the human race, and it is very likely caused by increasing concentrations of carbon emissions, which mainly results from such human activities as fossil fuel burning and deforestation (IPCC, 2007).

Several Climate Change Conferences have been organized by the United Nations to talk over countermeasures aiming to face and solve the environmental problems caused by climate change (Liu et al., 2015).

The COP22 (COP, Conference of the Parties) was held in Marrakech, in the North-African country of Morocco, on 7–18 November 2016, and faced two focal issues, at first water scarcity, water cleanliness, and water-related sustainability. This topic represents indeed a major issue for developing world, including many African states. The other focal issue was the need to reduce greenhouse gas emissions (GHG) and enhance the use of low-carbon energy resources. Mr. Peter Thompson, President of the UN General Assembly, required the transformation of the global economy in order to achieve a resilient and low emissions global economy (www.unfccc.int).

A powerful action is required to stabilize the rising temperatures, in order to avoid irreversible and catastrophic changes. Global measures are actually needed, involving many countries with a common objective. A cooperative solution has indeed to be reached; otherwise, without an effective global climate agreement no result will be accomplished (Stavins, 2008).

In order to mitigate global warming, the United Nations (UN), the European Union (EU), and many countries have introduced some policies and mechanisms to contain the total amount of greenhouse gas emissions. Among these, one of the primary legislation is the European Union Emission Trading System (EU-ETS). It has been launched in 2005 and it works on the "Cap and Trade" principle: a cap is set on the total amount of certain GHG that can be emitted by factories, power plants and other companies covered by the system. The cap is reduced over time, in this way the total emissions fall.

The carbon emission trading is generally considered as one of the most effective market-based mechanisms. It has been introduced in UN, EU, and many other governments (Hua et al., 2011).

In the United States there currently is little action on climate change policy at the Congressional level, but it is anyway possible to identify some regional and federal initiatives, for instance: RGGI, AB 32 in California, WCI between some US states and Canadian provinces.

Shen B. et al. (2014) describe California's emissions trading program as the most ambitious Cap and Trade scheme at the individual state level. The goals of this Cap and Trade program are to achieve a reduction in GHG emissions to 1990 levels by 2020, and ultimately to achieve an 80% reduction below 1990 levels by 2050. Moreover, in April 2015, Gov. Jerry Brown issued an additional emissions reductions target of 40% below 1990 levels by 2030 (http://www.arb.ca.gov/).

China, India and other developing countries were exempt from the requirements of the Kyoto Protocol, adopted in Kyoto, Japan, on 11 December 1997 (http://unfccc.int/kyoto_protocol). They were not part of the major emitters of GHG during the period of industrialization, which is believed caused climate change. Nevertheless, now these fast growing economies (China, India, Thailand, Indonesia, Egypt, and Iran) have GHG emissions rapidly increasing and their pollution is becoming a global issue.

China and India will probably achieve more than 35% of total CO2 emissions by 2030.

This emission increase is primarily due to higher coal consumption. The development of industrialization and urbanization requires for fast energy growth, which leads the growth of energy related carbon dioxide emissions (Liu L. et al., 2015).

In order to reduce the emissions growth, China has developed a national policy program, which included the closure of old, less efficient coal-fired power plants and more investments on green energy. Moreover, by the end of 2014, seven Cap and Trade pilot programs had been officially opened in Beijing, Shanghai, Shenzhen, Tianjin, Guangdong, Hubei and Chongqing (Liu L. et al., 2015) and in December 2017, China announced the initial details of its national emissions trading scheme.

Therefore, with the objective of reducing the negative impact of human species on the environment, GHG emissions, e.g. carbon dioxide (CO2), nitrous oxide (N2O), fluorinated gases and methane (CH4), have recently attracted a special attention (Helmrich, Jans, van denHeuvel, & Wagelmans, 2015). But just the CO2 is considered responsible for approximately half of the emission generated by human, and it has increased by 50% compared to its level in 1990 (Jaber, Glock, & El Saadany, 2013).

Since the emissions released by companies' operational activities into the air are one of the main causes of global climate change (He et al. 2015), businesses are becoming increasingly conscious of their carbon footprint and have begun to incorporate environmental thinking into their business strategy and supply chain management, making efforts to be more environmentally friendly.

As expressed by (Ortolani et al., 2011 and Rai et al. 2011), external emission costs have become an important issue for supply chain management because of several environment conservation agreements, such as the Kyoto Protocol and the Paris Agreement, and environmental economics policies, such as EU-ETS.

Therefore, it is clear that there is an increasing trend among firms to set up more environmental friendly manufacturing systems introducing new technologies, optimizing their production and inventory decisions by integrating environmental factors that can help on reducing GHG emissions (Kazemi et al. 2016).

As stated by (Miemczyk et al., 2012), Sustainable Purchasing means considering social, environmental and financial factors in taking goods procurement decisions. Many managers are now looking beyond the traditional economic parameters and are starting to take decisions based on the whole life cost, the associated risks, measures of success and impacts on society and environment.

Sustainability in material purchasing is a growing area of research. Goods purchasing decisions strongly affect transportation path flows, vehicle consolidation, inventory levels and related obsolescence costs. These choices have an economic impact on the supply chain, in terms of different logistic costs, and an environmental impact, in terms of carbon emissions produced during goods transportation, storage and final recovery.

Starting from the research agenda described in Andriolo et al. (2014), this research work aims to develop multi-objective lot sizing models together with useful tools and graphs for supporting managers in making sustainable purchasing decisions and assessing a Sustainable Supplier Selection. This comprehensive aim can be declined in three main Research Questions, described as follow.

1.1 Research questions

1. **Support companies in making sustainable and efficient purchasing decisions through a multi-objective Sustainable Economic Order Quantity (S-EOQ) Model.**

The proposed S-EOQ model is born as a conceptual evolution of the sustainable EOQ model by Battini et al. (2014) and tries to capture economic and environmental trade-offs in material purchasing lot sizing under a Cap and Trade policy.

It is presented a multi-objective optimization approach (Pareto, 1964) in which the optimal lot-sizing decision depends on a bi-objective model with two different objective functions (costs and emissions) and transportation capacity constraints.

The model is useful in practice to support managers in understanding the Pareto frontier shape linked to a specific purchasing problem, defining the cost-optimal and emission-optimal solutions and identifying a sustainable quantity to purchase when a Cap and Trade mitigation policy is present.

Moreover, the Cap and Trade system approach is integrated in the multi-objective model in order to understand the impact of economic incentives (the so-called carbon allowances) on taking sustainability-oriented purchasing decisions. The Trading system used here is inspired to the current EU ETS (Emission Trading System) system (www.ec.europa.eu) and on the carbon cap evolution forecasted in the medium term.

2. **Support managers in making sustainable and efficient purchasing and logistics decisions into a supply-chain context, through a multi-objective Sustainable Joint Economic Lot Size (S-JELS) Model.**

   It is introduced a new innovative bi-objective Sustainable Joint Economic Lot Size Model (S-JELS) under a Cap and Trade policy, in order to consider costs and emissions related to a two-echelon supply chain, not only to the buyer. By considering two different objective functions (costs and emissions), both economic and sustainable issues are equally considered and integrated in the contest of a supply chain.

   The model is useful in practice to support managers in understanding the Pareto frontier shape linked to a specific supply chain purchasing problem, defining the cost-optimal and emission-optimal solutions and identifying a sustainable quantity to purchase when a Cap and Trade mitigation policy is present. In this way, the model leads the decision makers to more sustainable and efficient logistic and purchasing solutions, considering a supply chain point of view.

   With the purpose of helping companies analyzing the trade-offs among different supplies, the S-JELS model can be run iteratively for many sourcing options, in order to build the Pareto Frontiers for each supplier and compare then the Frontier shapes, the cost-optimal solutions and the emission-optimal ones. In this way, the model can be useful to evaluate which sourcing option is the most sustainable, efficient or economical.

3. **Support managers in Sustainable Supplier Selection procedures with numerical KPIs and user-friendly graphs.**
   The objective is to exploit numerical KPIs and user-friendly graphs, obtained running the new bi-objective S-JELS model, into a procedure for assessing a Sustainable Supplier Selection. The aim is to help managers on analysing the trade-offs among different supplies and on evaluating the selection criteria for each potential supplier in an easier, faster, more analytical and correct manner.
   In this way, the decision makers are guided to understand the trade-offs among different supply options and supported to make the more efficient and sustainable supplier selection.
   In the end, it is presented a leather industry case study. The objective is to help managers on carrying out a Sustainable Supplier Selection between a Domestic and a Far East sourcing, by applying the S-JELS model integrated in an AHP supplier selection procedure.

1.2 Methodology

In order to carry out this research work in the most exhaustive and precise way, in a first phase a preliminary literature review has been carried out, in order to conduct a deep study and comparisons among the most relevant European and International Environmental Economics Policies to combat climate change, and investigating if there are cooperation and a global-level agreement.
A database of scientific papers dealing with the theme of the Environmental Economics Policies has been created using Scopus (www.scopus.com), Elsevier’s abstract and citation database. In order to identify the literature related to the focal topic, some keywords have been used, like: "Environmental Economics Policies", " Cap and Trade system ", "Carbon Trading System” and " Carbon Pricing ".

After that, the most relevant government policies introduced for achieving emissions reduction have been analyzed, by examining their institutional web sites.

Since the increasing international attention on environmental issues emphasizes the need to treat inventory management and goods purchasing decisions by integrating economic, environmental and social objectives, a literature review regarding the sustainable Economic Order Quantity (EOQ) model and Joint Economic Lot Size (JELS) model has been carried out. After studying the state of the art regarding Sustainable EOQ models, Sustainable JELS models and the gaps of the present literature; in order to meet some lacks, the sustainable EOQ model by Battini et al. (2014) has been evolved and an innovative multi-objective Sustainable Joint Economic Lot Size Model has been developed.

The sustainable material purchasing strategy is investigated by applying a multi-objective optimization approach in which the optimal lot-sizing decision depends on a bi-objective model with two different objective functions (costs and emissions) and transportation capacity constraints.

A bi-objective approach to material purchasing overcomes the limits of a direct cost accounting approach in which emissions are transformed in costs and only a single objective function is considered. As asserted by Andriolo et al. (2014), since in most cases the cost and the emission functions produce different optimal solutions, the cost trade-offs are different from the emission ones. When externalities need to be quantified, the limits of a direct accounting method are becoming visible (Bouchery et al., 2012; Battini et al., 2014). For these reasons the multi-objective optimisation approach has been exploited for this research work.

Costs and emissions are kept separated to better reflect the effect of the lot sizing problem under analysis by also providing managers with a new decision-support tool: the Pareto Frontier associated to a specific material purchasing choice.

By a practical point of view, the analysis of the Pareto frontier is useful to address managers towards the correct comprehension of the sustainable purchasing problem, by identifying the cost-optimal and the emission-optimal solutions, while having an immediate comprehensive visualisation of Pareto frontier shape.

The shape of the Frontier (that could be flat or steep around the cost-optimal solution) reflects the real cost and emission variations, which a manager who decides to move from a cost-optimal lot sizing solution to a more sustainable solution has to face, by better consolidating transportations.

Moreover, the Cap and Trade system approach is integrated in the bi-objective models in order to understand the impact of economic incentives (the so-called carbon allowances) on taking sustainability-oriented purchasing decisions. The Trading system used here is inspired to the current EU ETS (Emission Trading System) system (www.ec.europa.eu) and on the carbon cap evolution forecasted in the medium term.

1.3 Thesis outline

This Thesis work is organized as follows: Section 2 deeply analyses and compares the mitigation policies developed by some key countries, with particular attention to Europe, USA and China. In Section 3 it is presented the state of the art regarding sustainable lot sizing models and purchasing. In Section 4 the multi-objective S-EOQ model formulation is presented and the interactive decision-making approach is explained. Section 5 presents the mathematical formulation of two sustainable multi-objective joint economic lot size models (S-JELS) under Cap and Trade regulation. In section 6 the S-JELS model is exploited to support a supplier selection in a leather industry case study. Section 7 presents the conclusions of the research work and recommendations for future research. In Section 8 and 9 all the bibliography and sitography are reported. Section 10 collects the papers published in Scientific Journals or submitted for Conferences and reported into the Conference proceedings.

2 MITIGATION POLICIES AND CRITICAL COMPARISON

2.1 National and International commitments

The Intergovernmental Panel on Climate Change (IPCC) reports that global warming poses a grave threat to the world's ecological system and the human race, and it is very likely caused by increasing concentrations of carbon emissions, which mainly results from such human activities as fossil fuel burning and deforestation (IPCC, 2007).
A powerful action is needed to stabilize the rising temperatures, in order to avoid irreversible and catastrophic changes.
It is fundamental to:

- Drastically cut CO_2 and other greenhouse gasses emissions;
- Change the production and use of energy (more efficiency is needed);
- Promote renewable energy and innovative technologies.

Global measures are actually needed, involving many countries with a common objective.
A cooperative solution has indeed to be reached; otherwise without an effective global climate agreement no result will be accomplished (Stavins, 2008).
In order to mitigate global warming, the United Nations (UN), the European Union (EU), and many countries have introduced some policies and mechanisms to contain the total amount of greenhouse gas emissions and thereby to prevent or reduce such climate change.
In the U.S., there currently is little action on climate change policy at the Congressional level. Nevertheless, several U.S. states have introduced climate change policies.
Some other developed policies are: the national Cap and Trade system of New Zealand, Carbon Tax programs in various European and Scandinavian countries, a Carbon Tax introduced in the Canadian province of British Columbia, the European Emissions Trading Scheme to reduce greenhouse gas emissions by the nations involved, a pilot Cap and Trade scheme in China, and some efforts undertaken by nations that have signed on to the Kyoto Protocol (L. H. Goulder and A. Schein, 2013). As it is shown in Figure 2.1 Cap and Trade (C&T) and Carbon Tax are among the most widely implemented, effective and debated environmental regulations (Y. He et al., 2012).
Some other countries still consider the efforts to mitigate global warming as obstacles to striving for economic growth. However, without a comprehensive engagement, some actors

are advantaged and more competitive in the global economy. Some others, involved in emission saving policies, have to face stronger investments and restrictions, with the risk of suffering economic disadvantages and becoming therefore less competitive in the global economy.

As declared by the European Parliament resolution on the 2017 UN Climate Change Conference in Bonn, the efforts to avoid global warming should not be seen as an obstacle to economic growth but should, differently, be seen as a driving force for developing new and sustainable growth and employment: a valid climate mitigation policy can produce growth and jobs. However, giving that some specific sectors with a high carbon intensity and high trade intensity could suffer from carbon leakage, a suitable protection against carbon leakage is therefore needed to protect jobs in these specific sectors.

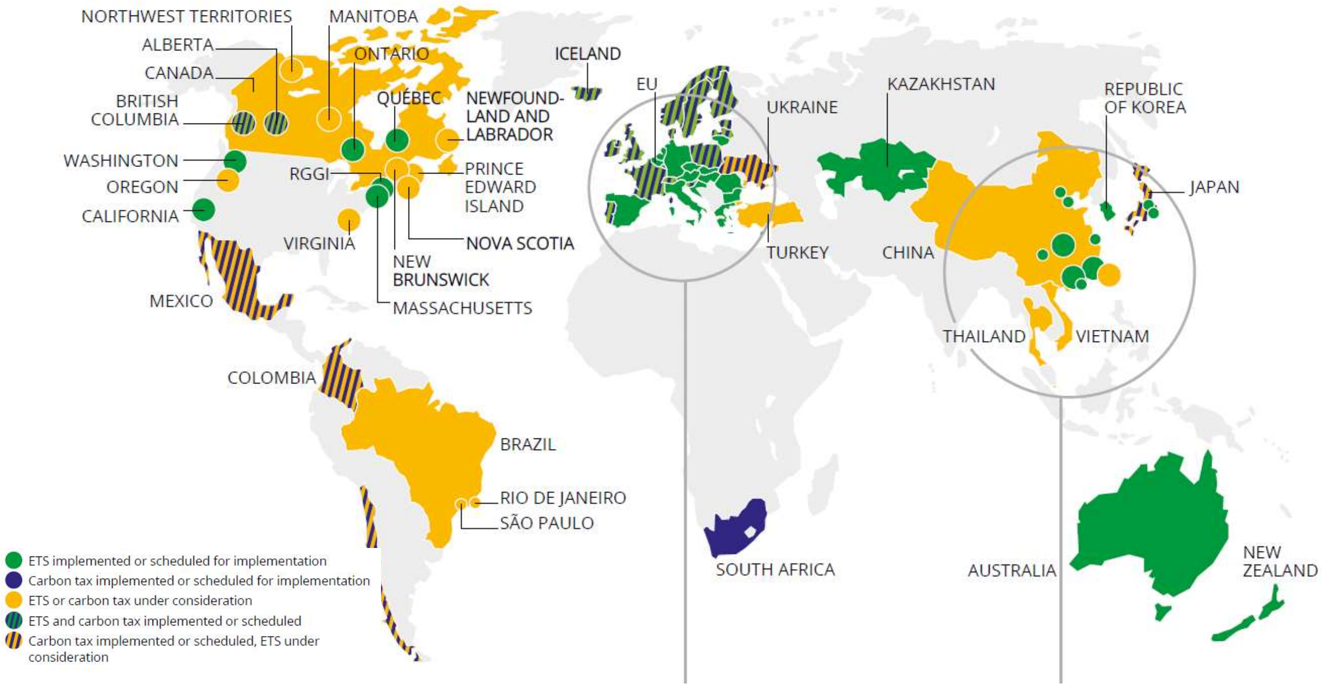


Figure 2.1 - Types of mechanisms introduced for cutting GHG emissions (Source: "State and Trends of Carbon Pricing 2017" World Bank Group)

In the next sections, it is presented a deep analysis and comparison of the environmental economics policies developed by some key countries, with particular attention to Europe, USA and China.

2.1.1 EU Position

The Emission Trading System (ETS) is a cost-effective way of the European Union's policy to combat climate change and to reduce industrial greenhouse gas emissions (GHG).
It has been launched in 2005 and it works on the "Cap and Trade" principle: a cap is set on the total amount of certain GHG that can be emitted by factories, power plants and other companies covered by the system. The cap is reduced over time, in this way the total emissions fall. The 2020 target is to achieve an emissions reduction of 21% compared to 2005 levels from sectors covered by the system.
This policy limits emissions from more than 11,000 heavy energy-using installations (power stations and industrial plants) and airlines operating between the 28 EU member states plus Iceland, Liechtenstein and Norway.
Moreover, the ETS allows also buying limited amounts of international allowances from emission-saving projects around the world. These projects must be recognised under the Kyoto Protocol's Clean Development Mechanism or Joint Implementation mechanism as producing real and genuine emission reductions. In this way EU ETS promotes many investments on clean technologies and low-carbon solutions in developing countries and economies (www.ec.europa.eu/clima/policies/ets).
The EU ETS regards in particular power plants, a wide range of energy-intensive industry sectors and operators of flights to and from the EU, Iceland, Liechtenstein and Norway. Under these conditions, around 45% of the EU's greenhouse gas emissions are covered.
Covering also the aviation in the EU Emissions Trading System (EU ETS) represents one of the policies required to reduce greenhouse gas emissions for a range of transport modes. The transport industry causes around the 25% of EU greenhouse gas emissions and while emissions from other sectors are generally falling, those from transport have increased until 2007, starting then a decrease mostly due to the growth of oil prices, to a stronger efficiency of passenger cars and to a slower growth in mobility (Figure 2.3).

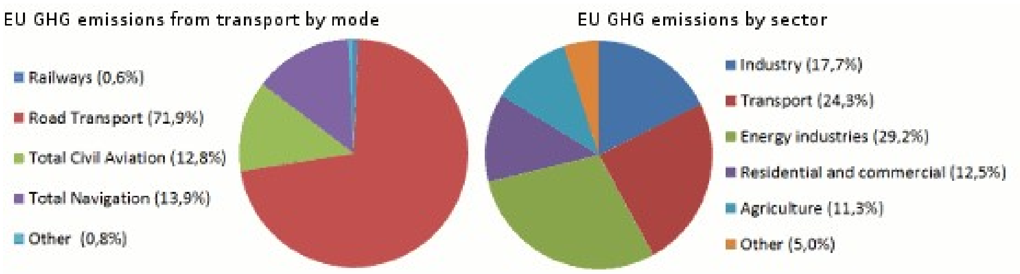


Figure 2.2 – EU28 GHG emissions by sector and mode of transport, 2012 (https://ec.europa.eu/clima/policies/transport_en)

Note: * Transport includes international aviation but excludes international maritime;
** Other include fugitive emissions from fuels, waste management and indirect CO2 emissions

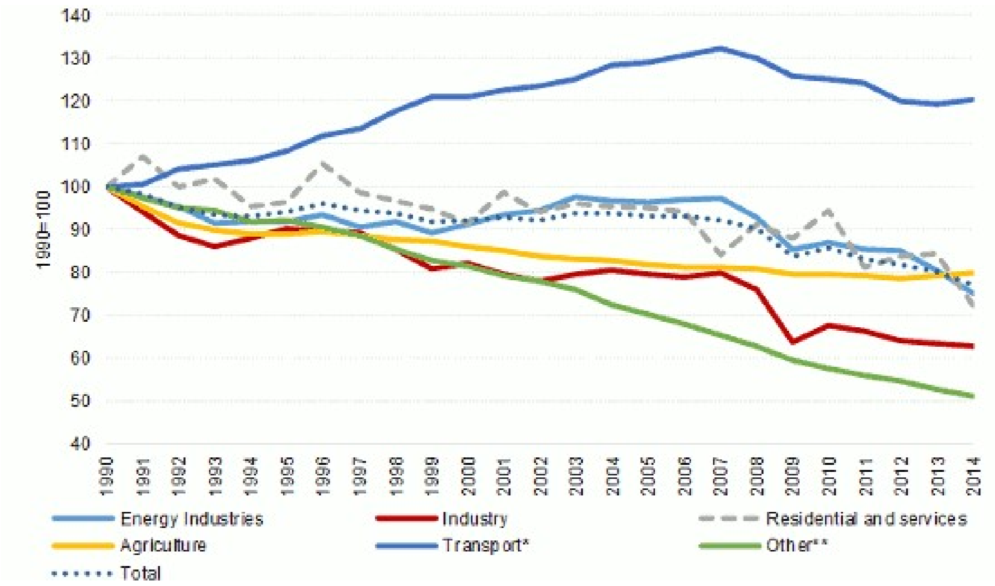


Figure 2.3 – Percentage Increase/Decrease of emissions according to sector (EU28), 1990-2014 (www.ec.europa.eu/clima/policies/transport_en)

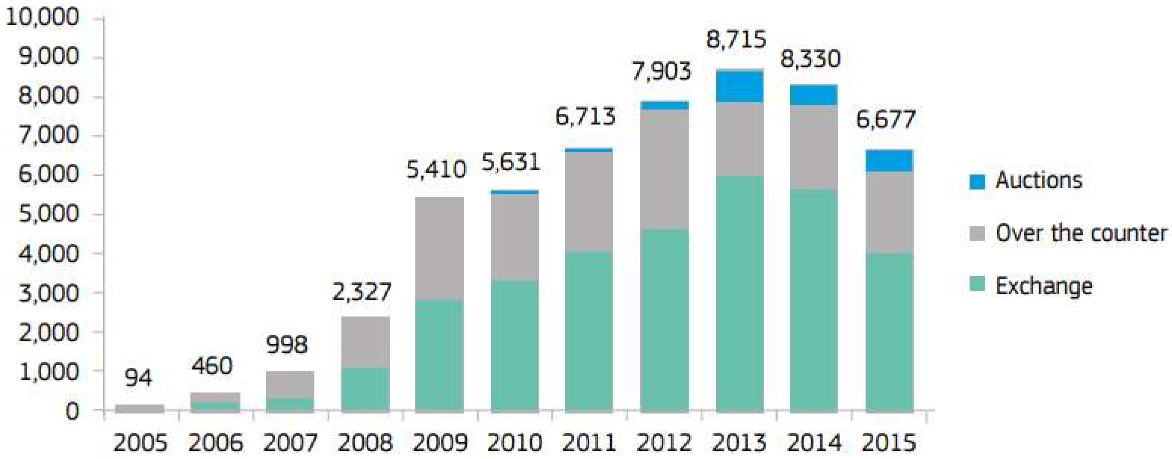


Figure 2.4 - The trading volumes in EU emission allowances (https://ec.europa.eu/clima/policies/ets)

The companies involved into the EU ETS system receive or buy emission allowances, which they can trade with one another as needed. Each allowance corresponds to the right to emit 1 tonne of CO_2.

Therefore, by putting a price on carbon this policy implies some interesting consequences:

- Each tonne of emissions saved has financial and commercial value (Figure 2.4);
- A sufficiently high carbon price promotes investment in clean, low-carbon technologies;
- The price of allowances is determined by supply and demand.

Businesses must monitor and report their EU ETS emissions for each calendar year; these have then to be checked by an accredited verifier. After that, companies must provide enough allowances to cover their total emissions by 30 April of the following year.
If a business does not surrender enough allowances to cover its emissions, it must buy allowances to make up the shortfall; its name is published, and has to pay a fine for each excess tonne of greenhouse gas emitted. The fine in 2013 was €100 per tonne of CO2 (www.ec.europa.eu).

2.1.1.1 How EU ETS is different

M. Grubb and K. Neuhoff (2006) have been able to clarify and emphasize some features that make the EU ETS different from previous emissions trading systems:

1. In terms of economic scale, the European emission trading scheme is still the biggest scheme in the world. The economic size of the EU ETS causes strong lobbying around allocation and competitiveness concern. At the same time, this system represents a source of profit-making incentives without precedents in the history of environmental policy.
   Due to its scale, the EU ETS could affect the costs of key industrial sectors more than any previous environmental policy.
2. The difficulty of reducing CO2 emissions (compared to many other pollutants), combined with the large-scale of the EU ETS led to two outcomes: cutbacks imposed in the first stages have been quite small; and prices have been volatile. Cutbacks during the 1st phase of EU ETS amounted to about 1% of projected needs. Conversely, the US SO2 programme required at the beginning cutbacks over 50% of historical emissions, with more additional reductions later.
   The difference between the EU ETS and other trading schemes is that during first phases the negotiated cutbacks have been within the range of projection uncertainty.

Therefore, if emissions turn out to be lower than the projections, it is inevitable the price volatility. The allowances price uncertainty delays investment decisions: by waiting, a company can obtain more knowledge about future CO2 prices, and thereby make better decisions. Therefore, in the presence of price uncertainty, risk aversion is also likely to cut investment.

3. A third characteristic is the tendency towards 'overcompensation'.
   CO2 costs feed into production costs; therefore in order to compensate, higher input costs cause the raise of product prices. In economic terms, free allocation represents an alternative way of compensating and protecting companies from the carbon cost. Firms, usually, in competitive markets maximize profits by defining prices relative to marginal cost of production. These marginal costs now include opportunity costs of CO2 allowances. Therefore, if the allowances are received for free, there is potential 'double compensation'. This creates the opportunity to make considerable profits.
   Smale et al. (2006) well explained this topic in their studies; Sijm et al. (2006) analysed it more for the electricity industry and Demailly and Quirion (2006) studied it with a focus on the cement industry.
4. Finally, by having negotiations of allocations for successive period, CO2 budgets and allowance allocations are defined for a limited time period, initially of only 3 and 5 years. Therefore, uncertainty about the future leads to a cost.

2.1.1.2 EU – International network

The European Commission has the aim to exploit the EU ETS for developing an **international network** of **emission trading systems**, by linking compatible domestic Cap and Trade systems. For instance, national or sub-national systems are already operating in Japan, New Zeeland, Switzerland and United States.

*"Linking the EU ETS with other Cap and Trade systems offers several potential benefits, including reducing the cost of cutting emissions, increasing market liquidity, making the carbon price more stable, levelling the international playing field and supporting global cooperation on climate change" (*European Commission, 2013a).

For instance, the EU and Switzerland signed in November 2017 (www.ec.europa.eu/clima) an agreement to link their emissions trading systems. Thanks to this link, the participants in the EU Emissions Trading System will be able to use allowances from the Swiss system for compliance, and vice versa. This is the first agreement of this kind for the EU and between two Parties to the Paris Agreement on climate change.
National or sub-national systems are already operating or under development also in China, Japan, New Zealand, South Korea and the United States, therefore a linkage between these Cap and Trade systems could be very convenient.

2.1.2 US Position

The US signed the Kyoto Protocol on 12 November 1998, but it has never been submitted to the Senate for ratification. Furthermore, by May 2012 US had indicated they would not sign up to the second Kyoto commitment period.
In the United States there currently is little action on climate change policy at the Congressional level, but such policy is being driven by the U.S Environmental Protection Agency under the Clean Air Act (L. H. Goulder and A. Schein, 2013).
The Clean Air Act is one of the United States' most important modern environmental federal laws. It has been introduced to control air pollution on a national level (www3.epa.gov) and it is one of the most exhaustive air quality laws in the world (www.nrdc.org). It is managed by the U.S. Environmental Protection Agency (EPA), in collaboration with state, local, and tribal governments.
The Trump administration has recently decided to withdraw the US from the Paris climate accord and US officials declared at the COP23 in Bonn to promote coal-fired power and nuclear energy. Nevertheless, in the United States it is possible to identify some regional and federal initiatives, for instance: RGGI, AB 32 in California, WCI between some US states and Canadian provinces. Moreover, California Governor Jerry Brown and former New York Mayor Michael Bloomberg published during COP23 the first progress report from America's Pledge, a coalition of states, cities and businesses representing more than half of the US economy and population.

2.1.2.1 Regional Greenhouse Gas Initiative (RGGI)

The Regional Greenhouse Gas Initiative (RGGI) has been adopted in 2009 (Murray et al., 2015). This system caps emissions from power generation in 9 US states: Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New York, Rhode Island and Vermont.

The 2020 target of this Cap and Trade program is to achieve a reduction of more than 45% in CO2 emissions from the power sector compared to 2005 emissions.

To reduce emissions of greenhouse gases, the RGGI States use a market-based Cap and Trade approach defining a multi-state CO2 emissions budget ("cap") and the CO2 allowances are allocated through quarterly, regional auctions. The proceeds from the CO2 allowance auctions have then to be invested in consumer benefit programs to improve energy efficiency and accelerate the deployment of renewable energy technologies.

Within the RGGI states, the initiative includes requirements for fossil-fuel-fired electric power generators with a capacity of 25 megawatts (MW) or greater ("regulated sources"), they are required to hold allowances equal to their CO2 emissions over a three-year control period. Moreover, an emissions and allowance tracking system has been introduced in order to record and track RGGI market and program data, including CO2 emissions from regulated power plants and CO2 allowance transactions among market participants (http://www.rggi.org/).

2.1.2.2 Emissions trading in California (AB 32)

Shen B. et al. (2014) describe California's emissions trading programme as the most ambitious Cap and Trade scheme at the individual state level. The goals of this Cap and Trade program are to achieve a reduction in GHG emissions to 1990 levels by 2020, and ultimately to achieve an 80% reduction below 1990 levels by 2050. Moreover, in April 2015, Gov. Jerry Brown issued an additional emissions reductions target of 40% below 1990 levels by 2030 (http://www.arb.ca.gov/). During the COP23, has been underlined that non-state actors are becoming a driving force in adaptation and mitigation climate change (www.europarl.europa.eu). Therefore, California represents an example of how non-state actors are providing leadership where is missing the national governments one.

The Californian program started on January 1, 2012, with an enforceable compliance obligation began on January 1, 2013, for greenhouse gas (GHG) emissions. This Cap and

Trade program covers the power and industrial sectors, and moreover the natural gas and transportation fuels. The program imposes a greenhouse gas emission limit that will decrease by 2% each year through 2015, and by 3% annually from 2015 through 2020. This rate will increase to around 5% post-2020 in order to meet the 2030 target (www.ieta.org). Emission allowances are distributed by a mix of free allocation and quarterly auctions. The number of free allowances will gradually be reduced over time and an increasing number will be auctioned. Freely allocated allowances are mostly provided to vulnerable industries that might move from California.

A distinguishing feature of the Californian Cap and Trade program is that law enabled it: the enactment of the Assembly Bill 32 (AB 32), also known as the California Global Warming Solutions Act of 2006, established the legal framework for leading the state's actions in reducing GHG emissions (Shen B. et al., 2014).

Jeffery B. Greenblatt (2015) developed four potential policy and technology scenarios in California using CALGAPS, a new model simulating GHG and criteria pollutant emissions in California from 2010 to 2050 (see Figure 2.5). The first simulated scenario Committed Policies (S1) includes all policies either underway or extremely likely by 2020; while all the financial commitments were considered achievable. S2, Uncommitted Policies, includes existing policies and targets that lack of precise implementation plans, financial commitments or supports. S3, Potential Policy and Technology Futures, includes speculative policies, considering extensions of S1 or S2 policies and targets proposed by non-governmental organizations. This scenario may not represent the maximum feasible level of GHG reductions. Finally, the Counterfactual scenario (S0) was constructed by disabling all policies included in S1.

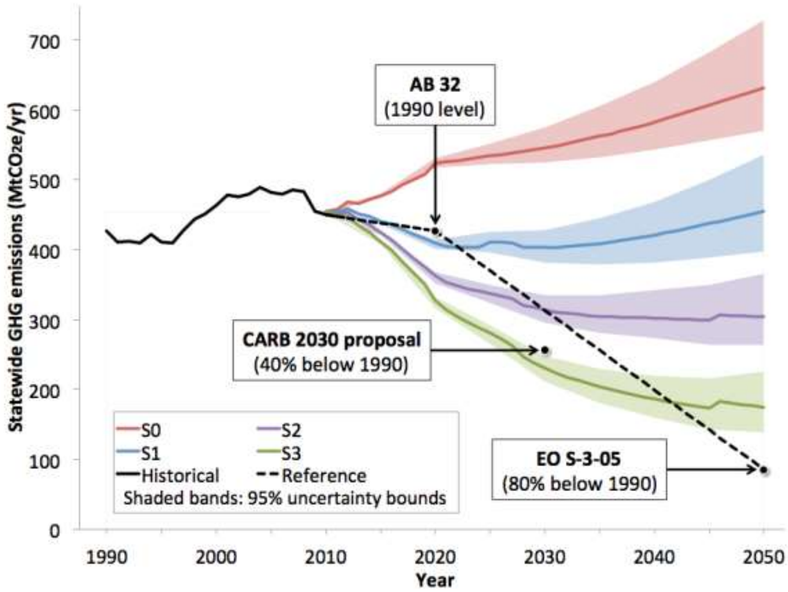


Figure 2.5 - GHG Emissions by scenario, with historical emissions and straight-line reference pathway between 2020 and 2050 GHG policy targets (Jeffery B. Greenblatt, 2015).

2.1.2.3 The Western Climate Initiative (WCI)

This scheme consists in a collective commitment, agreed between seven U.S. states and four Canadian provinces to identify, evaluate, and implement measures to reduce greenhouse gas (GHG) emissions (www.westernclimateinitiative.org).

This non-profit corporation has the goal of developing a multi-sector, market-based program to reduce greenhouse gas emissions (http://www.wci-inc.org/).

The WCI began in February 2007 when the Governors of Arizona, California, New Mexico, Oregon, and Washington signed an agreement in order to take part to a multi-state registry to track and manage GHG emissions in their regions, defining regional target for reducing greenhouse gas emissions and developing a market-based scheme to reach the objective.

By July 2008, the initiative had expanded to include two more U.S. states (Montana and Utah) and four Canadian provinces (British Columbia, Manitoba, Ontario and Quebec).

In November 2011, the Western Climate Initiative formed Western Climate Initiative, Inc., in order to provide administrative and technical services to support the implementation of state and provincial greenhouse gas emissions trading programs. In the same year Arizona, Montana, New Mexico, Oregon, Utah and Washington left WCI formally. This Cap and Trade program was scheduled to start in January 2012, covering six greenhouse gases (carbon

dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulphur hexafluoride). Actually Québec and California were the first systems to have started their compliance periods, in January 2013.
The WCI, in accordance with all the partners' individual goals, set a target of a 15% reduction from 2005 levels by 2020. With each partner reaching its own goal, the region is assured of achieving this level of reduction (www.westernclimateinitiative.org).
In May 2018 Nova Scotia chose the WCI to run its cap-and-trade system (www.wci-inc.org), while Ontario formally joined the WCI in September 2017, but cancelled its participation in the programme in July 2018.

2.1.3 China Position

China, India and other developing countries were exempt from the requirements of the Kyoto Protocol. They were not part of the major emitters of GHG during the period of industrialization which is believed caused climate change.
Now, these fast growing economies (China, India, Thailand, Indonesia, Egypt, and Iran) have GHG emissions rapidly increasing and their pollution is also becoming a global issue. As we can see from Figure 2.8 a large proportion of total CO2 emissions are caused by China. Its emission curve is indeed really steep after 2002, as we can notice from Figure 2.6. Therefore, while Europe aims to a continuous reduction according to IPCC, emissions will globally increase in the near future especially in developing countries (see Figure 2.8).
China and India will probably achieve more than 35% of total CO_2 emissions by 2030 (Figure 2.8). By the fact that these fast growing economies have GHG emissions rapidly increasing, some more effective systems are now required.

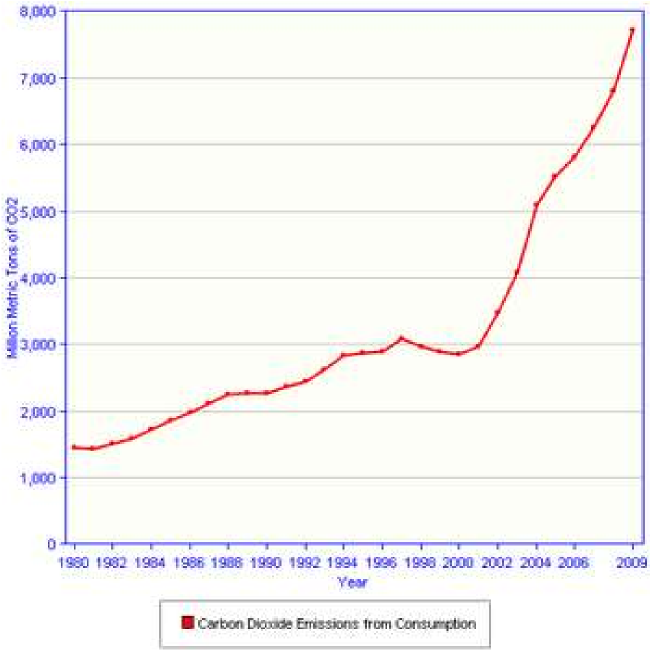


Figure 2.6 – China CO2 emission per millions of metric tons from 1980 to 2009.
(http://www.eia.gov/countries/img/charts_png/CH_co2con_img.png)

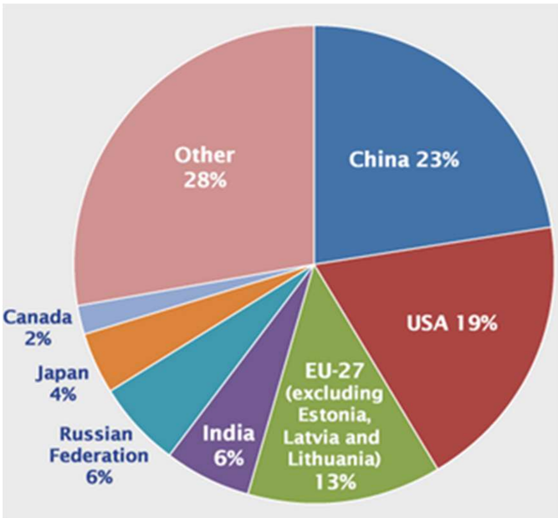


Figure 2.7 – 2008 Global CO2 Emissions from Fossil Fuel Combustion and some Industrial Processes (million metric tons of CO2), (http://www3.epa.gov/climatechange)

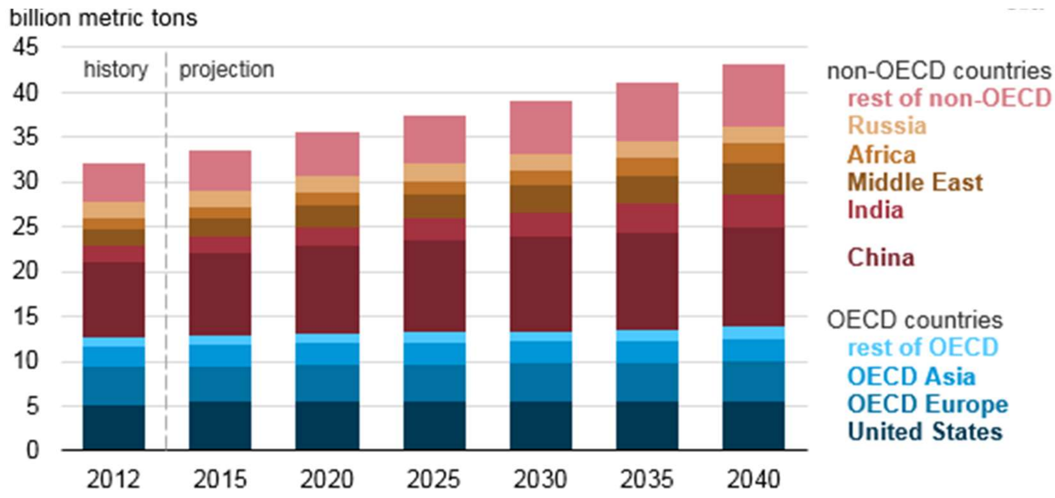


Figure 2.8 – Energy-related carbon dioxide emissions by country or region (2020 – 2040) (www.eia.gov/todayinenergy)

Liu L. et al. (2015) describe that between 1981 and 2002, China total CO2 emissions rose of 202%: from 1346 MMt to 3623 MMt. China's CO2 emissions additionally increase 50% in 2006 and in 2011 this country gave the biggest contribution to the global increase, with its emissions rising by 720 million tonnes (Mt). This emission increase is primarily due to higher coal consumption. The development of industrialization and urbanization requires for fast energy growth, which leads the growth of energy related carbon dioxide emissions (Liu L. et al., 2015).

China has had a national policy program to reduce emissions growth, which included the closure of old, less efficient coal-fired power plants and more investments on green energy. Another dominant approach in the Chinese environmental regulation system consists on emissions fees. But this policy is more likely less effective than tradable permits (Zhao, 2014).

In 2009, at the Copenhagen Climate Conference, the Chinese government pledged to reduce carbon-emission intensity per unit of GDP by 40-45% of 2005 levels by 2020.

In order to meet this goal, in October 2011, the NDRC (National Development and Reform Commission of the People's Republic of China) identified 4 municipalities (Beijing, Chongqing, Shanghai and Tianjin), 2 provinces (Guangdong and Hubei) and the special economic zone of Shenzhen City as regions for implementing carbon trading pilots. These 7 pilots were expected to build up the infrastructure needed to start a national system. By the end of 2014, the pilot trading programs had been officially opened in Beijing, Shanghai, Shenzhen, Tianjin, Guangdong, Hubei and Chongqing.

In December 2017, China announced the initial details of its national emissions trading scheme (ETS), its national carbon market will be by far the world's largest one and it will start covering the power sector (www.chinaenergyportal.org/en).

The comparison between the main features of the policies above described are collected in Table 2.1.

Table 2.1 - Comparison between the policies above described

	EU	USA			CHINA
KYOTO PROTOCOL	✓	✗			✗
POLICY	**EU ETS**	**The Regional Greenhouse Gas Initiative (RGGI)**	**AB 32**	**The Western Climate Initiative (WCI)**	**7 pilot trading programs**
REGULATION TYPE	Cap and Trade Sytem	Cap and Trade Sytem	Cap and Trade Sytem	Cap and Trade Sytem	Cap and Trade Sytem
INITIATIVE TYPE	Both Eurpean and National initiative	Federal (Not at a Congress level)	Federal (Not at a Congress level)	Federal and Regional	Regional (Objective: National system by 2017)
INVOLVED AREA	28 EU member states plus Iceland, Liechtenstein and Norway	9 US states: Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New York, Rhode Island and Vermont	California	Some US states and Canadian provinces	China
INVOLVED SECTORS	Power plants, energy-intensive industry sectors , operators of flights , production of certain acids and aluminium production	Fossil - Fuel Power Plants	The power and industrial sectors, natural gas and transportation fuels	Electricity generation, industrial and commercial facilities, transportation,residential and commercial fuel use	Electricity and power industries;carbon emissions industries; Iron and steel, cement, chemical and petrochemical industries; manufacturing industry and large buildings (Hotels, airports, ports)
START YEAR	2005	2005 (Trading program began 2009)	2006 (Cap & Trade in 2013)	2007 (WCI's Cap & Trade in 2013)	2013
REDUCTION TARGET FOR 2020	21% compared to 2005 levels	45 % in the region's annual power-sector CO2 emissions from 2005 levels	1990 levels	Regional target of 15 % below 2005 levels	40–45 % of 2005 levels
REDUCTION TARGET FOR 2030	43% below 2005 levels	-	40% below 1990	Quebec proposes a target of 37.5% under 1990 levels	-
TREATED POLLUTANT EMISSIONS	CO2 , N2O , PFCs	CO2	GHGs (CO2, CH4, N2O, HFCs, PFCs, SF6, NF3)	GHGs (CO2, CH4, N2O, HFCs, PFCs and SF6	GHGs (CO2, CH4, N2O, HFCs, PFCs, SF6)

2.2 Cap and Trade schemes - 3 different key studies

In the next paragraph, three different Cap and Trade schemes are analysed and compared, mainly focusing on 3 key features:

- Auction system;

- Allowances price / carbon cost;
- Main phases and trends.

2.2.1 EU key study

2.2.1.1 EU ETS – Phases

The EU ETS can be described by some phases; each of them with different main features and targets (www.ec.europa.eu/clima/policies/ets).

2005 – 2007: 1st TRADING PERIOD

This first period has been characterized by a "learning by doing" process and it made possible to build the infrastructure needed to monitor, report and verify emissions from the covered businesses.

During this 3-years pilot the UE ETS became the world's biggest carbon market, but only CO2 emissions from power generators and energy-intensive industries were covered and almost all the allowances were given to business for free.

Moreover, given the absence of reliable emissions data, the caps of this phase were set on the basis of estimates. As a result, the total amount of allowances issued exceeded emissions.

Therefore, by being the supply higher than the demand, in 2007 the price of allowances fell to zero (during Phase 1 allowances could not be banked for using them in Phase 2) (www.ec.europa.eu/clima/policies/ets/pre2013_en).

2008 – 2012: 2nd TRADING PERIOD

During the second phase the number of allowances has been reduced, but the economic downturn led once again to the surplus of unused allowances. Moreover 3 new countries joined the EU – ETS: Iceland, Liechtenstein and Norway.

An important step forward of this phase is that also the Nitrous oxide emissions from the production of nitric acid started being covered by a number of countries.

Moreover, the proportion of free allocation fell slightly to around 90% and several countries started holding auctions.

During the First Phase the penalty for non-compliance was €40 per tonne, this amount was increased during the Second Phase to €100 per tonne (https://ec.europa.eu/clima/policies/ets/pre2013_en).

2013 – 2020: 3rd TRADING PERIOD

During the third phase the sectors covered by the ETS have to reduce their GHG emissions by 21% compared to 2005 levels.

Therefore, from 2013 onwards, the cap on emissions from power stations and other fixed installations is reduced every year by 1.74% of the average total quantity of allowances issued annually in 2008-2012.

Another major reform is the introduction of a single, EU-wide cap on emissions applied in place of the previous system of national caps and has led the progressive shift from free allocation of allowances to an auctioning system (www.ec.europa.eu/clima/policies/ets_en).

In the first two trading phases, every Member State decided on how many allowances to allocate and on their distribution to the pertinent operators through National Allocation Plans (NAPs), which were reviewed by the Commission and could be rejected for failure to meet the requirements. This system, however, turned out to be complex, dysfunctional and not transparent, and the different methodologies adopted by Member States were deemed to create distortions of competition. As a consequence, the EU legislator has opted for the centralisation of the cap, abandoning the NAPs system from 2013. Also monitoring and verification procedures have been centralised (Mariotti C., 2016).

2030 and 2050 TARGETS:

Since the EU target for 2030 is a GHG reduction of 40% compared 1990 levels, the target for the sectors covered by the EU ETS is to reduce their GHG emissions by 43% compared to 2005 levels. In order to achieve this target the cap will need to be lowered by 2.2% per year from 2021, compared with the current 1.74%.

Moreover, the long-term objective for 2050 is a reduction of emissions by around 90% compared to 2005.

2.2.1.2 EU ETS Auction System

The European Union Emissions Trading Scheme (EU ETS) is the scheme for trading greenhouse gas emission allowances with the aim of reducing the emissions of the European Union. The involved sectors are the energy-intensive ones: electricity, cement, steel, aluminium, brick and ceramics, glass, chemical, aviation, etc.
From 2013, with some exceptions for protecting the international competitiveness of the manufactural sector, the allocation of allowances is done through auction platforms instead of cost-free allocation (GSE Report about the 3rd quarter of 2015 http://www.gse.it/).
In 2013, over 40% of the allowances were auctioned and The European Commission estimates that 57% of the total amount of allowances will be auctioned during the 3rd Period (2013–2020), while the remaining allowances will be available for free allocation (www.ec.europa.eu/clima/policies/ets/auctioning_en).
All the European allowances correspond to the right to emit 1 tonne of CO2. Moreover, it is possible to distinguish two different types of them:

- The EUA: European Union Allowances, they are usable by all the subjects involved in the EU ETS;
- The EUA A: European Union Allowances Aviation, they are valid only for aircraft operators.

The 88% of the allowances to be auctioned are assigned to states with reference to their share of verified emissions from EU ETS installations in 2005 or the average of the 2005-2007 period, whichever one is the highest. The 10% are allocated to the least wealthy EU member states as an additional source of revenue to invest for reducing the carbon intensity of their economies. The last 2% is given as a 'bonus' to nine EU member states which by 2005 had reduced their GHG emissions by at least 20% of levels in their Kyoto Protocol base year or period (www.ec.europa.eu/clima/policies/ets/auctioning_en).
Most governments use a common 'platform' for their auctions, but Germany, Poland and the UK have decided to use their own platforms.
Since 2013 four different auction platforms have been introduced indeed (Figure 2.9): the temporary common platform (EU t-CAP), the German one (EEX DE) managed by EEX, the Polish one (PL t-CAP) managed by EEX and the United Kingdom one (ICE UK) run by ICE.

25 Member States operated on EU t-CAP: Austria, Belgium, Bulgaria, Czech Republic, Cyprus, Croatia, Denmark, Estonia, Finland, France, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Portugal, Romania, Slovakia, Slovenia, Spain and Sweden.

The common auction platform also referred to as transitional common auction platform or EU t-CAP conducted auctions until 18 August 2016. The common auction platform referred to as the second common auction platform or CAP2 conducted by EEX was appointed on 13 July 2016 until July 2021 (www.eex.com).

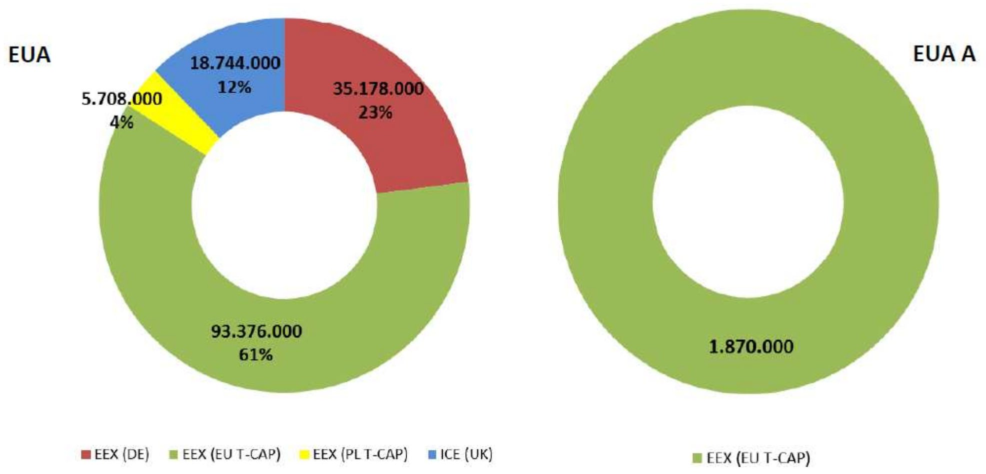


Figure 2.9 – Allowances allocations among the different platforms (EUA and EUA A) – 3rd quarter of 2015 (Report GSE from EEX and ICE data, http://www.gse.it)

2.2.1.3 Allowances Price Trends and Forecasts

The price of allowances is determined by supply and demand, therefore it is very floating. For this reason, it is interesting to:

- analyse its trend in the past;
- Forecast how it is going to change in the future.

2005 – 2007: 1st TRADING PERIOD

During the first phase of EU ETS (2005–2007), the price of allowances increased up to a peak level in April 2006 of about €30 per tonne of CO2 (www.publications.parliament.uk). In late April 2006, some EU countries, like Netherlands, Czech Republic, Belgium, France, and Spain; announced that their verified emissions were less than the number of allowances

allocated to installations. The spot price for EU allowances dropped 54% from €29.20 to €13.35 in the last week of April 2006. In May 2006, the European Commission confirmed that verified CO2 emissions were 4% lower than the number of allowances distributed to installations for 2005 emissions (http://web.mit.edu/globalchange). Therefore, in May 2006, prices fell to under €10/tonne. The excess of allowances during the first phase of the system continued through 2006 leading to a trading price of € 1.2 per tonne in March 2007 and to € 0.10 in September 2007. In 2007, carbon prices dropped to near zero for most of the year.
The estimated needs were excessive; this is way the allowances price falls to zero in 2007 (www.ec.europa.eu).

2008 – 2012: 2nd TRADING PERIOD

During the Phase II the carbon price increased to over €20/tCO2 in the first half of 2008 (CCC, 2008, p. 149 www.gov.uk/government). But during the first half of 2009 it decreased to €13/tCO2.
Two were the main reasons for this fall in prices (CCC, 2009, p. 67):

- Reduced output in energy-intensive sectors as a result of the economic downturn. This means that less abatement has been required to respect the cap, decreasing the carbon price.
- The market perception of future fossil fuel prices may have been revised downwards.

Prices for EU allowances for December 2010 dropped 8.7% to 12.40 euros a tonne.
In March 2012 the EUA permit price under the EU ETS had been persistently under €10 per tonne. Compared to nearly €30 per tonne in 2008, it was too low to provide incentives for firms to reduce emissions. The market had been oversupplied with permits, leading to the downfall of the price.
In July 2012, Thomson Reuters Point Carbon stated that without intervention to reduce the supply of allowances, the price of allowances would fall to four Euros (http://financial.thomsonreuters.com/).
The 2012 closed with a price around €6.67 a metric tonne (Figure 2.11).

2013 - 2020: 3nd TRADING PERIOD

For Phase III the European Commission has proposed a number of changes, including (CCC, 2008, p. 149 https://www.theccc.org.uk):

- the setting of EU-wide cap, with allowances then allocated to EU members. This overall cap decreases by 1.74% each year (www.ec.europa.eu);
- tighter limits on the use of offsets;
- limiting banking of allowances between Phases II and III;
- Shift from free allocation of allowances to an auctioning system. In particular the European Commission aim to auction at least 50% of the total permits, with an exception for the energy industry in which permits were already obtained 100% trough auction in 2013.

These changes led to some results: during the first three quarters of 2015 the allowances price trend has been rising (Figure 2.11 and Figure 2.10). In a troubled period for the markets, the European carbon market has instead registered the maximum values for the last 3 years (GSE Report about the 3rd quarter of 2015 http://www.gse.it/).
During the third quarter of 2015, the most important event, from a regulatory point of view, is the EU Commission's proposal for the 4th EU ETS phase. It consists in a strong reduction on allowances free allocations thanks to harder rules on carbon leakage and to the introduction of a linear reduction factor for reducing benchmarks. Moreover, the proposal suggests fixing the percentage of allowances to be auctioned to 57%.
This news gave more vigour to the upward trend of prices and the new mechanism should produce positive results for the revenue of the EU Member States.

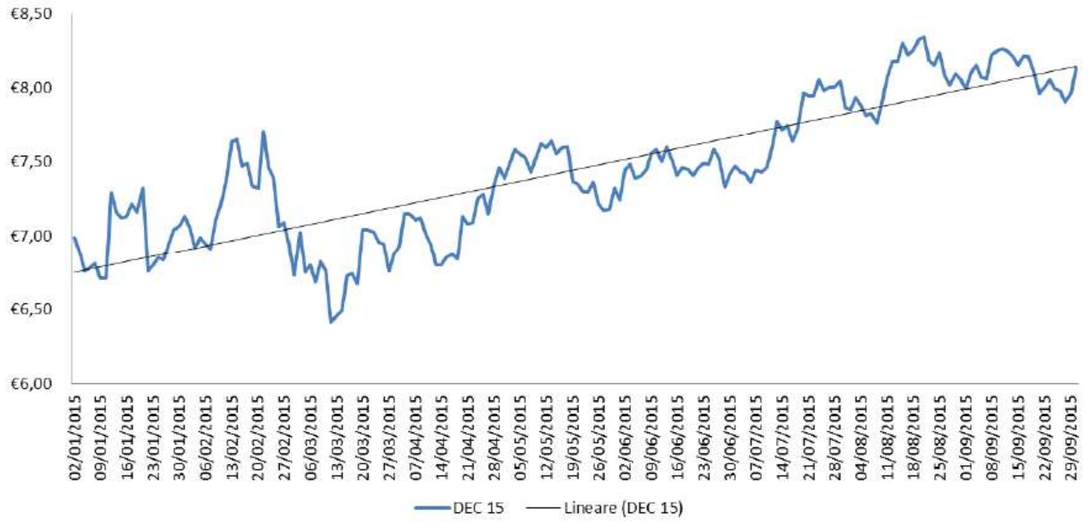
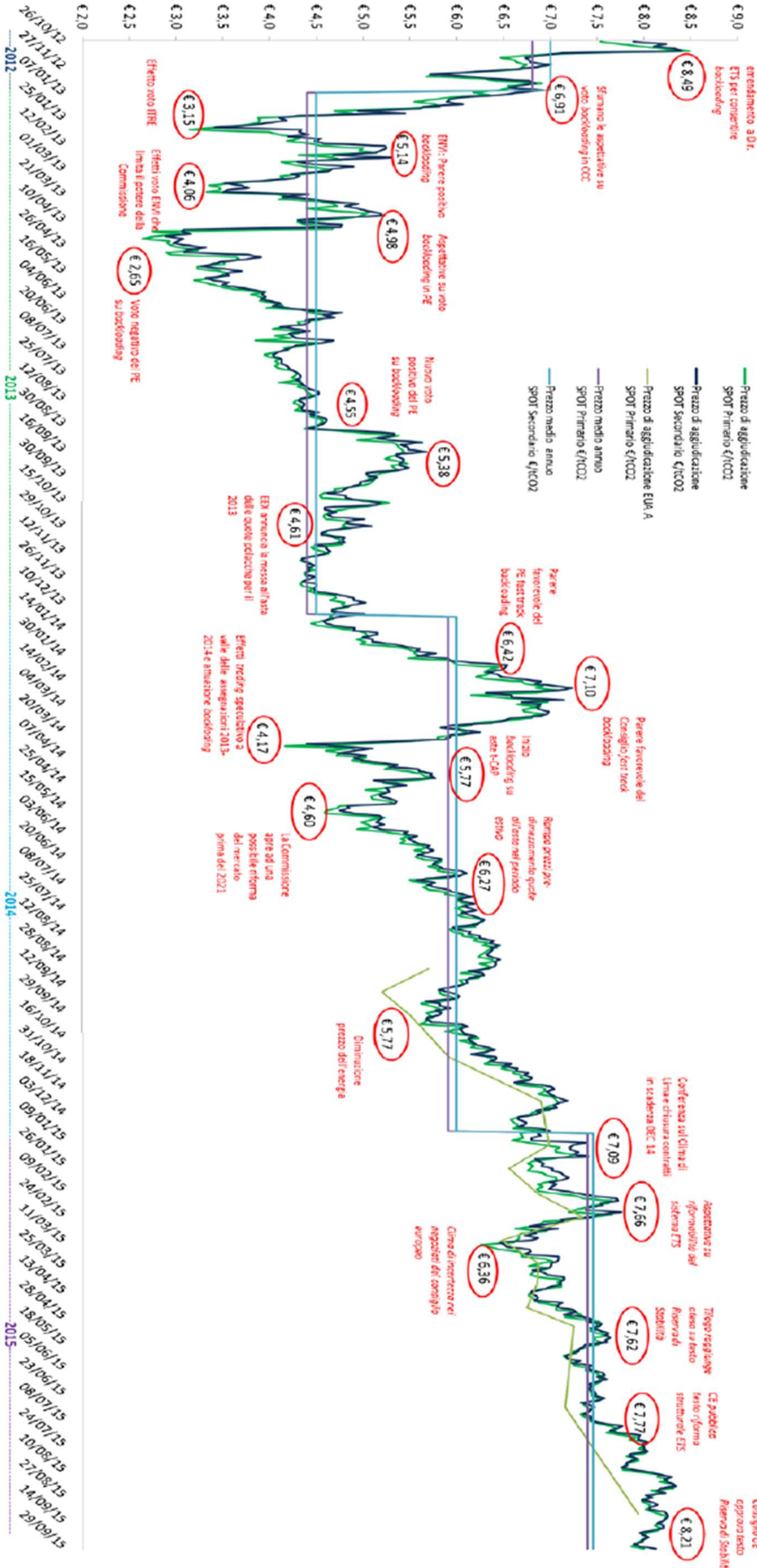


Figure 2.10 – EUA price trend (Jan. – Sept. 2015) (Source: GSE Report on Thomson Reuters http://www.gse.it)

Figure 2.11 – Allowances price trend (EUA and EUA A) – November 2012 – September 2015 (Source: GSE Report on EEX and ICE data



Some actions introduced during the 3rd trading period, like the backloading of allowances between 2014 and 2016 (a postponement in the global quantity of allowances to be auctioned during a certain year) and the sharp reduction in the use of international credits, contributed to reducing the supply of allowances, giving an effect on the supply and demand balance. Moreover, from 2015 onwards, emission reductions from the Phase II can no longer be used for compliance (EEA Report No 18/2017 www.eea.europa.eu/publications/trends-and-projections-EU-ETS-2017).

Thanks to these regulations, the EUA price increased in 2015 however, there was a sudden drop at the beginning of 2016 (see Figure 2.12).

In 2016, despite the further reduction in the cumulative surplus of allowances, the average annual carbon prices declined compared to the previous year (fluctuating around a level of EUR 5 per EUA). That drop was probably due to a decline in speculative activity and hedging needs and it suggests that market players expect a surplus of allowances to persist, in the short term at least (EEA Report No 18/2017 www.eea.europa.eu/publications/trends-and-projections-EU-ETS-2017).

In May 2017 an ascendant trend of the carbon price begun, it continued during the summer months, supported by lower auction volumes in August and a strengthened energy sector: the EUA price exceeded the 6 euros at the end of August and reached a maximum of € 7.42 in September 2017.

The weighted average price of the third quarter of 2017 was 5.91 euro, a sharp rise compared to the same quarter of 2016 (€ 4.48) and the second quarter of 2017 (€ 4.77) (GSE Report on Thomson Reuters http://www.gse.it).

Moreover, the reforms to the EU ETS have already led to triple the price of carbon allowances, from a low of €4.38 per tonne in May 2017 to €13.82 per tonne in April 2018, strongly improving their performance (www.carbontracker.org). The EU ETS Carbon Price registered on October 10th, 2018 was even higher: 22 €/tCO2e (www.markets.businessinsider.com/commodities/co2-emissionsrechte).

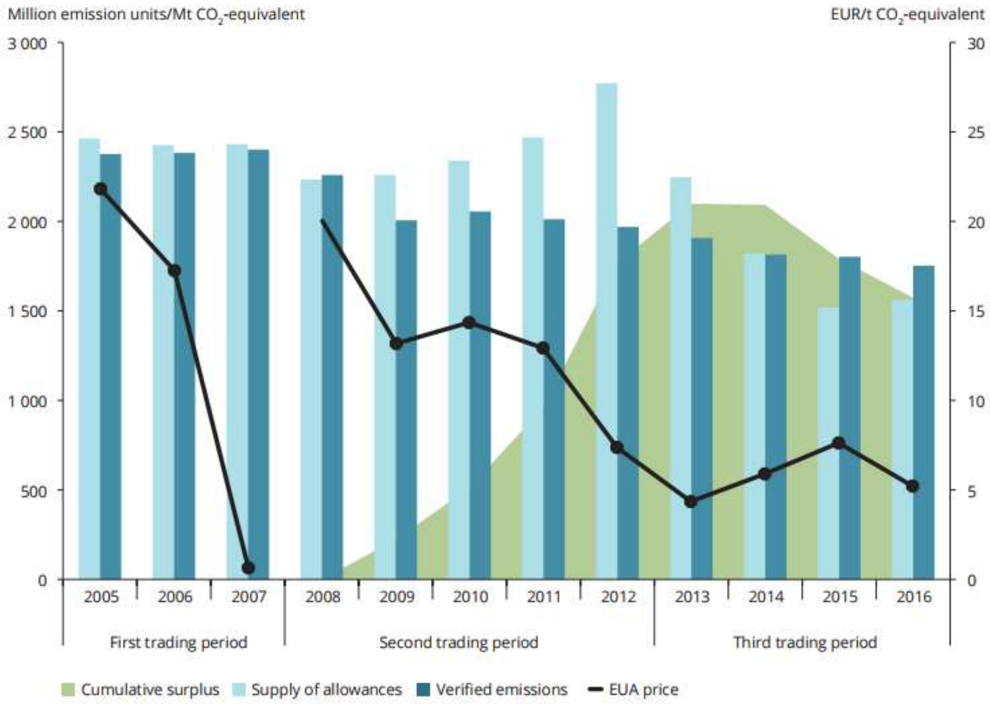


Figure 2.12 - Emissions, allowances, surplus and prices in the EU ETS, 2005-2016 (Source: www.eea.europa.eu/publications/trends-and-projections-EU-ETS-2017)

2.2.2 RGGI key study

2.2.2.1 RGGI – Phases

RGGI has begun in late 2003 in order to face the risks associated with climate change. On December 2005, seven states (Connecticut, Delaware, Maine, New Hampshire, New Jersey, New York and Vermont) released a Memorandum of Understanding (MOU), describing the overall goal of the RGGI initiative: to develop a cap and trade program with the objective of stabilizing and reducing emissions in the involved states, while remaining consistent with overall economic growth and the maintenance of a safe and reliable electric power supply system (www.ieta.org). In 2007 also Massachusetts, Rhode Island and Maryland signed the MOU, while New Jersey's withdrew from RGGI at the end of 2011.

The RGGI program is organized in three-year compliance periods. At the end of each period, covered entities must submit one allowance for each ton of CO2 generated during the three-year period.

RGGI's first auction of CO2 allowances was held in 2008, and the first compliance period began on 1 January, 2009 (www.rggi.org/design/history).

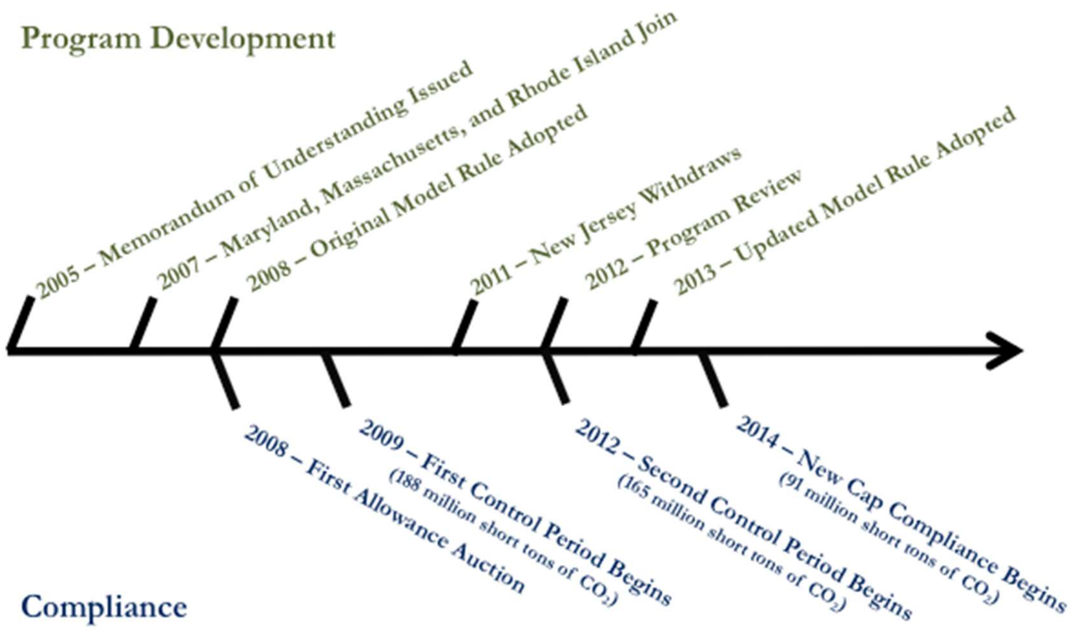


Figure 2.13 - RGGI Historical Timeline (Source: www.rggi.org/design/history)

In 2006 RGGI established the Model Rule, a framework that allows member states to establish their own Cap and Trade program. The Model Rule regulations set limits on in-state CO2 emissions from electric power plants, issued CO2 allowances, and established state participation in regional CO2 allowance auctions.

In February 2013, RGGI completed its program review with the release of an updated Model Rule. This took effect on 1 January, 2014 and has been adopted by each of the nine involved states.

The RGGI consists of three-year compliance periods; each of them with different main features and targets (www.rggi.org, www.ieta.org).

- **1st Period (2009-2011**): during this first period the MOU set the states' overall emissions cap at 170 million tCO2.

- **2nd Period (2012–2014):** for the second compliance period, the annual emission budget was adjusted down to 150 million tCO2, in order to consider New Jersey's withdrawal from RGGI at the end of 2011. After the 2012 review, the cap decreased to 83 million tCO2. Following the comprehensive 2012 Model Rule review, the cap has been decreased to 83 million tCO2 in 2014 (equal to 2012 emissions levels for the RGGI states). These adjustments have been introduced to account for RGGI allowances that emitters banked during the first and second compliance periods (see Figure 2.14). After the start of RGGI, it became clear that the allowances supply was higher than actual emissions. Allowance prices consequently fell down, making it particularly inexpensive to purchase allowances and bank them for use in later periods.

- **3rd Period (2015–2017)**: During the third compliance period the 2015 cap was 80.49 million tCO2, then adjusted to 60.63 million tCO2 because of allowances banked. Moreover, the Model Rule stated to maintain the annual cap decline of 2.5% from 2015 to 2020. Therefore, the RGGI cap and RGGI adjusted cap for the years 2018-2020 are as follows (https://www.rggi.org/program-overview-and-design/elements).
  2018: RGGI cap is 82,235,598, RGGI adjusted cap is 60,344,190
  2019: RGGI cap is 80,179,708, RGGI adjusted cap is 58,288,301
  2020: RGGI cap is 78,175,215, RGGI adjusted cap is 56,283,807

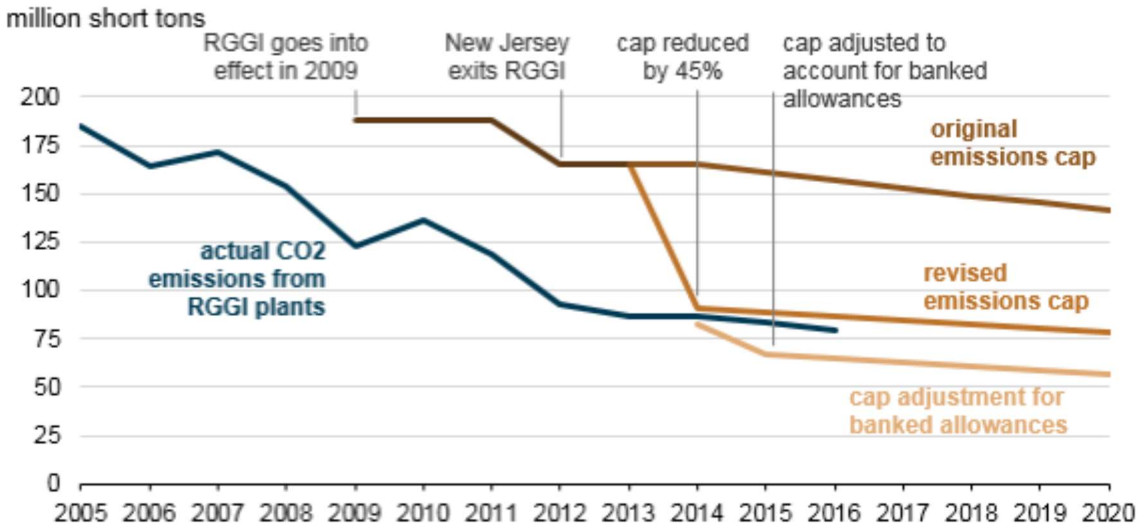


Figure 2.14 - Regional Greenhouse Gas Initiative CO2 emissions cap vs. actual emissions (Source: www.eia.gov)

2.2.2.2 RGGI Auction System

RGGI is one of the only Cap and Trade systems that mainly uses auctions to distribute allowances, rather than freely allocating some or all of them. RGGI Inc. coordinates quarterly central auctions on behalf of the RGGI states, for allocating approximately 90% of RGGI

CO_2 allowances available (www.rggi.org). Each state establishes how to allocate allowances, either via free allocation or auctions and sells those allowances that are not auctioned off directly to qualifying affected sources or distributes them through set-aside programs.

RGGI auctions are characterized by a single-round, sealed-bid, uniform-price format, in which each bidder may submit multiple confidential bids for a certain quantity of allowances at a specific price. Auctions are open to all the buyers, who meet certain criteria e.g. financial security. However, qualified single buyers or groups of affiliated buyers must respect a purchase limit of no more than 25% of the allowances offered at a single auction.

At the end of the first compliance period (2009-2011), proceeds from auctioned allowances and direct sales were calculated for $952 million, and at the end of 2014, the total auction proceeds were equal to $1.93 billion (www.rggi.org). Table 2.2 shows cumulative proceeds after the second control period (2012-2014).

Proceeds from the auctions are distributed to states and then disbursed back to economy through: energy efficiency measures, community-based renewable power projects, and assistance to low-income customers to help pay their electricity bills, education and job training programs, etc.

Table 2.2 – Cumulative Allowances and Proceeds through the Second Period (Source: www.rggi.org/docs/ProceedsReport)

State	Cumulative First Control Period Allowances Sold	Cumulative Second Control Period Allowances Sold	Cumulative Proceeds ($)
Connecticut	24, 343, 412	22, 338, 727	130,554,467.36
Delaware	9, 952, 619	12, 949, 207	67,857,838.33
Maine	11, 797, 376	10, 591, 027	62,221,516.39
Maryland	74, 943, 417	75, 239, 644	418,425,090.90
Massachusetts	62, 024, 346	56, 331, 176	330,779,846.93
New Hampshire	14, 479, 101	14, 435, 469	80,927,555.23
New York	144, 305, 904	128, 764, 643	760,186,645.02
Rhode Island	6, 270, 050	6, 444, 140	38,233,979.59
Vermont	2, 877, 123	2, 565, 272	15,139,597.73
New Jersey (before its withdrawal)	46, 266, 477	2, 217, 293	113,344,551.27

Monitoring and Reporting

Compliance is evaluated at the end of each three-year control period. Starting in the 3rd Control Period, the RGGI states have also conducted interim control period compliance, which requires each CO2 budget source to hold allowances equal to 50% of their emissions during each interim control period (the first two calendar years of each three-year control period). The affected source must cover 100% of the remaining emissions at the end of the three-year control period (www.rggi.org/allowance-tracking/compliance).

During the 3rd Control Period the guidelines established that on the 30th of January of a compliance year, covered facilities have to submit their previous years CO2 emissions data through the US EPA's Clean Air Markets Division Business System, which then provides the emissions data to the RGGI CO2 tracking system (www.rggi.org). On 1st of March, covered emitters must surrender allowances equal to 50% of their generated emissions in year-one and year-two of the compliance period, and 100% of all the remaining emissions at the end of the final year of the compliance period. After the end of a compliance period, from March to June of the next year, Member States are required to check if the covered facilities have provided enough allowances to meet their compliance obligation. After that, on the 4th of June, covered facilities are required to align.

In the case that a covered facility does not follow its annual obligation, the RGGI Member State in which the emitter is located can require the entity to pay a fine, a penalty, or consider another remedy. If a covered facility has not provided enough allowances to meet its three-year compliance obligation, the facility will have to surrender an amount of allowances equal to three times the quantity of emissions exceeded. In this situation, the RGGI Member State can also impose some specific penalties.

2.2.2.3 RGGI Allowances Price

Very soon, after RGGI began, it became clear that there was a surplus of supplied CO2 allowances. For this reason, during the initial years of RGGI, the value of these allowances remained close to the program's price floor of $1.93/ton of CO2 allowed in each quarterly auction.

The RGGI auctions during the First Compliance Period reflect this over-allocation: at the first RGGI auction in September 2008, all 12.6 million allowances supplied were sold at a single clearing price of $3.07 per allowance (https://www.rggi.org/docs/Retrospective_Analysis_Draft_White_Paper.pdf). In contrast, at the September 2011 auction, only 18% of the 42.19 million allowances offered for sale were purchased, at the low price of $1.89 per allowance (www.ieta.org/resources).

By analysing the trend of the carbon price in the RGGI system, it is possible to see the impact of the Updated Module Rule on the allowances price (see Figure 2.15). With the change in legislation and the adjustment to the overall RGGI cap that came into effect in 2013, demand for allowances increased, leading to the increase of the carbon price: the auctioning price continued to increase between March 2013 ($2.80) and March 2015 ($5.41).

In 2016 the total CO2 emissions from member states measured 79.2 million tons of CO2, therefore a total amount lower than the revised cap of 86.5 million tons CO2. Even though RGGI reduced its emissions cap, actual emissions have kept below the cap, leading to a surplus of allowances.

The downward trend in clearing prices since the start of 2016 reflects the excess of RGGI allowances and their relatively low demand (www.eia.gov). In March 2017 the lowest price in more than three years has been reached: more than 14 million allowances were sold at a clearing price of $3.00 per short ton of CO2.

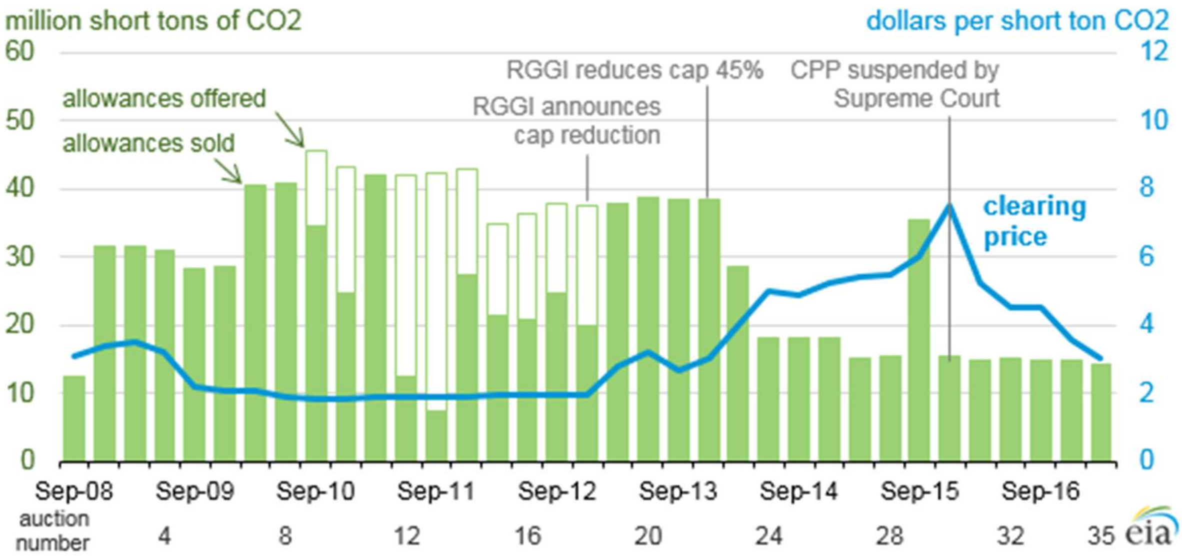


Figure 2.15 – RGGI Auction Allowances and Carbon Price Development (Source: www.eia.gov, rggi.org)

The current RGGI rules provide several flexibility measures including the use of offsets, banking and price collars like: a Cost Containment Reserve and an auction reserve price.

The **Cost Containment Reserve** consists of a fixed quantity of allowances, beyond the cap, that are held in a reserve. This policy is intended to moderate the increase of price when the allowances demand is higher than expected (www.ieta.org). If bids exceed the CCR trigger price during an auction, the CCR allowances are released and can be purchased by bidders. In 2014, the CCR contained 5 million allowances, and since 2015 onwards it contains 10 million allowances, replenished at the start of each calendar year. The price trigger started at $4/ton of CO2 in 2014, rises to $10/ton of CO2 in 2017, and will thereafter rise by 2.5% per year through 2020. With reference to the 2017 Model Rule, after 2020 the CCR size and trigger price trajectory will change: the CCR trigger price will be $13/ton in 2021 and will increase by 7% per year thereafter. Moreover, the CCR's portion will represent 10% of the regional cap each year (www.rggi.org). The CCR trigger price was first reached in the 2014 March auction, releasing an additional 5 million allowances, all of which were purchased (www.rggi.org/market/market_monitor).

Each auction also has a **reserve price,** the price under which no allowance can be sold. The 2015 auction reserve price was $2.05 per CO2 allowance and each year it increases by 2.5%. The reserve price for 2016 was indeed $2.10 per ton CO2 and the one for 2017 was $2.15 per ton CO2 (www.eia.gov).

2.2.3 CHINA - CTP (Carbon Trading Pilots) key study

2.2.3.1 China CTP – Phases

In 2009, at the Copenhagen Climate Conference, the Chinese government pledged to reduce carbon-emission intensity per unit of GDP by 40-45% of 2005 levels by 2020.

In March 2011, China released its **Twelfth Five-Year Plan for National Economic and Social Development (2011-2015)**, in which the establishment of a carbon-emissions trading market was stated for the next five years. Moreover, a set of short and long-term national targets regarding the carbon trade in China were established (L. Liu et al., 2015).

Short-term Targets (Twelfth Five-Year Plan)

1. Set up the carbon trade market and accelerate the implementation of pilot projects of low- carbon cities;

2. 17% reduction in the carbon intensity (carbon dioxide emission per unit GDP) in 2011–2015;
3. 16% reduction energy intensity (energy consumption per unit GDP) in 2011-2015;
4. Increasing the non-fossil energy use to 11.4% of the total energy use by 2015.

Long-term Targets (China's commitment on Copenhagen Climate Conference in 2009)

1. Reducing carbon intensity by 40-45% of 2005 levels by 2020;
2. At least the 15% of the primary consumption has to come from non-fossil fuel by 2020.

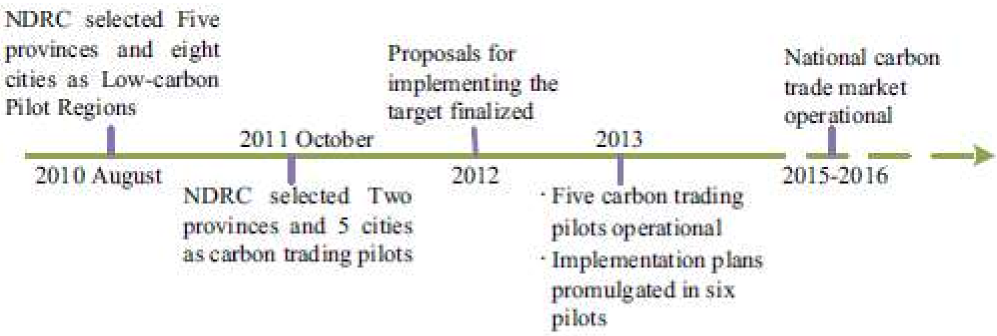


Figure 2.16 – Timeline in implementation of carbon emission trading schemes in China (Source: L. Liu et al., 2015)

Therefore, China is trying to gradually set-up a national carbon-emission trading market, for this reason the National Development and Reform Commission (NDRC) in August 2010 promoted **"Five provinces and eight cities"** as "Pilot Low-carbon regions" (see Figure 2.16). The involved areas were: Guangdong Province, Liaoning Province, Hubei Province, Shanxi Province and Yunnan Province, Tianjin, Chongqing, Shenzhen, Xiamen, Hangzhou, Nanchang, Guiyang and Baoding. These regions were expected to work as tests to promote GHG reduction through market mechanisms, by defining their own emission reduction goals and building up their own low-carbon strategies (L. Liu et al., 2015). To obtain more experience, the NDRC announced in October 2011 that carbon-emission trading would be developed in **7 pilot areas** at different stages of economic development and industrial structure. The seven areas involved were 4 municipalities (Tianjin, Beijing, Shanghai and Chongqing) 2 provinces (Guangdong and Hubei Province) and the special economic zone of Shenzhen City (see Figure 2.17). These 7 Carbon Trading Pilots (CTP) have been intended as testing grounds for implementing then a national ETS.

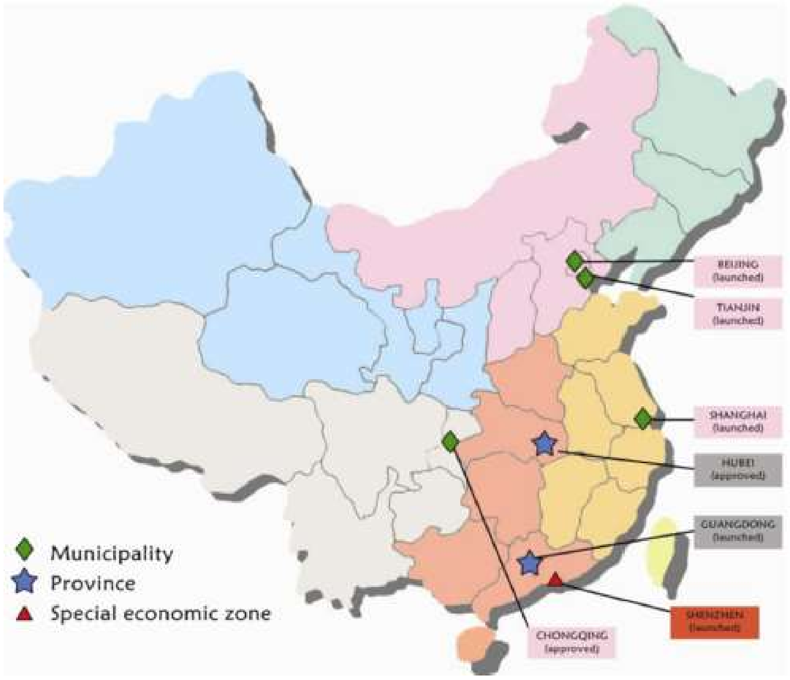


Figure 2.17 – Map of approved and launched China's carbon trading pilot areas (Source: L. Liu et al., 2015)

Between 2013 and 2014, the five carbon trading pilots became operational; the first pilot lunched was the Shenzhen pilot, while in June 2014 Chongqing is the last pilot starting carbon-emissions trading (see Table 2.3).

The emitters covered by these projects are those enterprises with high energy consumption and high emissions, and the main traded product is carbon dioxide (L. Liu et al., 2015).

The launch of these 7 carbon trading pilots demonstrates the Chinese government's determination to set up a national carbon-trade market and position itself on the international stage.

The objective for the **Thirteen Five-Year plan period (2016-2020)** is to gradually extend the carbon-trading market nation-wide, by creating a unified system of carbon trading (L. Liu et al., 2015).

In December 2017, China announced the initial details of its national emissions trading scheme (ETS), its national carbon market will be by far the world's largest one and it will start with the power sector alone (www.chinaenergyportal.org/en).

Table 2.3 – The basic features of the seven China's pilots (L. Liu et al., 2015)

Region	Launch Time	Emission Covered *	Industry involved
Shenzhen	6/18/2013	40%	Electricity and other 26 carbon emissions industries
Guangdong	9/11/2013	58%	Iron and steel, cement, power and petrochemical industries
Shanghai	11/26/2013	57%	Iron and steel, Chemical industry, Petroleum chemistry Electric Power, Building including hotel, shopping Aviation, Ports, Airport etc.
Beijing	11/28/2013	40%	Heat supply power, thermal power supply and other industries in the 'direct' field; manufacturing industry and large public buildings.
Tianjin	12/27/2013	50-60%	Iron and steel, chemicals, electricity and heat, petrochemical, oil and gas in the 'indirect' areas,
Hubei	4/2/2014	33%	Electricity, steel, cement, chemicals and other 12 industries
Chongqing	6/19/2014	39.5%	The industrial enterprises over 20,000 t of carbon dioxide emissions.

*: "Emission covered" represents the proportion of A in the B. A= the carbon emissions by the enterprises which are required to participate in the carbon-trading by the local government. B=The total carbon emissions in the specific region.

2.2.3.2 China CTP Auction System

The majority of allowances in China's CTPs were allocated for free, with very small percentage (3%-5%) of total allowances being auctioned (Figure 2.18). The Guangdong Province, the world's second largest market just after EU ETS, was the first CTP to hold an auction for allocating carbon allowances (Liu et al., 2015). For 2013 and 2014, 97% of the permits were given for free, while 3% were sold at auction.

The free allocation is useful in order to reduce the compliance cost for covered entities in the initial phase of a carbon trading scheme, but at the same time it reduces the efficiency of China's CTPs, leading to a less carbon reduction and to higher abatement cost resulting from lack of motivation to innovate.

Also, the free allocation cannot provide proceeds to governments, which are essential to support government and community programs in reducing carbon emissions. It is therefore fundamental for China pilots to shift from free allocation to auctioning of permits, at least starting from leakage-prone industries or particular sectors that are characterized by overcapacity (L. Xiong et al., 2015).

Distribution Patterns	China's CTPs						
	BJ	SH	TJ	SZ	CQ	GD	HB
Free distribution	≥ 95%	100%	100%	≤ 95%	100%	≤ 97%	≥ 90%
Competitive auction	< 5%	0%	0%	≥ 3%	0%	≥ 3%	≤ 3%
Fixed price sale	< 5%	0%	0%	≥ 2%	0%	0%	< 7%

Figure 2.18 – Distribution patterns of allowances in China's pilots (Ling Xiong et al., 2015)

As described by L. Liu et al. (2015), there are several methods for allocating quotas: for example, the historical emission method (grandfathering), the public auction and so on. In China's CTPs the historical emission method was the most used for allocating the carbon allowances, while in some pilots the auction method was also tried. A big issue China has to deal with is that few facilities and enterprises have complete records on what they have emitted, so the accuracy of quota allocation to the emitters is clearly scarce. Moreover, also the emission caps determination cannot be accurate: it is based on historical data from enterprise as well.

L. Liu et al (2015) state that the accuracy of the China's Carbon-Trading Pilots is highly influenced by three factors:

1. Slow response to real-time information, which greatly leads the inaccuracy of the quota allocation. The economic level, economic structure and energy structure vary continuously; therefore, a flexible quota allocation mechanism, linking enterprise operation with economic growth in China, might be a better solution; instead of using historical standards to determine future emissions.
2. The verification mechanism differs among the seven carbon-trading pilots. Therefore, the randomness in settings greatly affects the fairness and validity of data.
3. The verification mechanism in operation is not able to satisfy the real-time and high frequency requirements of carbon trading. Enterprises participating in carbon trading need to know how much they have emitted, how much they have reduced emissions and how many allowances they should purchase. Only in this way the carbon price would be able to link directly with production behaviour. It is clear that with the present verification settings these requirements are not satisfied.

2.2.3.3 China CTP Allowances Price

As assert before, in China, most allowances were freely allocated, therefore the carbon price equilibrium was difficult to ascertain since it was related to the success or failure of an auction (Zhang et al., 2017). Moreover, the seven CTP produced seven different carbon prices in China as shown in Table 2.4 . For this reason, allowances and offsets can only be traded on local emissions exchanges in the 7 pilots.

During 2016 prices in China range from €1.75 to €7 per tonne, with a peak to over €15 in the Shenzhen pilot (Swartz J., 2016). During 2013 and 2014, sometimes carbon prices in China's pilots were higher compared to the EU ETS one. The main reasons for these fluctuations in the seven ETS pilots are over allocation of allowances and policy uncertainties about banking/borrowing allowances from the carbon-trading pilots to the China's national ETS. The lack of transparent market information and the uncertainty about the transition from the regional to the national ETS may have reduced the demand for carbon permits among the 7 ETS pilots. It is quite clear that the total volume of carbon trades by these pilots is quite limited, and the transaction price of carbon is not currently economically based. The carbon prices were indeed formed based on agreement and they almost played no guiding role (L. Liu et al., 2015).

Table 2.4 – First price of carbon in China's pilots (L. Liu et al., 2015)

Region	First price of carbon
Shenzhen	28 Yuan / ton ($4.57)
Guangdong	61 Yuan/ ton ($9.95)
Shanghai	First transaction prices were 27 Yuan / ton ($4.40), 26 Yuan / ton ($4.24), 25 Yuan / ton ($4.08)
Beijing	50 Yuan / ton ($8.15)
Tianjin	28 Yuan ($4.57) per ton of carbon quota
Hubei	20 Yuan / ton ($3.26)
Chongqing	30–30.15Yuan/ ton ($4.89–5.13)

As asserted by Liu et al. (2015), the enterprises covered by the 7 pilots still cannot completely understand the carbon-trade mechanism because of insufficient publicity, policy and theory explanations of carbon-emissions trading by the Government. Therefore, many of them consider participation in carbon trading just a social responsibility or a way to protect environment, and do not consider the changes or benefits which can be produced by carbon trade.

It is clear that at the moment the legislation for the administrative supervision and control and the operation of trading markets are still inadequate. For instance, among the seven carbon trading pilots, only the one in Shenzhen has legislative power (Liu et al., 2015). In particular, by focusing on penalties, the ones which will be imposed if covered emitters exceed their caps yet refuse to pay the resulting fees are still missing. Carbon prices strongly depend on penalties, because they influence the enterprises production behaviour by choosing penalty or carbon reduction. Without standardized rules defining penalties, the carbon price will not be a representative and instructive one (Liu et al., 2015).

Carbon price is a significant problem for the China's ETS pilots. It is evident that theory support, market system and mechanism design, scientific quota allocation, verification, a legal system, regulatory authority and potential changes are all important factors influencing carbon price. They all need to be developed and improved to build a representative carbon price that is fundamental for future integration of local markets into a national one.

The comparison between the 3 analysed Cap and Trade schemes is reported in Table 2.5.

Table 2.5 - Comparison between the cap and trade schemes above described

POLICY	EU - ETS	RGGI	CHINA - CTP (Carbon Trade Pilots)
REDUCTION TARGET FOR 2020	21% compared to 2005 levels	45 % in the region's annual power-sector CO_2 emissions from 2005 levels	40–45 % of 2005 levels
ETS PHASES	**1st Period (2005–2007)**: 3-year **pilot**, the total amount of allowances issued exceeded emissions **2nd Period (2008–2012)**: **Lower cap** on allowances; 3 new countries joined - Iceland, Liechtenstein, Norway **3rd Period (2013–2020)**: introduced a single, EU-wide cap; the cap on emissions from power stations and other fixed installations is reduced every year by 1.74%	**1st Period (2009-2011)**: annual states' overall emission budget set at 170 million tCO_2 **2nd Period (2012–2014)**: annual emission budget ajusted down to 150 milliom tCO_2 (New Jersey's withdrawal). Afeter the 2012 review, the cap decreased to 83 million tCO_2. **3rd Period (2015–2017)**: Introduced an annual cap decline of 2.5% from 2015 to 2020. 2015 cap was 80.49 million tCO_2, adjusted to 60.63 million tCO_2 because of allowances banked.	**"Twelfth Five-Year Plan"period (2011-2015):** in 2013 carbon-trading pilots have been lunched in 4 municipalities, 2 provinces and the special economic zone of Shenzhen City. **"Thirteen Five-Year plan" period (2016-2020):** the carbon-trading market will be gradually extended nation wide
AUCTION SYSTEM	**1st and 2nd period**: almost all allowances given to businesses for free **3rd period: > 50**% of total permits distributed through auctions	Approximately **90%** of RGGI CO_2 allowances are available on central **auctions**	The majority of allowances is currently **free** with very small percentage **(3%-5%)** of total allowances being auctioned
ALLOWANCES PRICE	**1st Period (2005–2007)**: peak level of about 30€/tCO_2 (2006), the **excess** of allowances led to a price near to zero in 2007 **2nd Period (2008–20012)**: peak level of about 20€/tCO_2 (2008). During 2009 the price fell down, one of the causes: the economic recession. 2012 closed with a price of 6.67€/tCO_2 **3rd Period (20013–2020)**: adjustment on the allowances supply and limits on allowances banking led to a rising price trend in 2014 and 2015 (Dec 2015 around 8 €/tCO_2) but there was a sudden drop at the beginning of 2016. However, a strengthened energy sector led to an ascendent trend in 2017 (€ 7.42 in September 2017)	**1st Period (2009-2011)**: first RGGI auction in Sep. 2008 all the allowances supplied were sold at $3.07 per allowance. Since the program was over-allocated with CO_2 allowances, in Sep. 2011 only 18% of the offered permits were sold at a lower price of $1.89 per allowance. **2nd Period (2012-2014):** in 2013, with the cap adjustemts, the deman for allowances increased as well as the price ($2.80 Q1 2013 and $5.41 Q1 2015). **3rd Period (2015-2017)**: the auctioning price continued to increase between 2013 and 2015 (March 2015 $5.41), however in 2016 a surplus of allowances led to a downward price trend (In March 2017 $3.00, the lowest price in more than three years)	The 7 CTP produced **7 different carbon prices** in China. Allowances and offsets can only be traded on local emissions exchanges in the 7 pilots. 2016 prices in China range from €1.75 to €7 per tonne, with a peak to over €15 in the Shenzhen pilot. The **price fluctuations** are due to overallocation of allowances and policy uncertainties.
INITIATIVE TYPE	Both Eurpean and National initiative	Federal - Not at a Congress level	Regional (Objective: National system gradually from 2017)

3 STATE OF THE ART: SUSTAINABLE LOT SIZING MODELS AND PURCHASING

With the objective of reducing the negative impact of human species on the environment, GHG emissions, e.g. carbon dioxide (CO2), nitrous oxide (N2O), fluorinated gases and methane (CH4), have recently attracted a special attention (Helmrich, Jans, van denHeuvel, & Wagelmans, 2015).

But just the CO2 is considered responsible for approximately half of the emission generated by human, and it has increased by 50% compared to its level in 1990 (Jaber, Glock, & El Saadany, 2013).

Since the emissions released by companies' operational activities into the air are one of the main causes of global climate change (He et al. 2015), businesses are becoming increasingly conscious of their carbon footprint and have begun to incorporate environmental thinking into their business strategy and supply chain management, making efforts to be more environmentally friendly.

As expressed by (Ortolani et al., 2011 and Rai et al. 2011), external emission costs have become an important issue for supply chain management because of several environment conservation agreements, such as the Kyoto Protocol and the Paris Agreement, and environmental economics policies, such as EU-ETS.

Therefore, it is clear that there is an increasing trend among firms to set up more environmental friendly manufacturing systems introducing new technologies, optimizing their production and inventory decisions by integrating environmental factors that can help on reducing GHG emissions (Kazemi et al. 2016).

Moreover, as assert by Benjaafar et al. (2013), companies that are optimizing their production and inventory using sustainable initiatives may benefit much more rather than exploiting new facilities. As claimed by many researchers (Glock, Grosse, & Ries, 2014; Vastag & Montabon, 2001), inventory management is one of the most important operational activities of industrial and trading companies. Therefore, determining the lot size (EOQ) or the economic production quantity (EPQ), it is fundamental for a firm that adopts an inventory management system (Bushuev, Guiffrida, Jaber, & Khan, 2015).

The increasing international attention on environmental issues emphasizes the need to treat inventory management and goods purchasing decisions by integrating economic, environmental and social objectives.
As stated by (Miemczyk et al., 2012), Sustainable Purchasing means considering social, environmental and financial factors in taking goods procurement decisions. Many managers are now looking beyond the traditional economic parameters and are starting to take decisions based on the whole life cost, the associated risks, measures of success and impacts on society and environment.
Therefore, making decisions with this new approach requires taking into account various factors related to goods procurement:

- economic measures (such as product price, inventory costs, ordering and transportation costs);
- the entire product life cycle (i.e. Jaber et al, 2013, Battini et al, 2014);
- use of recycled materials and product remanufacturing (i.e. Liu B. et al., 2015);
- environmental aspects (i.e. Bonney and Jaber, 2011);
- social aspects, as the effects on issues such as poverty eradication, inequality in the distribution of resources, labor conditions, human rights, fair-trade, as well as social consequences of air pollution due to goods transportation (i.e. Ortolani et al, 2011; Andriolo et al, 2016).

In the next paragraphs a literature review, regarding the Economic Order Quantity (EOQ) model and the Joint Economic Lot Size (JELS) model is presented; highlighting how in the present literature these models have extended integrating environmental issues.

3.1 The EOQ Model – Literature Review

The economic order quantity (EOQ) model is a pure economic model in the classical inventory control theory. The model objective is to find the order quantity so as to minimize the total average cost of replenishment for a company under deterministic demand conditions and assumptions. (Arslan and Turkay, 2013).
As asserted by Andriolo et al. (2014), an increasing number of works have been published from 2011 with the aim of integrating sustainability criteria in the traditional EOQ theory.

First, Bonney and Jaber (2011) present an illustrative model that includes vehicle emissions cost into the traditional into EOQ model.
Hua et al. (2011) extend the EOQ model by considering carbon emissions under the Cap and Trade system. They obtain the optimal order quantity, and evaluate the impacts of carbon trading price and carbon cap on the optimal decisions, total costs and carbon emissions. Analytical and numerical results are illustrated, and insights for managers are derived.
Benjaafar et al. (2013) integrate carbon emission constraints on single and multi-stage lot-sizing models with a cost minimization objective. Four regulatory policy schemes are considered: a strict carbon cap, a tax on the amount of emissions, the cap and trade system and the opportunity to invest in carbon offsets to mitigate carbon caps. Many observations and insights are obtained from a numerical study.
Arslan and Turkey (2013) formulate the classical EOQ model incorporating many different carbon emission regulation policies and show how the triple bottom line (social, environmental and financial) considerations of sustainability can be add to traditional cost accounting in EOQ model.
Toptal et al. (2014) evolve the traditional EOQ model considering total cost and emission reduction investments under three emission regulation policies (carbon cap, cap and trade, and taxing regulations).
Battini et al. 2014 develop a “sustainable EOQ model” that, from an economic point of view, includes the environmental impact of transportation and inventory holding in the total cost function through a direct accounting approach. In particular, internal and external transportation costs, vendor and supplier location, and different freight vehicle utilization ratios are considered in order to provide an easy-to-use methodology.
Konur and Schaefer (2014) analyse an integrated inventory control and transportation planning problem incorporating carbon emissions regulations. They examine the economic order quantity model with less-than-truckload (LTL) and truckload (TL) transportation under carbon cap, cap and trade, cap and offset, and taxing policies. Analytical and numerical results comparing LTL and TL carriers are provided, showing that the retailer’s carrier preference depends on regulation parameters. The tools introduced allow analysing the effects of regulations, transportation costs and emissions on the retailer’s costs and emissions with each carrier.
Bazan et al. (2015) introduce two models that consider the energy needed for production along with the greenhouse gases (GHG) emissions from production and transportation

operations in a single-echelon (manufacturer or buyer) system under a multi-level emission-taxing scheme. The first model considers a classical coordination policy, while the second considers a vendor-managed inventory with consignment stock (VMI-CS) agreement policy. Numerical examples are illustrated as well as a comparison between the two models to better outline implications and insights for managers.

He et al. (2015) examine the production lot-sizing issues of a firm by integrating the EOQ model with Cap and Trade and Carbon Tax regulations, respectively. They compare the firm's optimal carbon emissions under the two regulations and investigate the impacts of production and regulation parameters on the optimal lot-size and emissions. They prove that under the Cap and Trade regulation, the differentiated permits trading prices influence the firm’s decisions of the optimal emissions as well as permits trading.

Shu et al. (2017) extend the classical EOQ model by considering carbon emissions in (re)manufacturing activities and product transportation, and provide an inventory cost model with carbon constraints. The optimal batch and quantity of manufacturing/ remanufacturing, and the frequency of cyclic remanufacturing are calculated with and without carbon constraints. Moreover, the analysis of carbon quota can offer some insights for governments and firms.

Lee et al. (2017) examine a sustainable economic order quantity (S-EOQ) problem with a stochastic lead-time and multi-modal transportation options. By applying the model to various numerical scenarios, they show the effects of incorporating sustainability considerations into the traditional inventory model on operational decisions: like the choice of transportation modal combination and the sourcing decisions.

All these studies are based on a direct accounting approach with a single cost objective function; indeed, they convert CO2 emissions or social effects into economic measures. Since in most cases the cost and the emission functions produce different optimal solutions, the cost trade-offs are different from the emission ones (Andriolo et al, 2014). When externalities need to be quantified, the limits of a direct accounting method are becoming visible (Bouchery et al., 2012; Battini et al., 2014), pushing future research to evaluate the best way for combining the cost function quantification with the emission function analysis, for instance exploiting a multi-objective optimisation approach.

A new way to integrate sustainability criteria into inventory models is proposed for the first time by Bouchery et al. (2012), in their paper the authors introduce a multi-objective formulation of the EOQ model overstepping the traditional approach with a single objective function.

Then, Andriolo et al. (2015) focus the attention on the lot sizing theory when horizontal cooperation is established by supply chain partners, developing the EOQ sustainable model when two partners are cooperating in sharing transportation paths and handling units. The paper proposes a three-step methodology based on a multi-objective optimization approach, in order to allow a complete evaluation of the costs and savings yield with a horizontal cooperation.

3.2 The JELS Model – Literature Review

As asserted by Zanoni et al. (2014), since global markets became more competitive, supply chain coordination became fundamental for enhancing its profitability and reactivity. Indeed, in the literature, coordination in the supply chain is proven important to increase the benefit of the entire system.

The Supply chain management consists in the integration of key business processes and activities in order to yield value to the end customers. In this contest, the production planning and the inventory control processes are considered very relevant processes (Beamon, 1998).

As expressed by Tao et al. (2017), The Joint Economic Lot Size (JELS) models represent a first attempt to advance inventory-based sustainability modelling in the contest of a supply chain, since they integrate the inventory lot sizing decision across two echelons.

The JELS ordering policy considers jointly the production and inventory aspects of a vendor and a buyer.

Goyal (1976) is assumed to be the first to introduce the idea of a joint total cost for a two-echelon system (single vendor – single buyer), where he considered an instantaneous production rate for a vendor with a lot-for-lot (LFL) shipment policy. According to the first model developed by Goyal, if we consider only one customer for a certain product produced by a single vendor, and supposing that they make a deal for cooperating, then a joint EOQ model can be defined, with considerable potential savings.

The work of Goyal (1976) has been evolved by Banerjee (1986), who assumed a finite production rate rather than an instantaneous one, and later by Goyal (1988), who considered the accumulation of vendor's inventory (not LFL shipment policy) and its distribution to the buyer through shipments of equal sizes. He considered a vendor producing in a lot, in order to supply an integer number of orders of the buyer. In all these models, the order quantity that is optimal for both parties was determined by the joint optimization of the cost functions of supplier and buyer.

In the recent literature, many works focused on how to integrate sustainability criteria in the traditional JELS models.

As already mentioned, Benjaafar et al. (2013) integrate carbon footprint on single and multi-stage lot-sizing models with a cost minimization objective. Four regulatory policy schemes are considered: a strict carbon cap, a tax on the amount of emissions, the Cap and Trade system and the opportunity to invest in carbon offsets to mitigate carbon caps. Many observations and insights are obtained from a numerical study. They exploited their model to explain the extent to which carbon emissions can be reduced through operational adjustments.

Jaber et al. (2013) examine the buyer-vendor coordination problem with the settings of a JELS model under carbon emission regulations, the CO2 emissions are a function of the manufacturer's production rate. The total cost function for this model is constitute by the following three terms: supply chain inventory related costs, the cost of emissions, and a penalty cost for exceeding the emission limits. They presented several numerical examples in order to show the behaviour of the model in different scenarios of emissions tax and penalties.

Zanoni et al. (2014) propose a joint economic lot size (JELS) model for a two-echelon (vendor–buyer) supply chain under vendor-managed inventory (VMI), consignment stock (CS) agreement and an emission-trading scheme. Their results show that a VMI-CS agreement yield to better performance of the system, giving the possibility to reduce the inventory holding costs and, in some cases, the GHG emissions tax and penalty costs.

Bazan et al. (2015) extend the JELS model by developing two mathematical models for a two-level supply chain between a manufacturer and a buyer that consider energy used for production, GHG emissions from production, and GHG emissions from transportation. The first model considers a classical coordination scheme, while the second considers a VMI with CS agreement policy. Numerical examples are provided and the two models are compared to highlight managerial implications and insights.

Recently Tao et al. (2017) investigates the joint optimal decisions on lot size in a two-level supply chain, between a retailer and a manufacturer, under carbon emission regulations. The comprehensive cost based models are meant to capture the influence of two carbon regulatory schemes (Carbon Tax and carbon Cap and Trade mechanism) on business

decisions. The paper results provide managerial implications in operations management and in carbon regulations.
All these studies are based on a direct accounting approach with a single cost objective function; indeed, they convert CO2 emissions or social effects into economic measures.

3.3 Overview of sustainable lot sizing models and purchasing

A comprehensive table is presented below to better visualize the state of the art regarding Sustainable EOQ and Sustainable JELS models, and the gaps of the present literature (Table 3.1).
This research work is born as a conceptual evolution of Battini et al. (2014) and aims to meet some lacks developing a multi-objective Sustainable Joint Economic Lot Size Model considering:

- two different objective functions, the total average annual cost of replenishment and the total annual emissions generated by the replenishment;
- costs and emissions for a two-echelon (vendor–buyer) supply chain, so related to both buyer and supplier;
- a discontinuous transportation cost function: transportation costs and emissions will be considered explicitly and modelled according to their true discontinuity nature due to the saturation of vehicles capacity;
- the costs and emissions related to poor quality products and scrapes;
- the integration of the Cap and Trade regulation mechanism for emissions reductions (such as EU-ETS).

Lastly, this research work aims to integrate the presented S-JELS model into a procedure for assessing a Sustainable Supplier Selection. The objective is to provide managers with numerical KPIs and user-friendly graphs, in order to help them on evaluating the selection criteria of the Supplier Selection procedure for each potential supplier in an easier, faster, more analytical and correct manner. In this way, the company decision makers are guided to understand the trade-offs among different supply options and supported to make the more efficient and sustainable supplier selection.

Table 3.1 - Overview of sustainable lot sizing models and purchasing

		Bonney and Jaber (2011)	Hua et al. (2011)	Bouchery et al. (2012)	Benjaafar etal. (2013)	Toptal et al. (2013)	Jaber et al.(2013)	Arslan and Turkay (2013)	Battini et al. (2014)	Zanoni et al. (2014)	Konur and Schaefer (2014)	Bazan et al. (2015)	He et al. (2015)	Shu et al. (2017)	Lee et al. (2017)	Tao et al. (2017)	Proposed Models
	Sustainable lot sizing model	SEOQ	SEOQ	SEOQ	SEOQ + JELS	SEOQ	JELS	SEOQ	SEOQ	JELS	EOQ	JELS	EOQ	EOQ	SEOQ	JELS	SEOQ + SJELS
C&T	Integrated in the model		x		x	x	x	x		x	x	x	x	x		x	X
OBJECTIVES	Supplier Selection model																X
	Transportation selection model								x						x		x
	Lot sizing and inventory optimization	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
DECISION MAKER APPROACH	Non- interactive	x						x					x	x		x	
	Interactive		x	x	x	x	x		x	x	x	x			x		x
METHOD	Single objective	x	x		x	x	x	x	x	x	x	x	x	x	x	x	
	Multi-objective			x													X
EMISSIONS	Poor quality emissions																X
	Transportation Emissions	x		x				x	x		x	x		x	x		x
	Order/setup Emissions		x	x	x	x		x			x		x			x	x
	Holding Emissions		x	x	x	x		x	x		x		x		x	x	x
	Obsolescence Emissions								x								x
	Production Emission				x		x	x		x		x	x	x			x
COSTS	Poor quality cost																X
	Discontinuous Transportation Cost								x								X
	Continuous Transportation Cost	x									x	x		x	x		
	Order/setup Cost	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Holding Cost	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Obsolescence/ Waste Cost	x							x					x			x

4 A SUSTAINABLE ECONOMIC ORDER QUANTITY MODEL UNDER CAP AND TRADE REGULATION (S-EOQ)

The mathematical formulation that follows is born as a conceptual evolution of Battini et al. (2014) and tries to capture economic and environmental trade-offs in material purchasing lot sizing under a Cap and Trade policy. In presence of this regulatory, a limit or cap on carbon emissions is assigned to a firm. If the amount of carbon emissions exceeds the carbon cap, it is possible to buy from the carbon trading market the right to emit extra GHGs. Otherwise, the company can sell its CO2e permits surplus. Clearly, this trading mechanism can merge environmental objective and economic objective (Hua et al. 2011).

This policy, by putting a price on carbon, implies some consequences: each ton of emissions saved has a financial and commercial value and a sufficiently high carbon price can encourage investment in more sustainable processes and clean, low-carbon technologies. The price of carbon allowances (the so-called carbon price) is determined by supply and demand according to a market-oriented mechanism. The Trading system used here is inspired to the current EU ETS system (www.ec.europa.eu).

In the following formulation, it is considered the single-product replenishment problem based on the traditional EOQ model, assuming a deterministic product demand and the product price is exogenous. It is applied a bi-objective optimization approach by modelling the EOQ problem for incoming goods to be purchased by a company, considering two objective functions: the total annual cost function and the total annual emission function.

The process of delivering and storing a material lot size (from the beginning to the end of the order life) exhausts energy and money for transportation, warehouse operations, orders setups and obsolescence waste treatments; moreover, it produces emissions during all these phases. In the proposed model the transportation cost function and the transportation emission function are modelled according to their real nature: piecewise convex function of the ordering levels with discontinuities at the cost breaks (the transportation vehicles' saturation points), unlike the traditional model where the total cost is convex over the entire range of ordering levels (Bouchery et al., 2012). This formulation is essential to better understand and quantify the benefit of transportation consolidation when deciding goods purchasing lot sizes.

4.1 S-EOQ Model – Mathematical Formulation

In the next paragraphs, we introduce the mathematical formulation of a sustainable bi-objective lot-sizing model **Buyer oriented** under Cap and Trade policy.

INDICES:

i container/vehicle type

j transportation mode

DECISION VARIABLES AND COST FUNCTIONS:

Q decision variable [units/purchasing order]

$C(Q)$ total average annual cost of replenishment [€/year]

$C'(Q)$ total average annual cost of replenishment without considering the Cap and Trade costs or revenues [€/year]

$E(Q)$ total annual emission generated by the replenishment [CO2e/year]

$Q_c{}^*$ optimal order quantity for the cost function [units/purchasing order]

$Q'_c{}^*$ optimal order quantity for the cost function $C'(Q)$ [units/purchasing order]

$Q_e{}^*$ optimal order quantity for the emission function [units/purchasing order]

INPUT PARAMETERS:

D annual demand [units/year]

p unit purchase cost [€/unit]

p' unitary scrap price [€/unit]

b space occupied by a product unit with sale packaging [m3/unit]

a weight of a unit stored in the warehouse [ton/unit]

O fixed ordering cost per order [€/order]

h holding cost [€/unit]

β average inventory obsolescence annual rate [%]

y full load-vehicle/container capacity [units or m3]

v average freight vehicle speed [km/year]

d_j distance travelled by transportation mode j [km]

$c_{f,j}$ fixed transportation cost coefficient for transportation mode j [€/km]

$c_{v,j}$ variable transportation cost coefficient for transportation mode j [€/km m3]

$c_{ef,j}$ fixed transportation emission coefficient for transportation mode j [kgCO2e/km]

$c_{ev,j}$ variable transportation emission coefficient for transportation mode j [kgCO2e/km m3]

c_{eh} warehouse emission coefficient [kgCO2e/m3]

c_{eo} waste collection and recycling emission coefficient [kgCO2e/ton]

n_i number of full load-vehicle/container i [units]

y_i full load-vehicle/container i capacity [units]

k range of order quantity Q_s between the two discontinuity points DP_k and DP_{k+1}

DP_k Discontinuity Point for range k, defined as $\sum_i n_i * y_i$

S_j freight vehicle j utilization ratio in %

P value of carbon price quoted in the market [€/tCO2e]

s^+ amount of allowances sold by the organization [tCO2e]

s^- amount of allowances bought by the organization [tCO2e]

$s^+, s^- \geq 0$

Note that only one of these trading variables may be positive; i.e. the organization either buys or sells allowances.

CAP carbon cap according to a cap and trade system [tCO2e]

ΔE_{cap} emission reduction by reaching the cap value [tCO2e]

$\Delta E_{cap}\%$ emission reduction by reaching the cap value [%]

ΔC_{cap} cost increment by reaching the cap value [€]

It is now possible to introduce two objective functions: $f_1(Q)$, that quantifies the average annual cost of replenishment and $f_2(Q)$, the total quantity of emissions generated during the annual purchasing activity.

$f_1(Q)$ is expressed as follows:

$$f_1(Q) = C(Q) = p \cdot D + C_O(Q) + C_h(Q) + C_{obs}(Q) + C_t(Q) + C_{C\&T}(Q)$$

(1

In detail, the terms included in this formulation are defined as follows. Both the ordering cost, associated only to the buyer fixed cost of processing the order, and the holding cost are defined according to the traditional models (Battini et al, 2014):

$$C_o(Q) = \frac{D}{Q} \cdot O$$

(2

The holding cost considers both the traditional holding cost of carrying inventory in the warehouse and the cost related to hold inventory during the transportation activity. This one is not a function of Q, as shown in the following formula (derived from Axsäter and Grubbström,1979):

$$C_h(Q) = \frac{Q}{2}h + Q\left(\frac{d}{v}\right)\left(\frac{D}{Q}\right)h$$

(3

Where *v* represents the freight vehicle speed expressed in km/year.

The formulation for obsolescence cost is simple but reasonable, in order to make the application of this formulation less time-consuming. Usually the obsolescence of a product is due to specific causes that make unusable the stock on hand, like a change in the product design or in the product technical specification.

According to Battini et al. (2014), the inventory stocked in the warehouse presents a risk of obsolescence at the end of the year, expressed by the obsolescence annual risk rate *β*. Therefore, at the end of each year, the amount of stock to be wasted due to obsolescence reasons is sold by the buyer to a specific waste treatment company for disposal at the unitary scrap price *p'*, lower than *p*.
Moreover, in some cases, *p'* could also be negative if the owner has to pay the waste treatment company for the disposal service.

$$C_{obs}(Q) = \frac{Q}{2}(p - p') \cdot \beta$$

(4

The transportation cost on the optimization of the order quantity has strong relevance as stressed by Zaho et al (2004), for this reason its formulation considers both fixed and variable costs. Moreover, in a real logistic system, it is not a continuous function (Zaho et al., (2004) and Birbil et al., (2009) and it presents Discontinuity Points DP_k when the vehicle capacity is saturated. Therefore, as explained by Battini et al. (2014) the transportation cost is calculated as the sum of a fixed portion (expressed in €/km since it does not increase with the order quantity but only with the travelled distance) and a variable portion, which varies with the quantity transported and the vehicle saturation.

After evaluating all the saturation ranges of different kinds of container *i*, applied in the same purchasing cycle, the vehicle saturation S_j can be express as follow (Battini et al., 2014). It depends on the quantity transported, on the vehicle capacity y_i and on the number of vehicle used in the order cycle n_i:

$$S_j = \frac{Q}{\sum_i n_i y_i}$$

(5

Under the following constraint:

$$\sum_i n_i y_i \geq Q$$

(6

As discussed in previous studies (Battini et al., 2014), the transportation cost is not a continuous function and it cannot be differentiated during the whole interval. Moreover, the value *n* depends on the number of different vehicle types used in the transportation (e.g. different containers with different capacities). Therefore, in a global supply chain scenario, many types of vehicle can be used, with different capacities and costs. Hence, it is necessary to accurately evaluate all the discontinuity points and ranges between them and apply a step by step approach, as already adopted in literature.

To simplify the problem, when DP_k is the Discontinuity Point k, obtained after the precise evaluation of all capacity saturation ranges of different kinds of container *i* applied in the same purchasing cycle, it is possible to consider:

$$S_j = \frac{Q}{\sum_i n_i y_i} = \frac{Q}{DP_k}$$

(7

Therefore, the transportation cost $C_t(Q)$, for each kind of transportation mode *j* used, can be calculated as (Battini et al, 2014):

$$C_{t\,j}(Q, d_j, S_j) = \left(c_{f,j} \cdot d_j \cdot \sum_i n_i + c_{v,j} \cdot d_j \cdot DP_k \right) \cdot \frac{D}{Q}$$

(8

When a carbon cap is set according to a Cap and Trade regulatory policy a company needs to reduce the total emissions below the cap in order to respect the governmental constraint. By a traditional cost-oriented optimization approach, a company prefers to apply a cost-optimal solution in order to minimize the total annual purchasing cost, so that the costs are at minimum.

In order to reduce the total annual emissions below the cap value, the company will inevitably increase its annual costs, but there staying under the cap value, the company will have the right to trade the rest of the carbon allowances at the current carbon price. Conversely, if the annual company emissions are higher than the cap value, it will be necessary to buy more permits from the market. Giving that, $C_{C\&T}(Q)$ represents the Emissions Trading Cost (or Revenue) resulted from buying or selling permits at the current carbon price *P*.

$$C_{C\&T}(Q) = P \cdot (s^- - s^+) = -[CAP - E(Q)] \cdot P$$

(9

Concluding, the first function to optimize is finally expressed as follows and it considers the costs (or revenues) related to the Cap and Trade regulatory policy in use.
C'(Q) (or $f_1'(Q)$) represents the sum of the average annual costs of replenishment, without considering the Cap and Trade contribution, so the Emissions Trading Cost (or Revenue).

$$f_1(Q) = C(Q) = f_1'(Q) + C_{C\&T}(Q) = C'(Q) + C_{C\&T}(Q)$$

(10

$$f_1(Q) = C(Q) = p \cdot D + \frac{D}{Q} \cdot O + \frac{Q}{2} \cdot h + \frac{d}{v} \cdot D \cdot h + \frac{Q}{2} \cdot (p - p') \cdot \beta + [\sum_j \left(c_{f,j} \cdot d_j \cdot \sum_i n_i + c_{v,j} \cdot d_j \cdot DP_k \right)] \cdot \frac{D}{Q} - [CAP - E(Q)] \cdot P$$

(11

The second objective function $f_2(Q)$ is the average total quantity of emissions generated during the annual purchasing activity and it can be defined as the sum of the emissions generated during these three phases: warehousing, waste collection and treatment of the obsolete items and material order transportation. Thus, it is possible to homogeneously expressed these three terms in tons of CO2e in order to calculate the average total quantity of emission.

$$f_2(Q) = E(Q) = E_h(Q) + E_{obs}(Q) + E_t(Q)$$

(12

The first term expresses the average quantity of equivalent carbon emissions generated by warehousing during the time unit of one year (Battini et al., 2018):

$$E_h(Q) = c_{eh}\left(\frac{Q}{2} \cdot b\right)$$

(13

In this formula c_{eh} represents the warehouse emission coefficient expressed in kgCO2e/m3. The parameter b measures the cube meters occupied by a product unit with its packaging materials stored in the warehouse.
The inventory stocked in the warehouse has an obsolescence annual risk rate *β*. Therefore at the end of each year, the obsolescence goods are sold by the buyer to a specific waste treatment company for disposal at the unitary scrap price *p*', lower than *p*.
In this case, as proposed by Battini et al. (2018), only the emissions generated during the waste collection and treatment process are taken into account. Therefore:

$$E_{obs}(Q) = \frac{Q}{2} \cdot \beta \cdot a \cdot c_{eo}$$

(14

In this formula a represents the weight of an obsolete unit stored in the warehouse in tons/unit, and c_{eo} is the emission coefficient for obsolete inventory waste collection and recycling expressed in kgCO2e/ton.
Finally, due to the reasons described above and to the discontinuity nature of the transportation cost function, also the emission function linked to the transportation activity is described by a discontinuous function, as follows (Battini et al., 2018):

$$E_{t\,j}(Q, d_j, S_j) = \left(c_{ef,j} \cdot d_j \cdot \sum_i n_i + c_{ev,j} \cdot d_j \cdot DP_k \right) \cdot \frac{D}{Q}$$

(15

Therefore, by considering the whole mix of transportation modes used in the product supply from vendor to buyer, the second objective function to optimize can be expressed as follows:

$$f_2(Q) = E(Q) = c_{eh}\left(\frac{Q}{2} \cdot b\right) + \frac{Q}{2} \cdot \beta \cdot a \cdot c_{eo} + \left[\sum_j \left(c_{ef,j} \cdot d_j \cdot \sum_i n_i + c_{ev,j} \cdot d_j \cdot DP_k \right)\right] \cdot \frac{D}{Q}$$

(16

According to a generic Pareto design optimization problem (Pareto 1964, 1971), involving the two conflicting objective functions introduced above, it can be assert:

$$Minimize \{f_1(Q), f_2(Q)\}$$

(17

A Pareto-optimal solution is also defined "Pareto-efficient solution", and the set of all the efficient points is called the Pareto Frontier. Generally, it is not possible to express the Pareto Frontier with an analytical expression; however, it is possible to assert that:

"Q is a Pareto-optimal solution to the problem posed by Eq. (11 and Eq. (16, if there does not exist any other design Q such that* $f_1(Q) \le f_1(Q^*)$ *and* $f_2(Q) \le f_2(Q^*)$ *simultaneously."*

The number of Pareto-efficient solutions Q^* can be wide, for this reason it is necessary to select the best compromise design(s) among them. In the sustainable lot sizing problem here proposed, a sustainable purchasing choice normally increases $f_1(Q)$, while decreases $f_2(Q)$, since the two objective functions are competitive in nature.

If Q^*_c is the single optimal solution of the objective function $f_1(Q)$ and Q^*_e is the single optimal solution of $f_2(Q)$, *EF* can be defined as the Efficient Frontier of the sustainable lot sizing problem here proposed and EF^c its image in the criterion space, then:

$$EF = [Q_c^*, Q_e^*]$$

(18

EF_+^c is convex and there exists $Q_{min} < Q_{max}$ such that $Q^* \in [Q_{min}, Q_{max}]$.

As a consequence, the shape of the EF strongly affects the possibility to move from a cost-optimal solution to an emission-optimal one.

4.2 S-EOQ Model – Practical Application

A numerical application of the model is described in this paragraph, in order to better explain how the Pareto Frontier is built. The data set is directly inspired by a real industrial case, to illustrate the mathematical model described above.

The buyer's company is considered located in the North-East part of Italy and close to intermodal terminals, while the vendor is situated overseas (e.g. in Hong Kong). Transportations are made by adopting a rail-ship intermodal transport with only a final short handling by truck. Transportation costs are obtained from (Battini et al., 2014) and carbon footprint coefficients are calculated using the Ecoinvent database in SimaPro Software (www.simapro.co.uk). The cost and emission functions, described in formula (11 and (16, are computed considering the set of discontinuity points DP_i determined according to the different handling units adopted in the purchasing network (container 1: ISO 20 feet and container 2: ISO 40 feet).

All constant input parameters used for running the S-EOQ model are summarized in Table 4.1, while the variable input parameters are presented in Table 4.2. Table 4.3 lists all the dependent variables in the model, describing their relation to the input data. The saturation of the two kinds of containers can be reached by volume or by weight, depending on the characteristics of the product. The Apparent Density ρ is considered equal to 300 kg/m3 and the risk of obsolescence of the inventory β is supposed fixed and equal to 0.15. From Table 4.2, it can be noticed that the emission reduction by reaching the cap value *(∆Ecap%)* has been introduced and it is fixed at 0.1 (that is 10%). In the present numerical application, the Carbon Average Price *P* is fixed at 22 €/ tCO2e, that is the EU ETS Carbon Price registered on October 10th, 2018 (www.markets.businessinsider.com/commodities/co2-emissionsrechte).

Table 4.1 - Constant Input data

Constant Input Data	**Value**
D	40,000
O [€/order]	400
d [km on road]	100
d [km by train]	500
d [km by ship]	14,000
Inner volume container1 [m3]	33.2
Load Capacity container1 [tons]	21.75
Inner volume container2 [m3]	67.2
Load Capacity container2 [tons]	26.70
v_{road} *[km/year]*	525,600
v_{rail} *[km/year]*	788,400
v_{ship} *[km/year]*	219,000
$c_{f,road}$ *[€/km]*	0.8
$c_{v,road}$ *[€/km·m³]*	0.01

Constant Input Data	**Value**
$c_{f,rail}$ *[€/km]*	0.6
$c_{v,rail}$ *[€/km·m³]*	0.007
$c_{f,ship}$ *[€/km]*	0.48
$c_{v,ship}$ *[€/km·m³]*	0.003
c_{eh} *[kgCO2e/m3·year]*	24
c_{eo} *[kgCO2e/ton]*	77.004
$c_{ef,road}$ *[kgCO2e/km]*	2.20017
$c_{ev,road}$ *[kgCO2e/ton·km]*	0.154398
$c_{ef,rail}$ *[kgCO₂e/km]*	1.28017
$c_{ev,rail}$ *[kgCO2e/ton·km]*	0.0392892
$c_{ef,ship}$ *[kgCO2e/km]*	0.06443
$c_{ev,ship}$ *[kgCO2e/ton·km]*	0.0088875
β *[%]*	15
ρ *[kg/m3]*	300

Table 4.2 - Variable Input Data

Variable Input Data	**Value**
p [€/unit]	5
a [kg/unit]	0.5
ΔE_{cap}*% [%]*	10
P [€/tCO2e]	22

Table 4.3 - Dependent Variables

Dependent Variables	**Value**
b [m3/unit]	*a*/(ρ ·1000)
p' [€/unit]	0.5·*p*
h [€/unit]	0.25·*p*
y_1*[units/container1]*	Min (Inner volume container1/*b*; Load Capacity container1/*a*)
y_2 *[units/container2]*	Min (Inner volume container2/*b*; Load Capacity container2/*a*)
CAP [tCO2e]	*E(Q'c*)*·(1-ΔE_{cap}*%)*

Figure 4.1 shows the trend of the Pareto Frontier built running the model with the parameters described above. As already discussed, the Efficient Frontier EF of the sustainable lot sizing problem is composed by the set of all efficient points ranging from the cost optimal solution ***Qc**** to the emission optimal solution ***Qe*.***

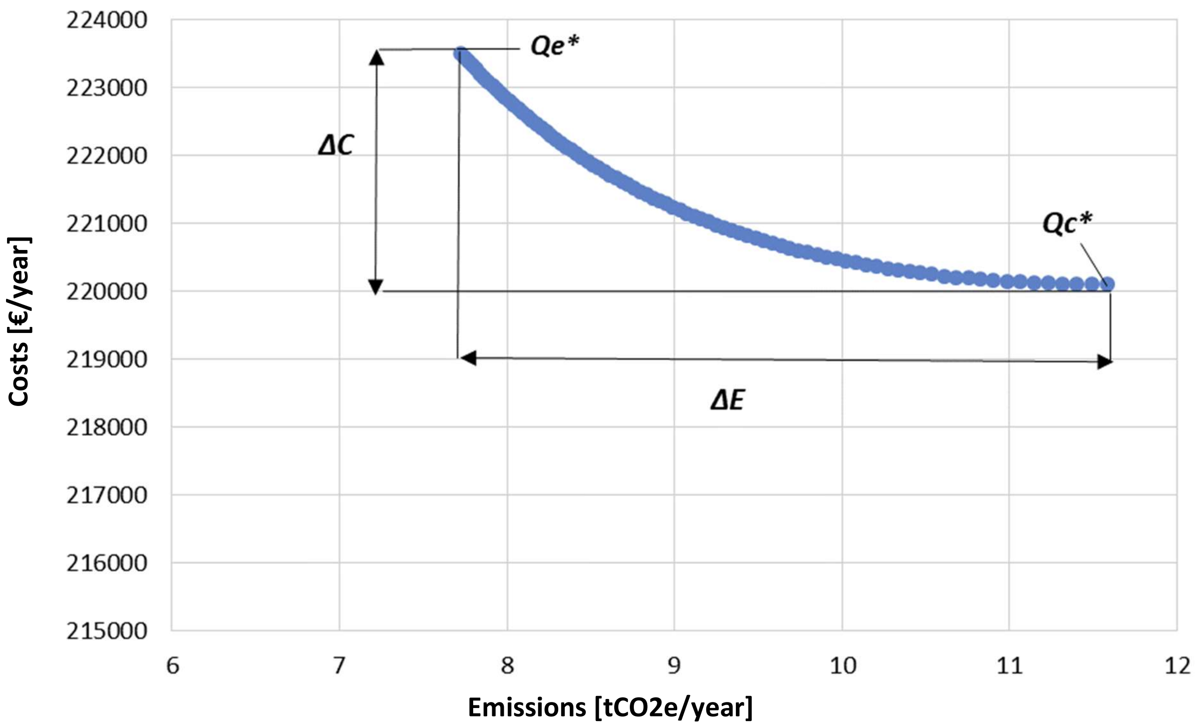


Figure 4.1 - S-EOQ Pareto Frontier

Therefore, it is evident that the S-EOQ bi-objective model does not aim at finding a single optimal solution at once. As stated by Miettinen (1999), the problem could be solved only by an interactive approach during the decision making.

4.3 Interactive approach to decision

As explained by Hwang and Masud (1979) and Miettinen (1999), multi-objective optimization methods can be classified into four categories according to the role of the Decision Maker (DM) in the solution process.

A first class is the one of the ***no-preference methods***. Sometimes there is no DM available, so no preference information is provided and, in this case, some neutral compromise solution needs to be identified. In ***a priori methods***, the DM provides preference information and expectations before the solution process. The problem in this case is that the DM does not necessarily know the all the restrictions and possibilities of the problem and may have too optimistic or pessimistic expectations. Otherwise, in ***a posteriori methods***, a set of Pareto optimal solutions are generated first and then the DM is supposed to choose the most preferred one among them. Usually, evolutionary multi-objective optimization

algorithms are part of this category. If more than two criteria are considered in the problem, it may be too demanding for the DM to analyze in advance the large amount of information and, on the other hand, generating the set of Pareto optimal or non-dominated alternatives may require much computational effort.
The drawbacks of both a priori and a posteriori methods can be overcome in the so-called ***interactive methods***, where the DM takes part to the solution process and leads it according to his or her preferences. These methods build a solution pattern that is iteratively repeated as long as the DM wants. After each iteration, the DM is provided with one or some Pareto optimal solutions that meet the preferences expressed as much as possible and he or she can consider them for giving more preference information. For example, the DM could evaluate trade-offs, build pairwise comparisons, classify objective functions, and so on. The responses are used to produce better solutions. In this way, the DM can learn more about the problem during the iterations and review the preferences progressively during the solution process if needed. In other words, the phases of preference elicitation and the one of solution generation alternate until the DM has found the most satisfying solution.
Moreover, the interactive and a posteriori methods can also be hybridized in order to better support the DM (Klamroth and Miettinen,2008 and Thiele et al. (2009).
Therefore, as discussed above, when dealing with multi-objective optimization problems, the interaction with the DM's preferences is important in order to help him or her on getting a better knowledge of the problem and on finding the most preferred solutions without exploring the whole set of Pareto optimal solutions.
Hence, as stated by Miettinen (1999), the multi-objective optimization problem presented in paragraphs 4.1 and 4.2 could be solved only through an interactive approach with the decision maker during the solution process.
By considering the same numerical application introduced in paragraph 4.2, the decision maker could interact with the S-EOQ model by iterating the solution process varying some parameters of interest like: the Carbon Average Price, the cap imposed on emissions, the total demand, or the mix on used transportation systems (for example: more ship, less truck). The DM by iterating the solution process can obtain and compare different pareto frontiers, improving its knowledge and being able to consider trade-offs before taking a decision.
In the next sections, the S-EOQ multi-objective model introduced in paragraphs 4.1 and 4.2 is run iteratively, by varying the Carbon Average Price and the cap imposed on the total amount of emissions.

4.3.1 Iterations by varying the cap on emissions

The numerical application introduced in paragraph 4.2 is here processed by varying the cap imposed on the total amount of emissions. The input parameters subject to variations are reported in Table 4.4.

Figure 4.2 and Figure 4.3 show the trend of the Pareto Frontiers built by iterating the running of the S-EOQ multi-objective optimization model varying each time the value of $\Delta E_{cap}\%$.

It is evident that, as the cap lowers (so the emission reduction required for reaching the cap increases), at equal emissions the efficient solutions move towards higher values for costs. This means that the company has to sustain an extra cost in order to buy the amount of allowances that exceeds the cap.

Table 4.4 - Variable Input Data

Variable Input Data	Value
$\Delta E_{cap}\%$ [%]	[10; 20; 30; 40; 50]

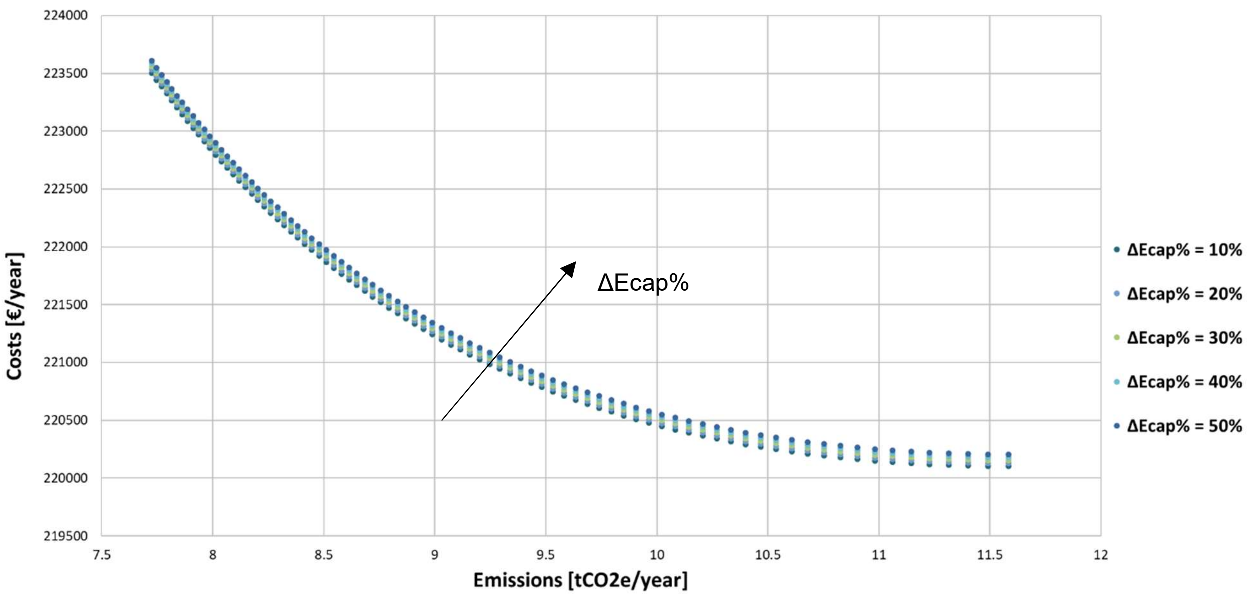


Figure 4.2 - Sensitivity analysis of the S-EOQ Pareto Frontier according to variations on the Emissions CAP

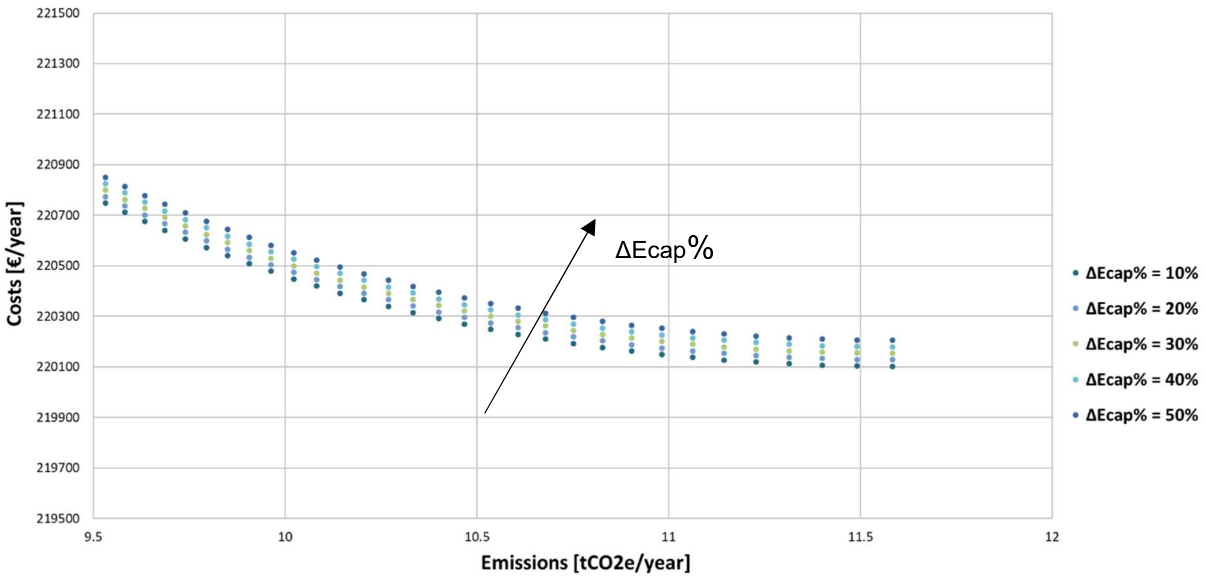


Figure 4.3 - Zoom on the sensitivity analysis of the S-EOQ Pareto Frontier according to variations on the Emissions CAP

4.3.2 Iterations by varying the carbon average price

The numerical application introduced in paragraph 4.2 can be processed by varying the Carbon Average Price, which is a parameter that depends on the market. The price of carbon allowances (the so-called carbon price) is determined by supply and demand according to a market-oriented mechanism. Moreover, by putting a price, each ton of emissions saved has a financial and commercial value, and a sufficiently high carbon price could promote investment in more sustainable processes and clean, low-carbon technologies.

The input parameter subject to variations is reported in Table 4.5. The carbon price is considered varying from €7.92 (value registered during 3rd quarter of 2015, Battini et al. 2016, Conference Proceedings: 19th International Working Seminar on Production Economics, 2016, Innsbruck) to €14 (value registered in May 2018), to €22 (value registered in October 2018), until €100.

Figure 4.4 and Figure 4.5 show the trend of the Pareto Frontiers built by iterating the processing of the S-EOQ multi-objective optimization model varying each time the value of *P,* the Carbon Average Price.

It is evident that, for an amount of total emissions lower than the CAP, as the Carbon Price increases at equal emissions the efficient solutions move towards lower values for costs.

This means that the company is being sustainable, so it is earning money by selling the amount of extra allowances. Clearly the higher the Carbon Price, the higher the total gain. On the contrary, if the company is exceeding the cap on emissions, it needs to buy CO2e permits from the market, increasing the total cost. So, as shown in Figure 4.4 and Figure 4.5, at equal emissions values as the Carbon Price increases, the efficient solutions move towards higher values for costs. Obviously, the higher the Carbon Price, the higher the total cost for the organization.

Table 4.5 - Variable Input Data

Variable Input Data	**Value**
P [€/tCO2e]	[7.92; 14; 22; 44; 66; 88; 100]

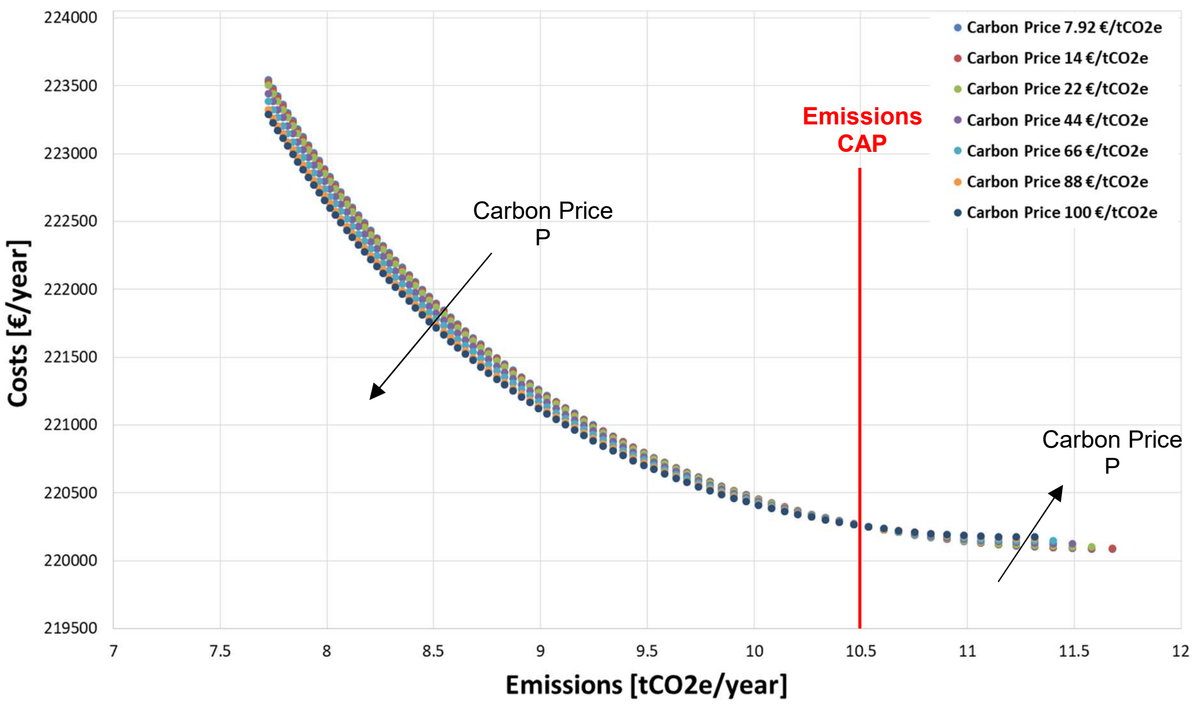


Figure 4.4 - Sensitivity analysis of the S-EOQ Pareto Frontier according to variations on the Carbon Average Price

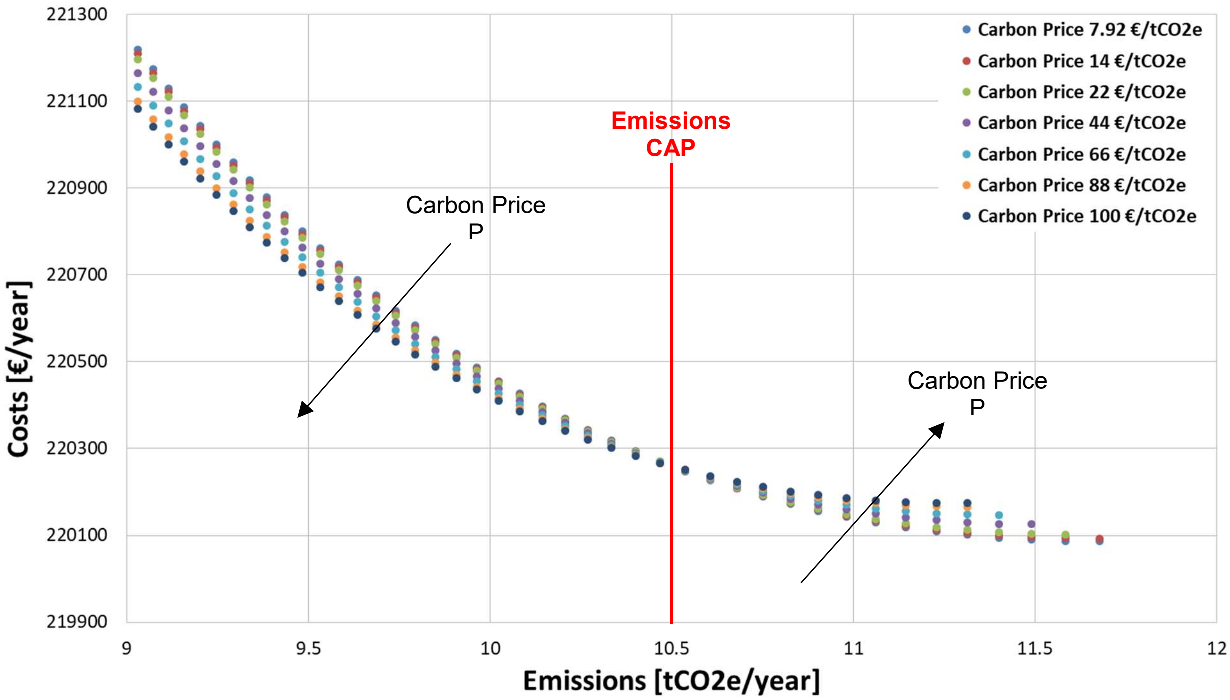


Figure 4.5 - Zoom on the sensitivity analysis of the S-EOQ Pareto Frontier according to variations on the Carbon Average Price

4.4 Sensitivity analysis and discussion of φ parameter

4.4.1 Introduction of φ parameter

In order to support managers on evaluating logistics choices during the decision process, it is possible to introduce a useful tool for interacting with the Pareto Frontier EF, built solving the S-EOQ multi-objective optimization model introduced in paragraph 4.1.

The decision makers (as managers and buyers) by yielding all of the potentially optimal solutions and by examining the shape of the Pareto Frontier in each specific case, can understand the trade-offs between extra-logistic costs and economic incentives (carbon allowances) and finally define how to improve their purchasing strategy.

The cost function $f_1'(Q)$ considered in the following formulations does not include the Emissions Trading Cost (or Revenue) $C_{C\&T}(Q)$, because in this sensitivity analysis we only want to consider the logistics costs, without the effect of carbon allowances trading.

At first, it is needed to define the following three measures; all related to the EF shape (see Figure 4.6):

$$\Delta Q = Q_{max} - Q_{min} = |Q'^*_c - Q^*_e|$$
(19

$$\Delta C' = f_1{}'(Q_{max}) - f_1{}'(Q_{min})$$
(20

$$\Delta E = f_2(Q_{max}) - f_2(Q_{min})$$
(21

The first one describes by a quantitative point of view the extension of the efficient frontier curve in the space and, in other words, the distance between the emission-optimal solution and the cost-optimal solution in term of purchasing units.

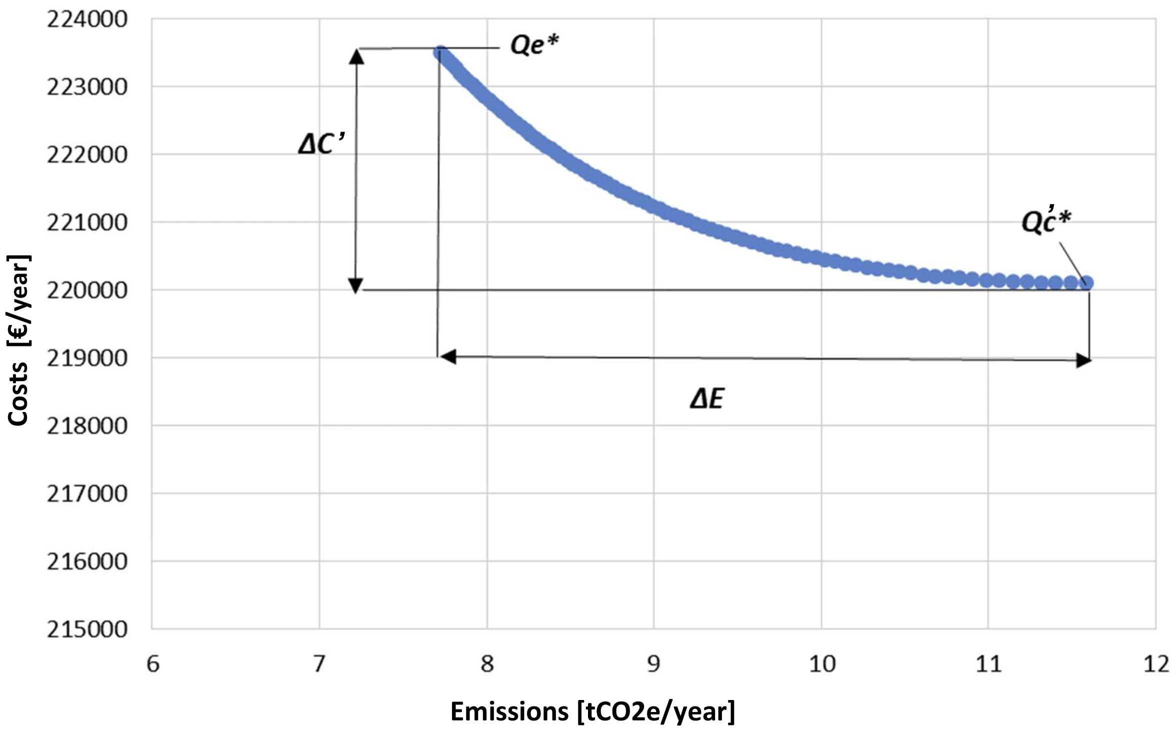


Figure 4.6 - S-EOQ Pareto Frontier

By computing the rate *ΔC'/ΔE*, it is calculated the expected marginal increment in annual logistic cost per ton CO2e, in order to move towards an emission optimal solution instead of a cost optimal one.

The solution of the S-EOQ multi-objective problem studied can be achieved exploiting the concept of indifference band (Passy and Levanon, 1984). An indifferent band is the area on the Cartesian coordinate plane where the feasible solutions are all desirable in the same way to the decision maker. Between any two solutions in the indifference curve, there is a trade-off, so that a decrement in the value of one objective function f_i certainly determines an increment in the other objective function f_j.

When a carbon cap is set according to a Cap and Trade regulatory policy, a company can decide to reduce the total emissions below the cap in order to respect the governmental constraint; on the contrary, the company has to buy carbon allowances on the carbon market. By a traditional cost-oriented optimization approach, a company prefers to apply a cost-optimal solution in order to minimize the total annual purchasing cost, so that the costs are minimized but, consequently, the emissions are maximized (Q'_c*).

In order to reduce the total annual emissions below the cap value, the company has to move in the Pareto Frontier from right towards left until it is possible to define a transportation quantity that is applicable as a purchasing lot size. In this way, the company will inevitably increase its annual costs. This marginal increment in total annual costs can be defined as the Marginal Logistic Cost (MLC) (Battini et al., 2018):

$$MLC = \frac{\Delta C'_{cap}}{\Delta E_{cap}}$$

(22

The MLC concept is illustrated in Figure 4.7.

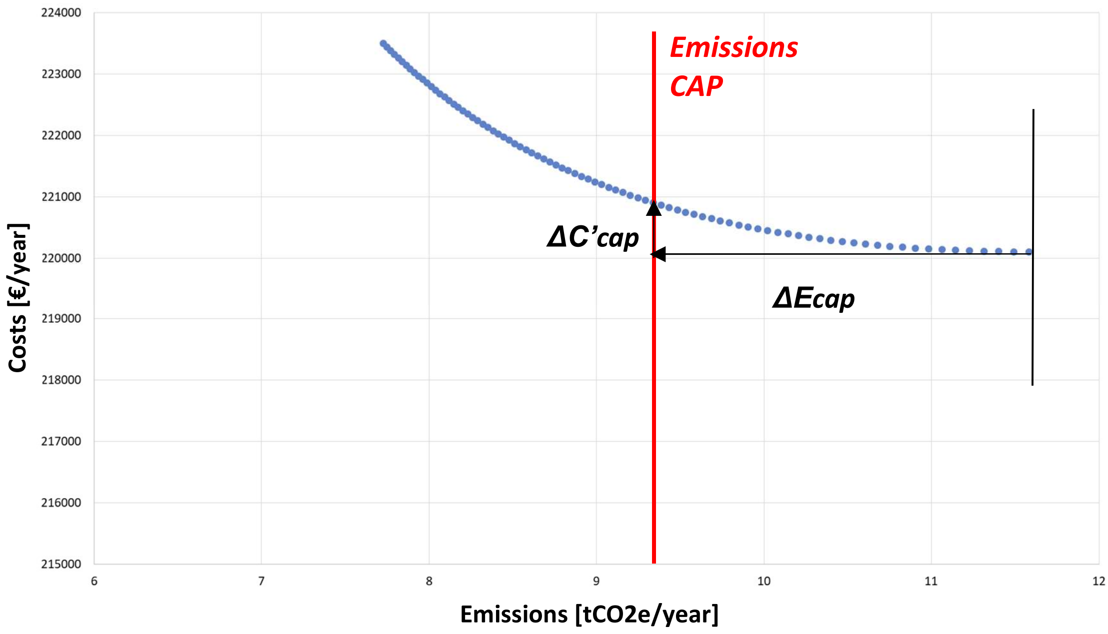


Figure 4.7 – Emissions cap effect in the Pareto Frontier

The MLC value varies according to the different shapes of the Pareto Frontier, which in some industrial sectors could be steep or on the contrary flatter. When a cap on the emissions is combined with a carbon allowance in a Cap and Trade system, the market carbon price P represents the allowance that supports the company to fit and go under the defined emissions limit (the cap).

By introducing the parameter ***φ*** defined as follows:

$$\varphi = \frac{MLC}{P} \quad (23$$

three different situations can be identified in practice:

1. ***φ>1****:* the MLC is major than the carbon price and the company has two possibilities:
   a. buy carbon allowances in the carbon market instead of investing in reducing emissions by transportation consolidation;
   b. autonomously sustain an extra cost equal to *MLC - P* in order to be more sustainable and reduce its emissions under the cap value.
2. ***0<φ≤1***: the *MLC* is lower or at maximum equal to *P* and the company could earn by the emission reduction an extra saving equal to: *P - MLC.*

For this reason, the company has economic benefits and the company decision maker is motivated in increasing the purchasing quantity of incoming materials while saturating vehicles.

3. There is **no feasible solution** to better consolidate transportation, since the cost optimal solution corresponds to the emission-optimal one: the company could only change the supplier or the transportation modality.

4.4.2 Sensitivity analysis of φ parameter

In order to understand how the Pareto Frontier shape could affect the value of the parameter φ and the consequent emission reduction, a numerical application of the model introduced in 4.1 is reported.

The model is run according to variations in product price (from 1 to 1,000 €/item) and product weight (from 0.5 to 20 kg/item), with the aim of understanding the incidence of the marginal logistic cost with respect to the market carbon price applied under a Cap and Trade approach. The testing set of variable data is reported in Table 4.6. Table 4.7 lists all the dependent variables in the model, describing their relation to the input data.

By considering a long-term growing trend of the carbon price (www.gsse.it), the model is iterated considering a value of P starting from 8 €/tCO2e to 156 €/tCO2e.

Table 4.6 - Variable Input Data

Variable Input Data	Value
p [€/unit]	[1 ; 5; 10; 50; 100; 500; 1000]
a [kg/unit]	[0.5; 1; 5; 10; 20]
$\Delta E_{cap}\%$ [%]	[10; 20; 30]
P [€/tCO2e]	[8; …; 156]

Table 4.7 - Dependent Variables

Dependent Variables	Value
CAP [tCO2e]	$E(Q)_{max} \cdot (1-\Delta E_{cap}\%)$

The results of the parametric analysis, reported in Table 4.8, visibly show that a Cap and Trade regulatory policy is strongly influenced by the type of product purchased and transported when it is applied to the material purchasing problem. In particular, the product physical characteristics (e.g. the weight) and its purchasing price highly affect the feasibility in practice of the Cap and Trade scheme when applied to inventory management and purchasing decisions.

Considering a carbon average price equal to 20 €/tCO2e (close to the value reached in September 2018) the results in Table 4.8 show clearly that the company:

1) has wide opportunities to improve its purchasing processes in order to be more sustainable and reduce emissions for all the cases reported by colored cells;
2) needs to sustain an extra cost in order to reduce its emissions below the imposed cap. This extra cost ranges from 5.0 to 54.2 times the carbon allowance value, that is the φ values reported in Table 4.8.

With reference to the results, in all the cases depicted with white empty cells in Table 4.8, the transportation system is already completely saturated and optimized by using a cost-optimal economic lot size and no other saving in emission could be achieved. These cases coincide with the option (3) described in the previous paragraph: the only way to reduce the total emissions below the cap, is by reducing the delivery distance, thus by purchasing materials closer to the buyer location instead of in the overseas market.

As illustrated in Table 4.8, with a carbon price equal to 26 €/tCO2e the φ value reaches a minimum of 3.8. This means that a company, in order to better optimize and consolidate the transportation system by purchasing higher lot sizing quantities, needs to invest 3.8 times the carbon allowance value per each ton of CO2e saved respect to the traditional cost-optimal solution.

By considering a long-term growing trend of the carbon price (www.gsse.it), the model has been iterated considering a carbon price value from 8 €/tCO2e to 156 €/tCO2e. By analyzing the results, it is clear that only with a carbon price equal to 100 €/tCO2e the φ reaches a minimum value of 1, coinciding with the option (2) described in the previous paragraph (see Figure 4.9 and Figure 4.11). In these cases, a company, in order to better optimize and consolidate the transportation system by purchasing higher lot sizing quantities, needs to invest an amount of money equal to the carbon allowance value per each ton of CO2e saved respect to the traditional cost-optimal solution. Therefore, in these cases, the extra cost equals the earnings from reducing emissions.

With a carbon price equal to 108 €/tCO2e the φ reaches a minimum value of 0.9. In this case a company able to better optimize and consolidate the transportation system by purchasing higher lot sizing quantities, needs to invest 0.9 times the carbon allowance value per each ton of CO2e saved respect to the traditional cost-optimal solution. This means that it starts earning 0.1 times the carbon allowance value per each ton of CO2e saved respect to the traditional cost-optimal solution.

Figure 4.8 and Figure 4.9 show the trend of the parameter φ in relation to the product weight. In the case illustrated the product price is set at 50 €/item and it is required an emission reduction to reach the cap of 10% ($\Delta E_{cap}\%$). It is shown that the higher the product weight, the higher is the φ value. This means that for a higher product weight, bigger extra costs are required to the company in order to reduce its annual emissions under the cap. Therefore, as illustrated in Figure 4.9, heavier products reach φ values equal or lower than 1 (see the dotted red line in Figure 4.9) for higher carbon price values, and always with a carbon price major than 100 €/tCO2e.

Moreover, Figure 4.10 and Figure 4.11 show the trend of the parameter φ in relation to the product price. In the case illustrated the product weight is set at 0.5 kg/item and it is required an emission reduction to reach the cap of 10% ($\Delta E_{cap}\%$). It is shown that the higher the product price, the higher is the φ value. This means that for a higher product price, larger extra costs and profit sacrifices are required to the company in order to reduce its annual emissions below the cap and perform an efficient transportation vehicle saturation. Therefore, it is illustrated in Figure 4.11 that more expensive products reach φ values equal or lower than 1 (see the dotted red line in Figure 4.11) for higher carbon price values. The φ value starts to be equal to 1 only with a carbon price major than 100 €/tCO2e when the product price is equal to 5€/item.

Therefore, with regard to the carried-out sensitivity analysis, with current carbon price values (22 €/tCO2e in the ETS system in October 10th, 2018) significant extra costs and profit sacrifices are necessary for the company in order to reduce its annual emissions under the cap and there is still a gap of 78% in order to reach a φ value equal to 1.

In the end, it is possible to state that a Cap and Trade system, if applied to the material purchasing and transportation sector, should be carefully adapted to each industrial sector and should also provide a higher value of the carbon price in order to really incentive companies towards sustainable choices. It has been demonstrated by a mathematical point of view, that current carbon price values are still far too low to motivate managers towards sustainable purchasing choices. However, managers highly oriented to sustainable choices could always decide to reduce emissions instead of buying carbon allowances by accepting to increase the total purchasing cost and reducing their profit margins.

Table 4.8 - Excerpt of the sensitivity analysis of the parameter φ according to different product unitary price, weight and volume, and with variations in the carbon price applied and in the emissions cap.

Carbon Price P [€/tCO2e]		8			14			20			26			32			40		
Emission reduction %		10%	20%	30%	10%	20%	30%	10%	20%	30%	10%	20%	30%	10%	20%	30%	10%	20%	30%
α [kg/item]	p [€/item]																		
0.5	1																		
1.0	1																		
5.0	1																		
10.0	1																		
20.0	1																		
0.5	5	12.4			7.1			5.0			3.8			3.1			2.5		
1.0	5																		
5.0	5																		
10.0	5																		
20.0	5																		
0.5	10	15.8	37.0	67.9	9.0	21.1	38.8	6.3	14.8	27.1	4.9	11.4	20.9	3.9	9.2	17.0	3.2	7.4	13.6
1.0	10	20.4	51.3		11.7	29.3		8.2	20.5		6.3	15.8		5.1	12.8		4.1	10.3	
5.0	10																		
10.0	10																		
20.0	10																		
0.5	50	12.8	29.8	52.6	7.3	17.0	30.1	5.1	11.9	21.0	3.9	9.2	16.2	3.2	7.5	13.2	2.6	6.0	10.5
1.0	50	14.8	34.6	62.5	8.5	19.7	35.7	5.9	13.8	25.0	4.6	10.6	19.2	3.7	8.6	15.6	3.0	6.9	12.5
5.0	50	25.1			14.3			10.0			7.7			6.3			5.0		
10.0	50																		
20.0	50																		
0.5	100	13.0	28.8	50.1	7.4	16.5	28.6	5.2	11.5	20.1	4.0	8.9	15.4	3.3	7.2	12.5	2.6	5.8	10.0
1.0	100	14.1	32.2	56.8	8.1	18.4	32.5	5.7	12.9	22.7	4.4	9.9	17.5	3.5	8.0	14.2	2.8	6.4	11.4
5.0	100	45.8	74.8		26.2	42.7		18.3	29.9		14.1	23.0		11.5	18.7		9.2	15.0	
10.0	100																		
20.0	100																		
0.5	500	13.4	29.3	48.9	7.6	16.7	27.9	5.3	11.7	19.6	4.1	9.0	15.0	3.3	7.3	12.2	2.7	5.9	9.8
1.0	500	14.6	30.5	51.4	8.3	17.4	29.3	5.8	12.2	20.5	4.5	9.4	15.8	3.6	7.6	12.8	2.9	6.1	10.3
5.0	500	18.3	41.7	76.1	10.5	23.8	43.5	7.3	16.7	30.4	5.6	12.8	23.4	4.6	10.4	19.0	3.7	8.3	15.2
10.0	500	65.2	100.7		37.3	57.6		26.1	40.3		20.1	31.0		16.3	25.2		13.0	20.1	
20.0	500																		
0.5	1000	12.8	28.4	47.4	7.3	16.2	27.1	5.1	11.4	19.0	4.0	8.7	14.6	3.2	7.1	11.9	2.6	5.7	9.5
1.0	1000	14.6	30.1	49.2	8.3	17.2	28.1	5.8	12.1	19.7	4.5	9.3	15.1	3.6	7.5	12.3	2.9	6.0	9.8
5.0	1000	16.3	37.1	66.6	9.3	21.2	38.0	6.5	14.8	26.6	5.0	11.4	20.5	4.1	9.3	16.6	3.3	7.4	13.3
10.0	1000	21.6	47.6	135.6	12.3	27.2	77.5	8.6	19.0	54.2	6.6	14.6	41.7	5.4	11.9	33.9	4.3	9.5	27.1
20.0	1000	23.6	61.8		13.5	35.3		9.4	24.7		7.2	19.0		5.9	15.5		4.7	12.4	

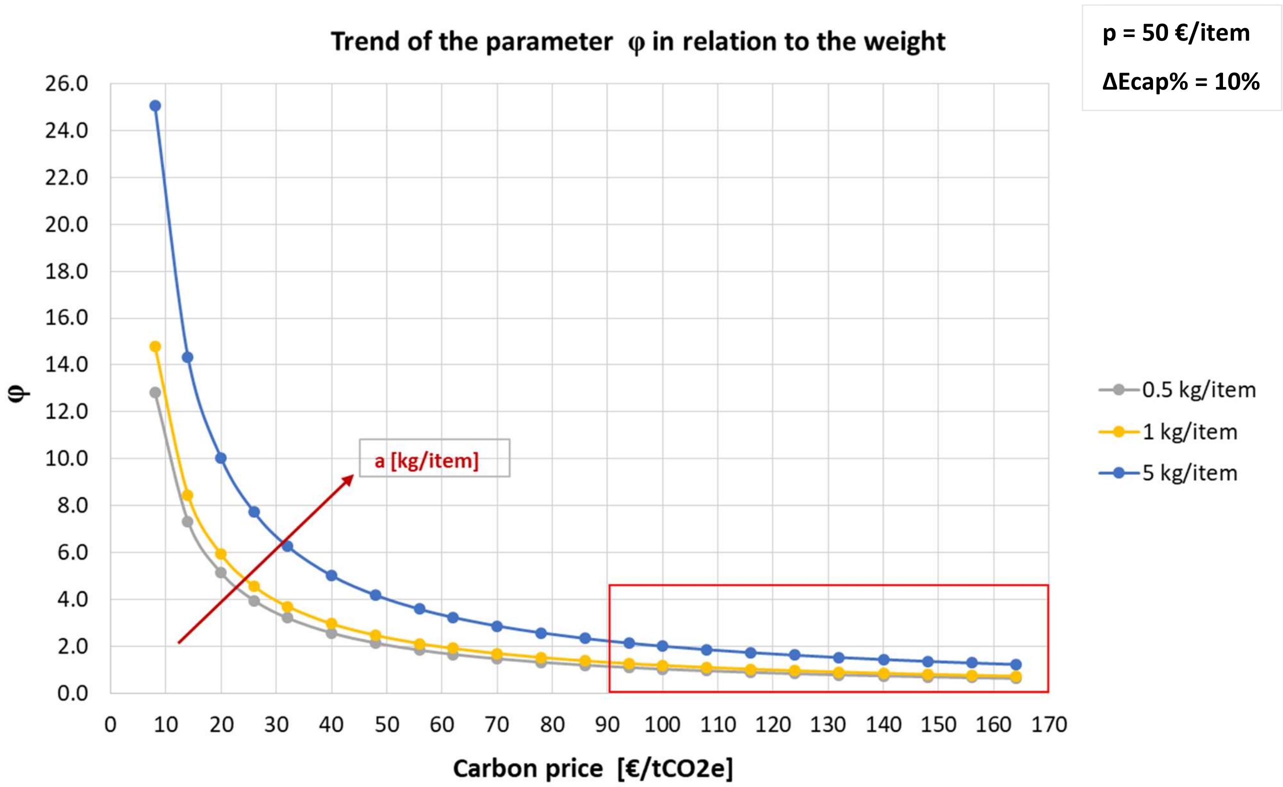


Figure 4.8 - Trend of the parameter φ in relation to the product weight

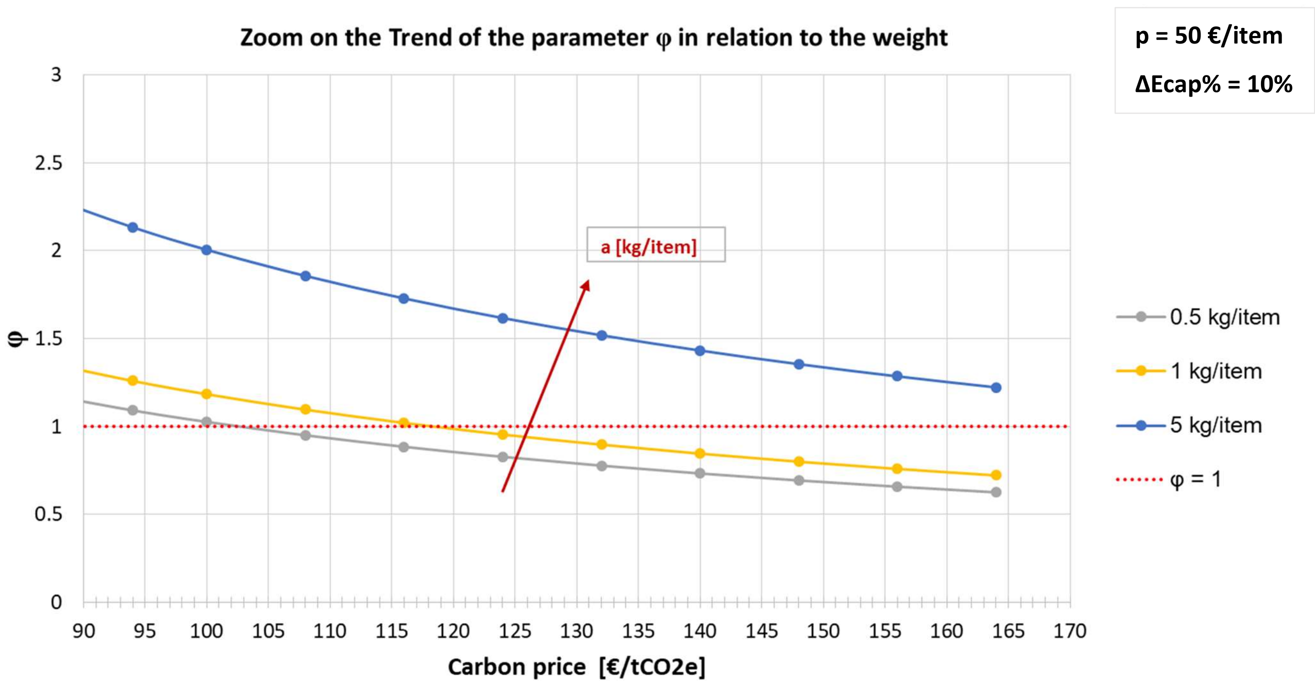


Figure 4.9 - Zoom on the trend of the parameter φ in relation to the product weight

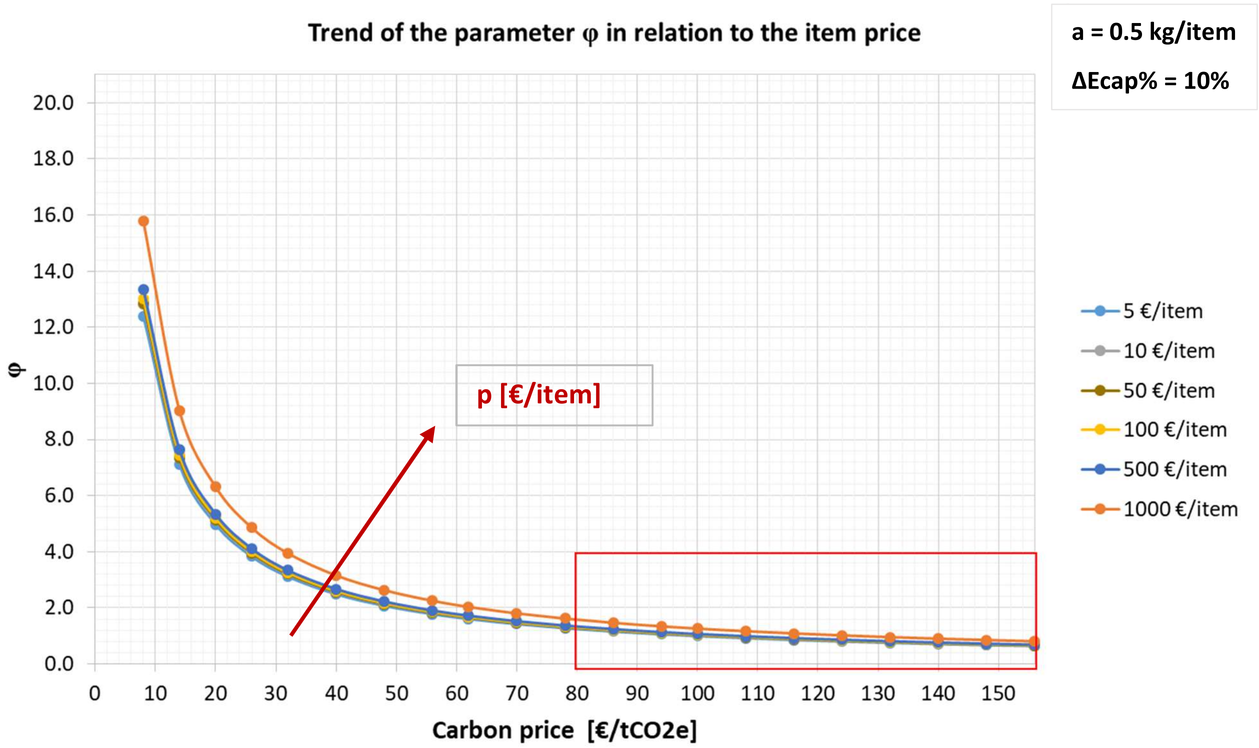


Figure 4.10 - Trend of the parameter φ in relation to the product price

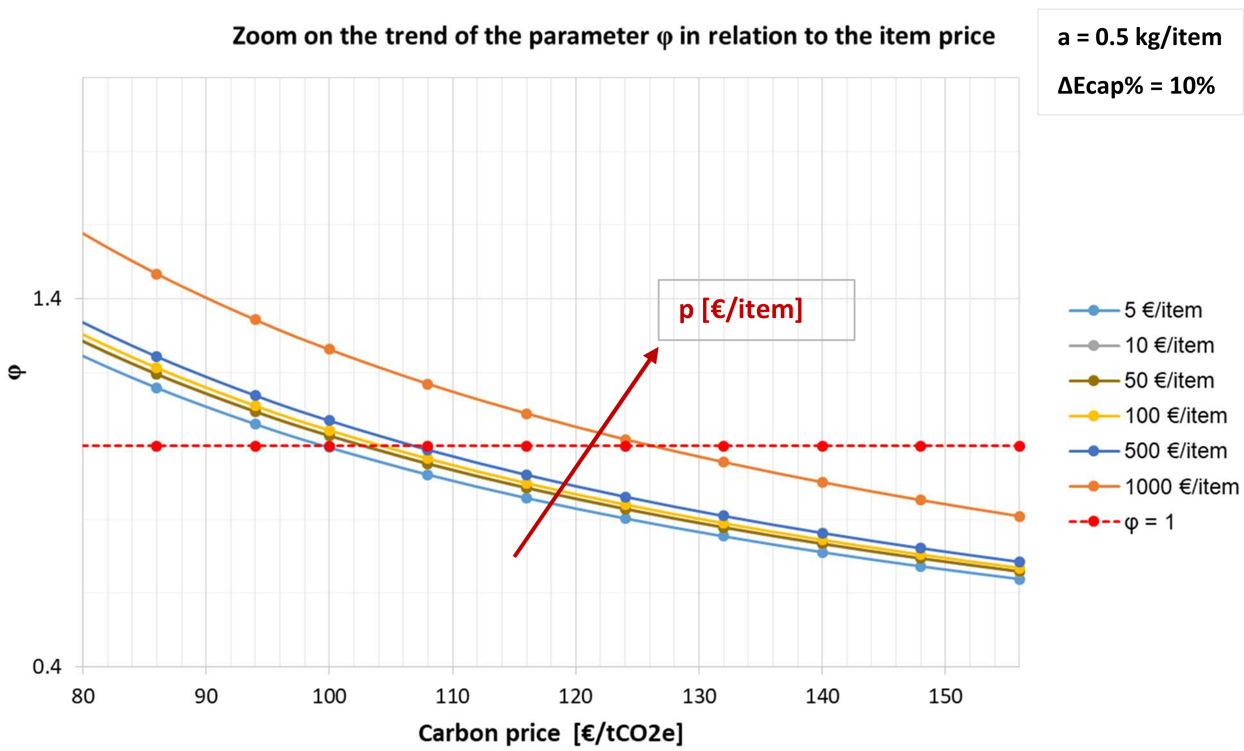


Figure 4.11 - Zoom on the trend of the parameter φ in relation to the product price

5 SUSTAINABLE JOINT ECONOMIC LOT SIZE MODELS UNDER CAP AND TRADE REGULATION (S-JELS)

As asserted by Zanoni et al. (2014), since global markets became more competitive, supply chain coordination became essential for increasing a supply chain's profitability and responsiveness. The JELS models integrate the inventory lot sizing decision across two echelons; therefore, they represent a first try to advance inventory-based sustainability modeling into the scope of a supply chain (Tao et al., 217).

In the next paragraphs, we introduce two Sustainable Joint Economic Lot Size Models under Cap and Trade policy in which the optimal lot-sizing solution depends on two different objective functions (costs and emissions) and transportation capacity constraints.

In this way, both economic and sustainable issues are equally considered and integrated in the contest of a supply chain; leading the decision makers to more sustainable and efficient logistic and purchasing solutions. Therefore, the following models are supply chain oriented, so they can give a more realistic support in the decision making activities.

As in chapter 4, the trading system used here is inspired to the current EU ETS system (www.ec.europa.eu). The first model applies the Cap and Trade regulations only to the buyer, while the second considers the cap on emissions for both Buyer and Supplier.

The developed models consider the case where a vendor produces for a buyer on a lot for lot basis (Banerjee, 1988). The assumptions are: we consider a two level supply chain: Single vendor- Single buyer, the demand rate is well known and constant, a shortage is not permitted, the supplier inventory is consumed by demands at rate *d'* and it produces at rate *i'* through a Lot for lot production.

5.1 Sustainable JELS Model – Buyer under Cap and Trade policy

The sustainable bi-objective order quantity model introduced in Chapter 4 can be evolved by considering the supplier average annual cost and total quantity of emissions generated during the annual activity related to the buyer replenishment. Therefore, in the formulation bellow the two objective functions: $f_1(Q)$ and $f_2(Q)$ will consider the costs and the emissions related not only to the buyer, but also to the supplier activities. Moreover, as already mentioned, it considers that the Cap and Trade regulation is applied only to the buyer.

ADDITIONAL DECISION VARIABLES AND COST FUNCTIONS:

$C'_{buy}(Q)$ *buyer* total average annual cost of replenishment without considering the Cap and Trade costs or revenues [€/year]

$C_{buy}(Q)$ *buyer* total average annual cost of replenishment [€/year]

$C_{sup}(Q)$ supplier average annual cost for buyer replenishment [€/year]

$E_{buy}(Q)$ buyer total annual emission generated by the replenishment [CO2e/year]

$E_{sup}(Q)$ supplier total annual emission generated by the buyer replenishment [CO2e/year]

$Q'_c{}^*_{buy}$ optimal order quantity for the cost function $C'_{buy}(Q)$ [units/purchasing order]

ADDITIONAL INPUT PARAMETERS:

d' buyer demand rate [units/year]

i' supplier inventory (production) rate [units/year]

I annual supplier production [units/year]

K_{sc} fixed setup cost per order [€/order]

K_{se} fixed setup emissions per order [kgCO2e/order]

h_b buyer holding cost [€/unit]

h_s supplier holding cost [€/unit]

η average defective items annual rate [%]

δ disposal cost of defective items [€/item]

CAP_b buyer carbon cap according to a cap and trade system [tCO2e]

s_b^+ amount of allowances sold by the buyer company [tCO2e]

s_b^- amount of allowances bought by the buyer company [tCO2e]

$s_b^+, s_b^- \geq 0$

Note that only one of these trading variables may be positive; i.e. the organization either buys or sells allowances.

$\Delta E_{cap\ b}\%$ buyer's emission reduction by reaching the cap value [%]

$c_{eh\ b}$ buyer warehouse emission coefficient [kgCO2e/m3]

$c_{eh\ s}$ supplier warehouse emission coefficient [kgCO2e/m3]

f emissions function parameter [ton·year²/unit³]

g emissions function parameter [ton·year/unit²]

m emissions function parameter [ton/unit]

We can now introduce the objective function $f_1(Q)$ that quantifies the average annual cost for both buyer and supplier, generated during the annual activity related to the buyer replenishment. The Cap and Trade regulation is applied only to the buyer.
The formulation is expressed as follows:

$$f_1(Q) = C(Q) = C_{buy}(Q) + C_{sup}(Q) = [p \cdot D + C_o(Q) + C_{h,b}(Q) + C_{obs}(Q) + C_t(Q) + C_{def} + C_{C\&T,b}(Q)] + [C_{h,s}(Q) + C_s(Q)]$$

(24

At first, we can introduce the terms that generate the **Buyer average annual cost** for the replenishment.

Ordering cost: $C_o(Q) = \frac{D}{Q} \cdot O$

(25

Buyer holding cost: $C_{h,b}(Q) = \frac{Q}{2} h_b + Q\left(\frac{d}{v}\right)\left(\frac{D}{Q}\right) h_b$

(26

Buyer cost related to obsolescence: $$C_{obs}(Q) = \frac{Q}{2}(p - p') \cdot \beta$$

(27

Transportation cost for each kind of transportation mode j used:

$$C_{t\,j}(Q, d_j, S_j) = \left(c_{f,j} \cdot d_j \cdot \sum_i n_i + c_{v,j} \cdot d_j \cdot DP_k \right) \cdot \frac{D}{Q}$$

(28

$C_{C\&T,b}$ represents the Buyer Emissions Trading Cost (or Revenue), resulted from buying or selling permits at the current carbon price P. By staying under the cap value, the buyer company will have the right to trade the rest of the allowances at the current carbon price. Conversely, if the annual emissions are higher than the cap value, it will be necessary to buy more permits from the market.

$$C_{C\&T,b}(Q) = P \cdot ({s_b}^- - {s_b}^+) = -\left[CAP_b - E_{buy}(Q)\right] \cdot P$$

(29

The Buyer cost related to the disposal of defective items is expressed as follows. η is the average defective items annual rate, while *δ* represents the disposal cost of defective items €/item.

$$C_{def} = D \cdot \eta \cdot \delta$$

(30

Then we need to introduce the terms that express the **Supplier average annual cost** for the buyer replenishment.

The holding cost for the vendor considers the traditional holding cost of carrying inventory in the warehouse as expressed by the following formula (Banerjee, 1988):

$$C_{h,s}(Q) = \frac{1}{2} h_s \cdot Q \cdot \left(\frac{d'}{i'}\right)$$

(31

d' represents the buyer demand rate, while *i'* the supplier inventory (production) rate.

The vendor undertakes a production setup every time the buyer places an order. Therefore, given the supplier fixed setup cost per order K_{sc}, expressed in €/order, the Setup cost for the vendor can be expressed as (Banerjee, 1988):

$$C_S(Q) = \frac{D}{Q} \cdot K_{sc}$$

(32

Concluding, the first function to optimize is finally expressed as follows and it includes the costs (or revenues) related to the Cap and Trade regulatory policy in use.

$$f_1(Q) = C(Q) = C_{buy}(Q) + C_{\sup}(Q)$$

(33

where:

$$C_{buy}(Q) = C'_{buy}(Q) + C_{C\&T,b}(Q)$$

(34

$$C_{buy}(Q) = p \cdot D + \frac{D}{Q} \cdot O + \frac{Q}{2} h_b + \left(\frac{d}{v}\right) D \cdot h_b + \frac{Q}{2}(p - p') \cdot \beta + D \cdot \eta \cdot \delta$$
$$+ [\sum_j \left(c_{f,j} \cdot d_j \cdot \sum_i n_i + c_{v,j} \cdot d_j \cdot DP_k \right)] \cdot \frac{D}{Q} - [CAP_b - E_{buy}(Q)] \cdot P$$

(35

$$C_{\sup}(Q) = \frac{1}{2} h_s \cdot Q \cdot (\frac{d'}{i'}) + \frac{D}{Q} \cdot K_{sc}$$

(36

The second objective function $f_2(Q)$ quantifies the average total quantity of emissions generated during the annual purchasing activity by buyer and supplier. It can be expressed by the sum of the emissions generated by the supplier in the following steps:

- Setup of the order;
- Warehousing;
- Production.

And the emissions generated by the buyer in the next steps:

- Warehousing;
- Waste collection and treatment of the obsolete stock;
- Disposal of defective items;
- Order transportation.

All these terms can be homogeneously expressed in tons of CO2e to calculate the average total quantity of emission.

$$f_2(Q) = E(Q) = E_{buy}(Q) + E_{sup}(Q) = [E_{h,b}(Q) + E_{obs}(Q) + E_t(Q) + E_{def}] + [E_{h,s}(Q) + E_s(Q) + E_p]$$

(37

At first, we can introduce the terms that generate the **Buyer total quantity of emissions** due to replenishment in the time unit of a year.

Carbon emissions generated by warehousing: $E_{h,b}(Q) = c_{ehb}\left(\frac{Q}{2} \cdot b\right)$

(38

Emissions related to obsolescence: $E_{obs}(Q) = \frac{Q}{2} \cdot \beta \cdot a \cdot c_{eo}$

(39

The emission related to the disposal of defective items can be expressed as follows:

$$E_{def} = D \cdot \eta \cdot a \cdot c_{eo}$$

(40

In this formula, η is the average defective items annual rate, a represents the weight of a unit stored in the warehouse in tons/unit and c_{eo} is the waste collection and recycling emission coefficient, expressed in kgCO2e/ton.

Transportation emissions:

$$E_{t\,j}(Q, d_j, S_j) = \left(c_{ef,j} \cdot d_j \cdot \sum_i n_i + c_{ev,j} \cdot d_j \cdot DP_k\right) \cdot \frac{D}{Q}$$

(41

Then, we need to introduce the terms that express the **Supplier total quantity of emissions** generated during the time unit of one year for facing buyer replenishment.
The average quantity of equivalent carbon emissions generated by the supplier in one year for the warehousing can by calculated as:

$$E_{h,s}(Q) = \frac{1}{2} \cdot c_{eh\,s}(Q \cdot b)(\frac{d'}{i'})$$

(42

Where $c_{eh\,s}$ is the supplier warehouse emission coefficient expressed in kgCO2e/m^3, the parameter b measures the cube meters occupied by a product unit with its packaging materials stored in the warehouse, *d'* represents the buyer demand rate and *i'* the supplier inventory rate.
The quantity of carbon emissions generated by the vendor during the production is given from Bogaschewsky (1995) as:

$$E_p = fI^2 - gI + m$$

(43

The carbon emissions generated during the order setup, for the order placement and inventory replenishment, can be expressed as (Arslan and Turkay, 2013):

$$E_s(Q) = \frac{K_{se} \cdot D}{Q}$$

(44

The parameter K_{se} represents the fixed setup emissions per order [kgCO2e/setup].

Therefore, by considering the whole mix of transportation modes used in the product supply from vendor to buyer, the second objective function to optimize can be expressed as follows:

$$f_2(Q) = E(Q) = E_{buy}(Q) + E_{\sup}(Q)$$

(45

where:

$$E_{buy}(Q) = C_{eh\,b}\left(\frac{Q}{2} \cdot b\right) + \frac{Q}{2} \cdot \beta \cdot a \cdot c_{eo} + D \cdot \eta \cdot a \cdot c_{eo} + [\sum_j (c_{ef,j} \cdot d_j \cdot \sum_i n_i + c_{ev,j} \cdot d_j \cdot DP_k)] \cdot \frac{D}{Q}$$

(46

$$E_{\sup}(Q) = \frac{1}{2} \cdot c_{eh\,s}(Q \cdot b)\left(\frac{d'}{i'}\right) + (fI^2 - gI + m) + \frac{K_{se} \cdot D}{Q}$$

(47

According to a generic Pareto design optimization problem (Pareto 1964, 1971), involving the two conflicting objective functions introduced above, it can be concisely stated:

$$Minimize \ \{f_1(Q), f_2(Q) \ \}$$

(48

A Pareto-optimal solution is also defined "Pareto-efficient solution", and the set of all the efficient points is called the Pareto Frontier. Generally, it is not possible to express the Pareto Frontier with an analytical expression; however, it is possible to assert that:

"Q is a Pareto-optimal solution to the problem posed by Eq. (33 and Eq. (45 ,if there does not exist any other design Q such that* $f_1(Q) \leq f_1(Q^*)$ *and* $f_2(Q) \leq f_2(Q^*)$ *simultaneously."*

The number of Pareto-efficient solutions Q* can be wide, for this reason it is necessary to select the best compromise design(s) among them. In the sustainable lot sizing problem here proposed, a sustainable purchasing choice normally increases $f_1(Q)$, while decreases $f_2(Q)$, since the two objective functions are competitive in nature.

If *Q*c* is the single optimal solution of the objective function $f_1(Q)$ and *Q*e* is the single optimal solution of $f_2(Q)$, *EF* can be defined as the Efficient Frontier of the sustainable lot sizing problem here proposed and EF^c its image in the criterion space, then:

$$EF = [Q_c^*, Q_e^*]$$

(49

EF_+^c is convex and there exists $Q_{min} < Q_{max}$ such that $Q^* \in [Q_{min}, Q_{max}]$.

As a consequence, the shape of the EF strongly affects the possibility to move from a cost-optimal solution to an emission-optimal one.

5.2 Sustainable JELS Model - Buyer and Supplier under Cap and Trade policy

The sustainable joint economic lot size model introduced in 5.1 can be evolved if we consider both the supplier and the buyer companies operating under a Cap and Trade policy.
In the next paragraphs, we introduce a Bi-objective joint economic lot size model with both buyer and supplier under Cap and Trade regulation.

ADDITIONAL INPUT PARAMETERS:

CAP_s supplier carbon cap according to a cap and trade system [tCO2e]

$\Delta E_{cap\ s}\%$ supplier's emission reduction by reaching the cap value [%]

s_s^+ amount of allowances sold by the supplier company [tCO2e]

s_s^- amount of allowances bought by the supplier company [tCO2e]

$s_s^+, s_s^- \geq 0$

Note that only one of these trading variables may be positive; i.e. the organization either buys or sells allowances.

$C'_{sup}(Q)$ supplier average annual cost for buyer replenishment without considering the Cap and Trade costs or revenues [€/year]

$Q'_c{}^*{}_{sup}$ optimal order quantity for the cost function $C'_{sup}(Q)$ [units/purchasing order]

We can now introduce the objective function $f_1(Q)$ that quantifies the average annual cost for both buyer and supplier, generated during the annual activity related to the buyer replenishment. The Cap and Trade regulations are applied to both buyer and supplier.
The formulation is expressed as follows:

$$f_1(Q) = C(Q) = C_{buy}(Q) + C_{sup}(Q)$$

(50

$$f_1(Q) = C(Q) = C_{buy}(Q) + C_{sup}(Q) = [p \cdot D + C_o(Q) + C_{h,b}(Q) + C_{obs}(Q) + C_t(Q) + C_{def} + C_{C\&T,b}(Q)] + [C_{h,s}(Q) + C_s(Q) + C_{C\&T,s}(Q)]$$

(51

At first, we can introduce the terms that generate the **Buyer average annual cost** for the replenishment, the formulation is the same introduced in 5.1.

$$C_{buy}(Q) = p \cdot D + \frac{D}{Q} \cdot O + \frac{Q}{2} h_b + \left(\frac{d}{v}\right) D \cdot h_b + \frac{Q}{2}(p - p') \cdot \beta + D \cdot \eta \cdot \delta + [\sum_j \left(c_{f,j} \cdot d_j \cdot \sum_i n_i + c_{v,j} \cdot d_j \cdot DP_k \right)] \cdot \frac{D}{Q} - [CAP_b - E_{buy}(Q)] \cdot P$$

(52

Then we need to introduce the terms that express the **Supplier average annual cost** for the buyer replenishment, including also the Supplier Emissions Trading Cost (or Revenue) $C_{C\&T,s}$, resulted from buying or selling permits at the current carbon price P. By staying under the cap value, the supplier company will have the right to trade the rest of the allowances at the current carbon price. Conversely, if the annual emissions are higher than the cap value, it will be necessary to buy more permits from the market.

$$C_{C\&T,s}(Q) = P \cdot (s_s^- - s_s^+) = -[CAP_s - E_{sup}(Q)] \cdot P$$

(53

Therefore, the **Supplier average annual cost** can be expressed as:

$$C_{sup}(Q) = \frac{1}{2} h_s \cdot Q \cdot (\frac{d'}{i'}) + \frac{D}{Q} \cdot K_{sc} - [\mathrm{CAP_s} - \mathrm{E_{sup}(Q)}] \cdot \mathrm{P}$$

(54

This first function to optimize is finally expressed as follows, considering all the formula introduced in paragraph 5.1 and including the supplier costs (or revenues) related to the Cap and Trade regulatory policy in use.

$$f_1(Q) = C(Q) = C_{buy}(Q) + C_{sup}(Q)$$

(55

$$C_{buy}(Q) = p \cdot D + \frac{D}{Q} \cdot O + \frac{Q}{2} h_b + \left(\frac{d}{v}\right) D \cdot h_b + \frac{Q}{2}(p - p') \cdot \beta + D \cdot \eta \cdot \delta + [\sum_j \left(c_{f,j} \cdot d_j \cdot \sum_i n_i + c_{v,j} \cdot d_j \cdot DP_k\right)] \cdot \frac{D}{Q} - [CAP_b - E_{buy}(Q)] \cdot P$$

(56

$$C_{\text{sup}}(Q) = \frac{1}{2} h_s \cdot Q \cdot (\frac{d'}{i'}) + \frac{D}{Q} \cdot K_{sc} - [\text{CAP}_s - \text{E}_{\text{sup}}(\text{Q})] \cdot \text{P}$$

(57

The second objective function $f_2(Q)$ is the average total quantity of emission generated during the annual purchasing activity by buyer and supplier. The formulation is the same introduced in 5.1.

$$f_2(Q) = E(Q) = E_{buy}(Q) + E_{sup}(Q) = [E_{h,b}(Q) + E_{obs}(Q) + E_t(Q) + E_{def}] + [E_{h,s}(Q) + E_s(Q) + E_p]$$

(58

$$E_{buy}(Q) = C_{eh\,b}\left(\frac{Q}{2} \cdot b\right) + \frac{Q}{2} \cdot \beta \cdot a \cdot c_{eo} + D \cdot \eta \cdot a \cdot c_{eo} + [\sum_j (c_{ef,j} \cdot d_j \cdot \sum_i n_i + c_{ev,j} \cdot d_j \cdot DP_k)] \cdot \frac{D}{Q}$$

(59

$$E_{\text{sup}}(Q) = \frac{1}{2} \cdot c_{eh\,s}(Q \cdot b)\left(\frac{d'}{i'}\right) + (fI^2 - gI + m) + \frac{K_{se} \cdot D}{Q}$$

(60

According to a generic Pareto design optimization problem (Pareto 1964, 1971), involving the two conflicting objective functions introduced above, it can be assert:

$$Minimize\ \{f_1(Q), f_2(Q)\}$$

(61

A Pareto-optimal solution is also defined “Pareto-efficient solution”, and the set of all the efficient points is called the Pareto Frontier. Generally, it is not possible to express the Pareto Frontier with an analytical expression; however, it is possible to assert that:

"Q is a Pareto-optimal solution to the problem posed by Eq. (55 and Eq. (58, if there does not exist any other design Q such that* $f_1(Q) \leq f_1(Q^*)$ *and* $f_2(Q) \leq f_2(Q^*)$ *simultaneously."*

The number of Pareto-efficient solutions Q* can be wide, for this reason it is necessary to select the best compromise design(s) among them. In the sustainable lot sizing problem here proposed, a sustainable purchasing choice normally increases $f_1(Q)$, while decreases $f_2(Q)$, since the two objective functions are competitive in nature.

If *Q*c* is the single optimal solution of the objective function $f_1(Q)$ and *Q*e* is the single optimal solution of $f_2(Q)$, *EF* can be defined as the Efficient Frontier of the sustainable lot sizing problem here proposed and EF^c its image in the criterion space, then:

$$EF = [Q_c^*, Q_e^*] \qquad (62$$

EF_+^c is convex and there exists $Q_{min} < Q_{max}$ such that $Q^* \in [Q_{min}, Q_{max}]$.

As a consequence, the shape of the EF strongly affects the possibility to move from a cost-optimal solution to an emission-optimal one.

6 THE S-JELS MODEL TO SUPPORT A SUPPLIER SELECTION – A LEATHER INDUSTRY CASE STUDY

6.1 Supplier Selection Models – Literature Review

In this era of global competition, the companies need to pay much attention on identifying and choosing alternative supply sources. Moreover, as stated by Chu and Varma (2012), suppliers are an important member of the supply chain. Their skills and performance strongly influence the success or failure of the entire supply chain. Therefore, a valid and effective supplier selection process is essential (A. Zouggari and L. Benyoucef, 2012) and it plays a fundamental role with a strong effect on supply chain purchasing management (Wu et al., 2013).

As explained by Chen et al. (2016), the supplier selection is a complex and delicate process composed of four main phases: *determining the problem formulations of suppliers, defining the selection criteria, prequalifying suitable suppliers, and making a final choice* (see Figure 6.1).

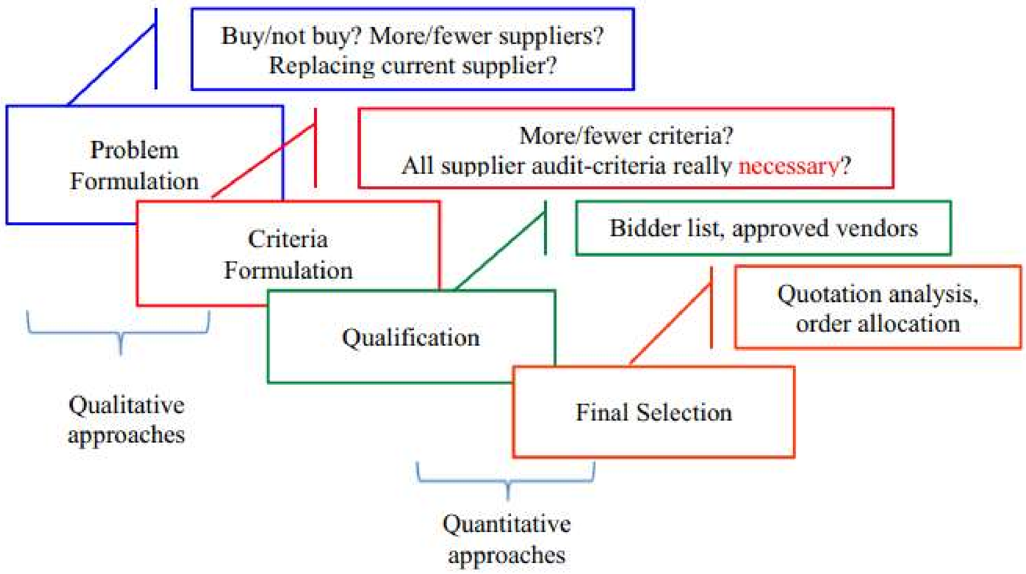


Figure 6.1 - Positioning the decision methods in supplier selection (De Boer et al., 2001)

The supplier evaluation and selection process is multi-objective in nature, since more than one criterion can be considered and valued during the process (Wang and Yang, 2009). Moreover, these various criteria must be taken into account simultaneously in the decision process. The analysis of such criteria and of supplier key performance indicators (KPI) has been widely studied by researchers since the 1960s. Dickson (1966), after a survey of 170 purchasing managers, identified 23 different criteria for supplier selection.
Among these, both Wang and Yang (2009) and Ho et al. (2010) identify as the most popular criteria for evaluating the suppliers' performance: quality, delivery and price or cost.
Chen et al. (2016) assert that the literature published from 1995 to 2005 focuses on these 9 criteria:

- ***finance*** (e.g. profitability, cost of product, logistics costs, taxes, gross profit rate, price of material, transportation price, management price);
- ***quality*** (e.g. conformance to specification, product reliability, product quality, quality system, claims, defect rate);
- ***delivery*** (e.g. punctuality of delivery, delivery performance, lead time, delivery flexibility);
- ***relationships*** (e.g. technique cooperation, market cooperation, relationship building, trust, credibility, consistency, ease communication)
- ***service*** (e.g. availability to support customer, supplier service performance, delivery reliability, flexibility and responsiveness, service standard, improvement capability);
- ***technology and product*** (e.g. R&D rate, process capability, supplier technological levels, product familiarity, support to design process, product flexibility);
- ***facility*** (e.g. Supply facility and infrastructure and market reputation);
- ***management*** (e.g. organization control, business plans, internal audit, data administration, honesty and integrity, flexibility, information technology).

In 2007 the ***environmental issues*** became one of the crucial supplier selection criteria and, for example, the carbon footprints (CO2) represents one of the supplier selection KPI. Also ***risk criteria*** gained importance since 2007 (e.g. geographical location, political stability and foreign policies, exchange rate and economic position, terrorism and crime rate, supply constraint).
As explained by Feng et al. (2011), to resolve the supplier selection problem, several evaluation techniques have been proposed in the literature, with methodologies ranging from conceptual to empirical and modeling currents. Since mid-1960s, many researchers

worked on literature surveys to outline the criteria and decision methods involved. According to the study of Wang and Yang (2009), the quantitative decision methodologies for solving the supplier selection problem can be grouped into three categories: (1) ***multi-attribute decision-making***, (2) ***mathematical programming models***, and (3) ***intelligent approaches***.

(1) The first category comprises the linear weighting method (Timmerman, 1986), the analytical hierarchy process (AHP) (Akarte, Surendra, Ravi, & Rangaraj, 2001) and the analytic network process (ANP).

(2) The mathematical programming models are the second most frequently used methods and in the literature survey by Ho et al. (2010), they are classified into the following five groups: linear programming (Pan, 1989), integer linear programming, integer non-linear programming, goal programming and multi-objective programming (Weber & Current, 1993).

(3) For what concerns the third category, it explores some newly developed techniques to deal with the activities of supplier selection, such as neural networks (Choy, Lee, & Lo, 2003), and expert system (Choy, Lee, & Lo, 2002).

Moreover, other methods have also been widely used for the supplier selection problem, such as integrated AHP and linear programming, principal component analysis (Petroni & Braglia, 2000), fuzzy mixed integer goal programming (Kumar, Vrat, & Shankar, 2004), voting AHP (Liu & Hai, 2005), the fuzzy decision-making approach (Amid, Ghodsypour, & O'Brien, 2006).

As asserted by Wang and Yang (2009), most studies often formulate supplier selection problem as a Multi-Objective Linear Programming (MOLP) problem, and then scale it down to a Mixed Integer Programming (MIP) problem to handle the multi-objectives simultaneously. However, with these techniques often scaling and subjective weighting issues are not taken into account.

For such reason in the next paragraph it is explained how the S-JELS model presented in paragraph 5.1 can be integrated into a Sustainable Supplier Selection based, for example, on an AHP approach.

The AHP approach, introduced by Saaty (1980), is a useful technique for solving complex decision problems. It organizes a decision problem into a hierarchy with a goal, decision qualitative and quantitative criteria, and alternatives; while the ANP builds it as a network. Both the two methods use a system of pairwise comparisons to measure the weights of the components of the structure, and finally to create a ranking of the alternatives in the decision.

Saaty (1996) introduced the ANP approach for extending the AHP in order to go beyond the hierarchical structure where criteria are independent from each other (Hashemi et al. 2015). The structural difference between AHP (hierarchy) and ANP (network) is shown in Figure 6.2.

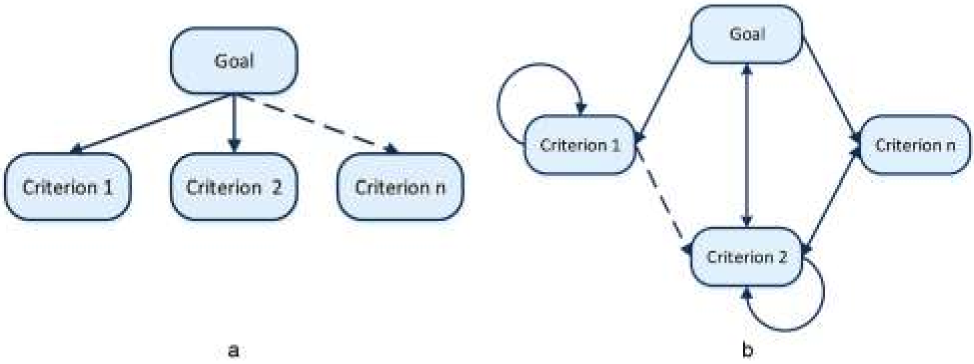


Figure 6.2 - AHP (a) and ANP (b) structure (Source:S.H. Hashemi et al. 2015)

6.2 S-JELS Model to Support a Sustainable Supplier Selection

In order to help companies on analyzing the trade-offs among different supplies and make the more efficient and sustainable supplier selection, the S-JELS model presented in 5.1 is here integrated into a procedure for assessing a Sustainable Supplier Selection.

The objective is to exploit the S-JELS model results for providing the managers with numerical KPIs and user-friendly graphs, in order to help them on evaluating the correspondent selection criteria for each potential sourcing option in an easier, faster, more analytical and correct way.

In the case study discussed in the following, the procedure explained below and depicted in Figure 6.3 has been applied, in order to finally perform a green supplier selection in the finished leather purchasing.

- The **1st** step of the proposed procedure consists in determining the problem formulations of suppliers: the company under analysis needs to identify and preselect potential suppliers in order to define an optimal one.
- In the **2nd** step of the procedure, the relevant criteria for the supplier selection are identified and selected, considering those highly recommended by the decision makers

involved in this case study (in this case C1 represents the cost criterion, C2 the environmental criterion and C3 the supplier reliability criterion).

- In the **3rd** and **4th** stages, the decision makers (DMs) identify the quantitative KPIs to be used for evaluating each selected criterion. In particular C(Q*e) and E(Q*e) are defined as KPIs for C1 (Total annual costs) and C2 (Total annual emissions), together with the comparison of the Pareto Frontier graphs of the alternative suppliers.
- In the **5th** step, a multi-criteria selection method (in this case study the AHP), by using pairwise comparisons, determines the relative importance of the criteria for the DMs, creates the pairwise comparison matrix and finally calculate their weights.
- In the **6th** phase the S-JELS model has to be run for each supplier.
- In the **7th** and **8th** stages, the DMs have to build the Pareto Frontier for each supply option, also identifying the emission optimal solution ***Q*e*** for each supplier.
- The **9th** step consists in calculating for each supply option, the total costs ***C(Q*e)*** and total emissions ***E(Q*e)*** correspondent to the ***Q*e*** lot size.
- During the **10th** phase, the Decision Makers analyze quantitative and qualitative KPIs data for each supplier.
- After the KPIs analysis, in the **11th** step, the DMs evaluate each supplier according to the selected criteria.
- Finally, in the **12th** stage the final scores of the suppliers are calculated, creating the Suppliers' final ranking.
- In the **13th** step, the supplier with the best final score is selected.

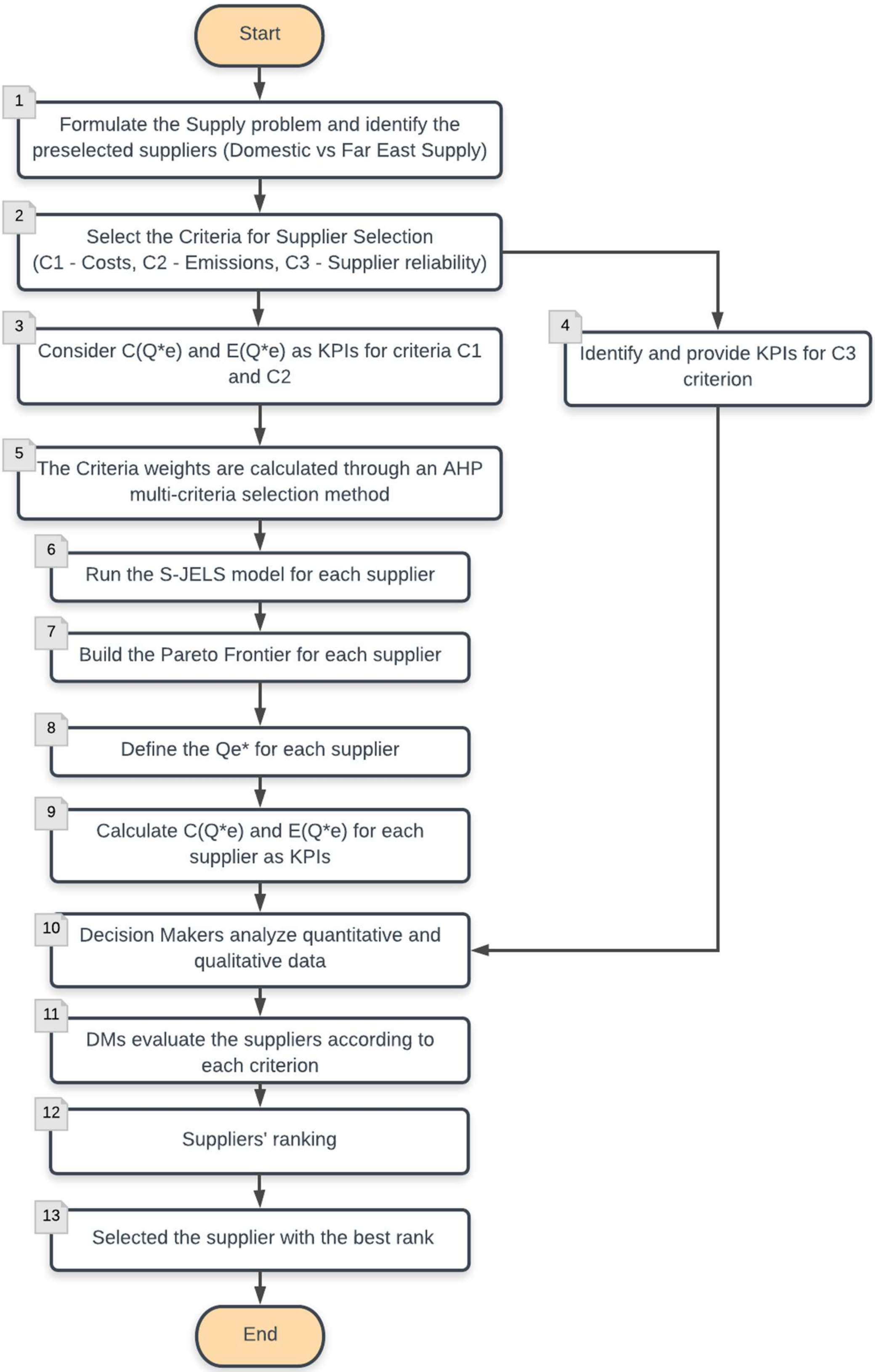


Figure 6.3 - Sustainable Supplier Selection Model

6.3 Domestic vs International sourcing – a Leather Industry case study

In this section two different sourcing options are going to be compared, a Domestic and a Far-East sourcing, in order to help a company on analyzing the trade-offs among the supplies and make the more efficient and sustainable supplier selection.
In the next paragraphs are illustrated:

- a numerical application of the S-EOQ model presented in 4.1, in order to compare the Efficient Frontiers of a Domestic and a Far East sourcing.
- a numerical application of the S-JELS model presented in 5.1, in order to compare the Efficient Frontiers of a Domestic and a Far East sourcing with a supply chain point of view. The S-JELS model results are then exploited as numerical KPIs, useful for evaluating the criteria selected by the Decision Makers for each sourcing option.

The case study considered regards the Finished Leather industry, and all the information and data are taken from the literature or inspired by experiential knowledge of the industrial sector. The buyer company is assumed located in Vicenza, in the north-east of Italy and could purchase material through a Domestic sourcing, or a Far East sourcing.
The finished leather is transported rolled up into boxes with the following dimensions: 150 cm width, 30 cm height and 30 cm depth. We consider that a box of this dimension can transport in average 15 m^2 of finished leather.
Let us assume that the domestic supplier is located in the province of Naples, while the international supplier is located in Taiwan, in New Taipei City. The two different shipping routes are illustrated in Figure 6.4 and Figure 6.5, while the travelled distances are reported in Table 6.1.
The aim is to exploit the developed S-JELS model to support a Sustainable Supplier Selection procedure, in order to provide the DMs with the tools for selecting the best sourcing option for their company. The DM by iterating the solution process can obtain and compare different Pareto Frontiers, being able to consider trade-offs before taking a purchasing strategy decision by defining the supplier and the optimal lot sizing.

Figure 6.5 - Domestic Sourcing Route

Figure 6.4 – Far-east sourcing route

Table 6.1 – Distances of domestic and far-east sourcing routes

Sourcing	Truck [km]	Ship [km]	Total [km]
Domestic	709	0	709
Far-East	81	15090	15171

6.3.1 S-EOQ model numerical application

In this paragraph a numerical application of the S-EOQ model presented in 4.1 is developed, in order to compare the Efficient Frontiers of a Domestic and a Far East supply.

As indicated in paragraph 4.2 transportation costs are obtained from (Battini et al., 2014) and carbon footprint coefficients are calculated using the Ecoinvent database in SimaPro Software (www.simapro.co.uk). The cost and emission functions, described in Eq. (11 and (16, are computed considering the set of discontinuity points DP_i determined according to the different handling units adopted in the purchasing network (container 1: ISO 20 feet and container 2: ISO 40 feet).

All constant input parameters used for running the S-EOQ model are summarized in Table 6.2, while the variable input parameters are presented in Table 6.3. Table 6.4 lists all the dependent variables in the model, describing their relation to the input data. It can be noticed that the emission reduction by reaching the cap value ($\Delta E_{cap}\%$) has been introduced and it is fixed at 0.1 (that is 10%).

In the present numerical application, the Carbon Average Price *P* is fixed at 22 €/tCO2e, that is the EU ETS Carbon Price registered on October 10th, 2018 (www.markets.businessinsider.com/commodities/co2-emissionsrechte).

Table 6.2 - Constant Input data

Constant Input Data	Value	Constant Input Data	Value
D [leather boxes/year]	6,000	$c_{f,ship}$ *[€/km]*	0.48
O [€/order]	400	$c_{v,ship}$ *[€/km·m³]*	0.003
Inner volume container1 [m3]	33.2	c_{eh} *[kgCO₂e/m3·year]*	24
Load Capacity container1 [tons]	21.75	c_{eo} *[kgCO₂e/ton]*	77.004
Inner volume container2 [m3]	67.2	$c_{ef,\ road}$ *[kgCO₂e/km]*	2.20017
Load Capacity container2 [tons]	26.70	$c_{ev,\ road}$ *[kgCO2e/ton·km]*	0.154398
v_{road} *[km/year]*	525,600	$c_{ef,\ rail}$ *[kgCO₂e/km]*	1.28017
v_{rail} *[km/year]*	788,400	$c_{ev,\ rail}$ *[kgCO2e/ton·km]*	0.0392892
v_{ship} *[km/year]*	219,000	$c_{ef,\ ship}$ *[kgCO₂e/km]*	0.06443
$c_{f,road}$ *[€/km]*	0.8	$c_{ev,\ ship}$ *[kgCO2e/ton·km]*	0.0088875
$c_{v,road}$ *[€/km·m³]*	0.01	*a [kg/box]*	15
$c_{f,rail}$ *[€/km]*	0.6	ρ *[kg/m3]*	111.1
$c_{v,rail}$ *[€/km·m³]*	0.007	β *[%]*	30

Table 6.3 - Variable Input Data for the Domestic and the Far East sourcing

Variable Input Data	Domestic sourcing Value	Far East sourcing Value
p [€/box]	1,200	900
$\Delta E_{cap}\%$ *[%]*	10	10
P [€/tCO2e]	22	22
d [km on road]	709	81
d [km by train]	0	0
d [km by ship]	0	15090

Table 6.4 - Dependent Variables

Dependent Variables	Value
b [m3/box]	*a/(ρ* ·1000)
p' [€/box]	0.5·*p*
h [€/unit]	0.25·*p*
y_1[units/container1]	Min (Inner volume container1/*b*; Load Capacity container1/*a*)
y_2 [units/container2]	Min (Inner volume container2/*b*; Load Capacity container2/*a*)
CAP [tCO2e]	*E(Q'c*)*·(1-ΔE_{cap}*%)*

Figure 6.6 shows the trend of the Pareto Frontiers for the two different sourcing options.
At a first glance, we immediately notice that Taiwan frontier is located in the left lower part of the Cartesian plane, so it is dominant in costs but also in emissions. Analyzing the results it is evident that for both Cost optimal solution ***Q*c*** and Emission optimal solution ***Q*e,*** the supplier located in Taiwan is convenient on both total annual emissions and average annual costs (see Table 6.5).
For example, considering the Emission optimal solutions ***Q*e***, the Italian option produces average annual costs 30% higher and emits the 4% more of CO2e compared to the sourcing in Taiwan. The S-EOQ model outcome would be even more evident if we would compare for example a Romanian sourcing and a Far-East sourcing. In this case, the international sourcing would result even more sustainable because of the use of more sustainable transportation modes (ship instead of trucks).
These results are in line with the outcome of Lee at al. (2017). They indeed assert that, the more the consideration of external emission costs becomes strong in the replenishment decisions, the more their sustainable EOQ model favors the international sourcing strategy, which includes more sustainable transportation modes.
However, the outcome of this model is a shortsighted result, because it only considers the emissions generated for the purchasing and transportation activity by the buyer, it is not evaluated the total amount of emission generated by the two-echelon supply chain for the purchasing activity.

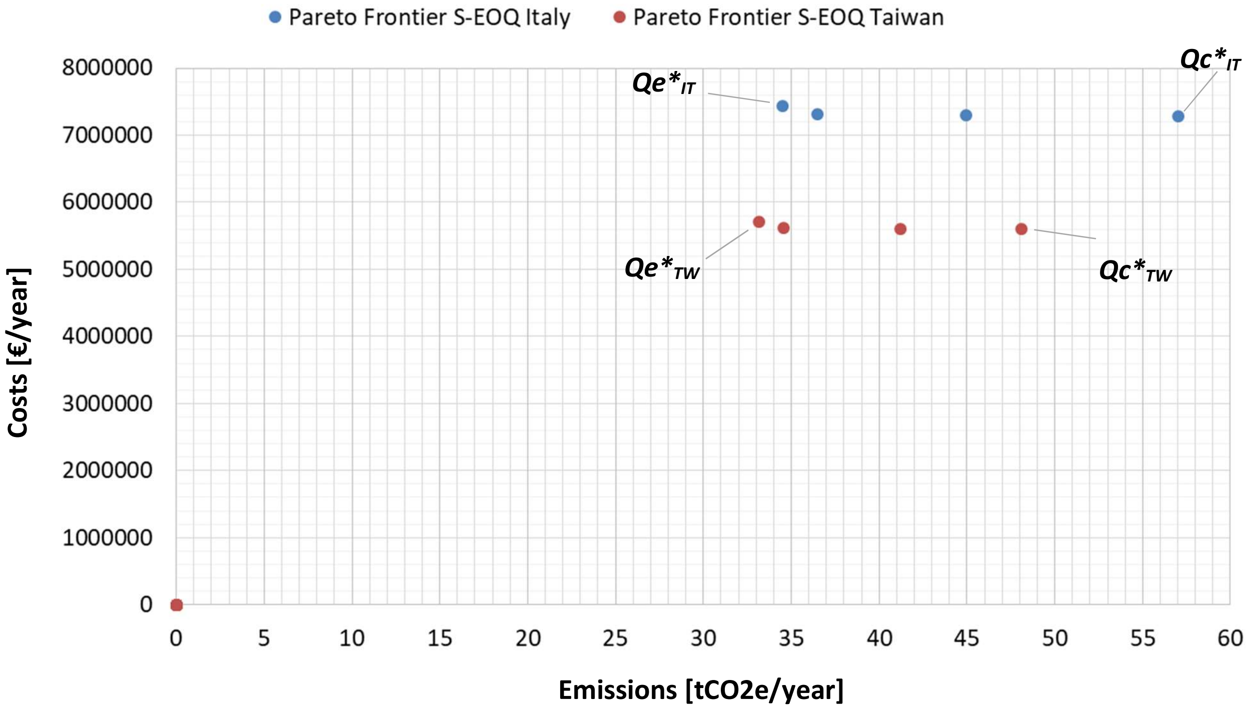


Figure 6.6 – S-EOQ Pareto Frontiers: Sourcing in Italy vs in Taiwan

Table 6.5 – S-EOQ Results Summary: Sourcing in Italy vs in Taiwan

		Italy	Taiwan	Δ IT vs TW	Δ% IT vs TW
Qe*	C(Q) – Costs [€/year]	€ 7,434,031	€ 5,705,519	€ 1,728,512	30%
	E(Q) - Emissions [tCO2e/year]	34.50	33.14	1.36	4%
	Q - Lot size [items/lot]	900	900	-	-
Qc*	C(Q) – Costs [€/year]	€ 7,285,312	€ 5,602,333	€ 1,682,980	30%
	E(Q) - Emissions [tCO2e/year]	57.01	48.07	8.94	19%
	Q - Lot size [items/lot]	200	200	-	-

6.3.2 S-JELS model mathematical formulation for a Leather Industry case study

The sustainable bi-objective joint economic lot size model introduced in 5.1 can be adapted to a Leather Industry case study. In the formulation bellow, the two objective functions: $f_1(Q)$ and $f_2(Q)$ will consider the costs and the emissions related not only to the buyer replenishment, but also to the related supplier activities. Moreover, as already mentioned, it applies the Cap and Trade regulations to the buyer emissions.

ADDITIONAL INPUT PARAMETERS:

D_n net annual demand [leather boxes/year]

η average annual waste rate from cutting [%]

δ disposal cost of leather waste [€/kg leather]

t carbon footprint for the finished leather production process [kgCO2e/m2]

r m2 of finished leather per unit stored in the warehouse [m2/leather box]

We can now introduce the objective function $f_1(Q)$ that quantifies the average annual cost for both buyer and supplier, generated during the annual activity related to the buyer replenishment. The Cap and Trade regulations are applied only to the buyer.
The formulation is expressed as follows:

$$f_1(Q) = C(Q) = C_{buy}(Q) + C_{sup}(Q) = [p \cdot D + C_o(Q) + C_{h,b}(Q) + C_{obs}(Q) + C_t(Q) + C_{def} + C_{C\&T,b}(Q)] + [C_{h,s}(Q) + C_s(Q)]$$

(63

At first, we can introduce the terms that generate the **buyer average annual cost** for the replenishment.

Ordering cost: $C_o(Q) = \frac{D}{Q} \cdot O$

(64

Buyer holding cost: $C_{h,b}(Q) = \frac{Q}{2}h_b + Q\left(\frac{d}{v}\right)\left(\frac{D}{Q}\right)h_b$

(65

Buyer cost related to obsolescence: $C_{obs}(Q) = \frac{Q}{2}(p - p') \cdot \beta$

(66

Transportation cost for each kind of transportation mode j used:

$$C_{t\,j}(Q, d_j, S_j) = \left(c_{f,j} \cdot d_j \cdot \sum_i n_i + c_{v,j} \cdot d_j \cdot DP_k\right) \cdot \frac{D}{Q}$$

(67

$C_{C\&T,b}$ represents the Buyer Emissions Trading Cost (or Revenue), resulted from buying or selling permits at the current carbon price P. By staying under the cap value, the buyer company will have the right to trade the rest of the allowances at the current carbon price. Conversely, if the annual emissions are higher than the cap value, it will be necessary to buy more permits from the market.

$$C_{C\&T,b}(Q) = P \cdot ({s_b}^- - {s_b}^+) = -\left[CAP_b - E_{buy}(Q)\right] \cdot P$$

(68

Since the largest quantity of finished leather waste is generated at the cutting phase, we need to calculate the buyer cost related to the average annual waste from cutting process. Leather cutting waste is what is left over after cutting away the desired shapes. These scraps are either too small to be used for anything else or contains damaged parts. A leather skin is never homogenous and rectangular, the quality of the leather at the side of the skin is generally poor and the shape of the pieces to be cut is scarcely the same. The waste from cutting process for leather can range in average 25 – 35% (14th Meeting of the UNIDO Leather Panel, 2000). The larger and more perfect the animal skin surface, the lower the leather cutting waste. η is the average annual waste rate from cutting, a represents the weight of a leather box, while δ represents the disposal cost of leather waste expressed in €/kg of leather.

$$C_{def} = D \cdot \eta \cdot a \cdot \delta$$

(69

Then we need to introduce the terms that express the **supplier average annual cost** for the buyer replenishment.

The holding cost for the vendor considers the traditional holding cost of carrying inventory in the warehouse as expressed by the following formula (Banerjee, 1988):

$$C_{h,s}(Q) = \frac{1}{2} h_s \cdot Q \cdot (\frac{d'}{i'})$$

(70

d' represents the buyer demand rate, while *i'* the supplier inventory (production) rate.

The vendor undertakes a production setup every time the buyer places an order. Therefore, given the supplier fixed setup cost per order K_{sc}, expressed in €/order, the Setup cost for the vendor can be expressed as (Banerjee, 1988):

$$C_S(Q) = \frac{D}{Q} \cdot K_{sc}$$

(71

Concluding, the first function to optimize is finally expressed as follows and it includes the costs (or revenues) related to the Cap and Trade regulatory policy in use.

$$f_1(Q) = C(Q) = C_{buy}(Q) + C_{\sup}(Q)$$

(72

$$C_{buy}(Q) = C'_{buy}(Q) + C_{C\&T,b}(Q)$$

(73

$$C_{buy}(Q) = p \cdot D + \frac{D}{Q} \cdot O + \frac{Q}{2} h_b + \left(\frac{d}{v}\right) D \cdot h_b + \frac{Q}{2}(p - p') \cdot \beta + D \cdot \eta \cdot a \cdot \delta + [\sum_j \left(c_{f,j} \cdot d_j \cdot \sum_i n_i + c_{v,j} \cdot d_j \cdot DP_k \right)] \cdot \frac{D}{Q} - [CAP_b - E_{buy}(Q)] \cdot P$$

(74

$$C_{\sup}(Q) = \frac{1}{2} h_s \cdot Q \cdot (\frac{d'}{i'}) + \frac{D}{Q} \cdot K_{sc}$$

(75

The second objective function $f_2(Q)$ is the average total quantity of emission generated during the annual purchasing activity by buyer and supplier. It can be expressed by the sum of the emissions generated by the supplier in the following steps:

- Warehousing;
- Setup of the order and Production.

And the emissions generated by the buyer in the next steps:

- Warehousing;
- Waste collection and treatment of the obsolete stock;
- Disposal of waste from defective finished leather and cutting process;
- Order transportation.

All these terms can be homogeneously expressed in tons of CO2e to calculate the average total quantity of emission.

$$f_2(Q) = E(Q) = E_{buy}(Q) + E_{sup}(Q)$$
$$= \left[E_{h,b}(Q) + E_{obs}(Q) + E_t(Q) + E_{def}\right] + [\, E_{h,s}(Q) + E_p]$$

(76

At first, we can introduce the terms that generate the **Buyer total quantity of emissions** due to replenishment in the time unit of a year.

Carbon emissions generated by warehousing $E_{h,b}(Q) = c_{ehb}\left(\frac{Q}{2} \cdot b\right)$

(77

Emissions related to obsolescence $E_{obs}(Q) = \frac{Q}{2} \cdot \beta \cdot a \cdot c_{eo}$

(78

The emission related to the average annual waste from defective finished leather and cutting process can be calculated as:

$$E_{def} = D \cdot \eta \cdot a \cdot c_{eo}$$

(79

In this formula, η is the average annual waste rate from cutting, a represents the weight of a leather box and c_{eo} is the waste collection and recycling emission coefficient, expressed in kgCO2e/ton.

Transportation emissions:

$$E_{t\,j}(Q, d_j, S_j) = \left(c_{ef,j} \cdot d_j \cdot \sum_i n_i + c_{ev,j} \cdot d_j \cdot DP_k \right) \cdot \frac{D}{Q}$$

(80

Then, we need to introduce the terms that express the **Supplier total quantity of emissions** generated during the time unit of one year for facing buyer replenishment.
The average quantity of equivalent carbon emissions generated by the supplier in one year for the warehousing can by calculated as:

$$E_{h,s}(Q) = \frac{1}{2} \cdot c_{eh\,s}(Q \cdot b)(\frac{d'}{i'})$$

(81

Where $c_{eh\,s}$ is the supplier warehouse emission coefficient expressed in kgCO2e/m^3, the parameter b measures the cube meters occupied by a product unit (leather box) with its packaging materials stored in the warehouse, *d'* represents the buyer demand rate and *i'* the supplier inventory rate.
The carbon footprint for producing finished bovine leather includes material and operations in a cradle to gate scenario of finished bovine leather. In particular, we consider in this formula the upstream process, which corresponds to the raw material extraction, and the core process, which corresponds to the finished leather manufacture (see Figure 6.7). The carbon footprint of the downstream process includes the emissions related to distribution and retailer (Chen et al., 2014; EPD DANI S.p.A., 2015). Therefore, this is not included in this formulation, since it is calculated through more specific formulas in the model. The carbon footprint for producing the finished bovine leather can by calculated through the Eq. below:

$$E_p = D \cdot r \cdot t$$

(82

The parameter *t* represents the carbon footprint generated during the finished leather production process and it includes the emissions generated for the order setup. It is expressed in kgCO2e/m2 of finished leather. The parameter *r* represents the m2 of finished leather contained into a leather box.

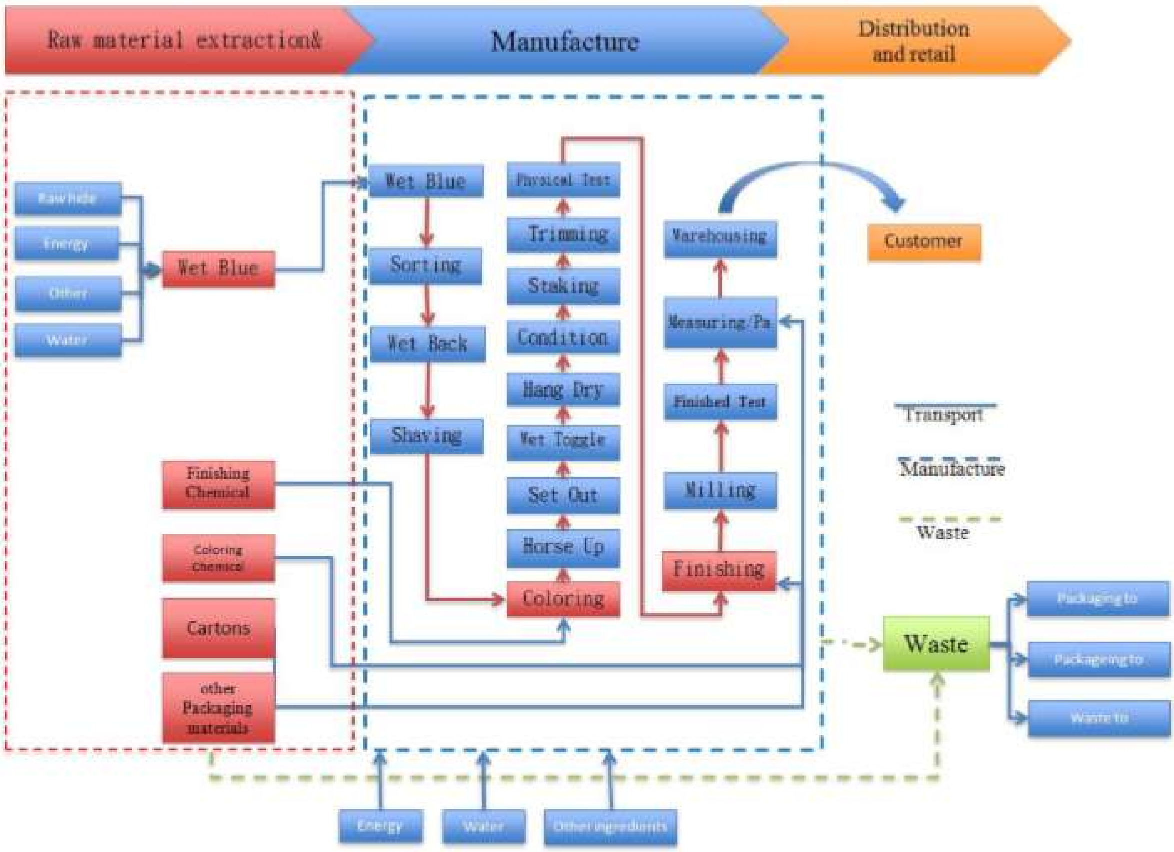


Figure 6.7 - Process map of the finished bovine leather (Chen et al., 2014)

Therefore, by considering the whole mix of transportation modes used in the product supply from vendor to buyer, the second objective function to optimize can be expressed as follows:

$$f_2(Q) = E(Q) = E_{buy}(Q) + E_{\sup}(Q)$$

(83

$$E_{buy}(Q) = c_{eh\,b}\left(\frac{Q}{2}\cdot b\right) + \frac{Q}{2}\cdot\beta\cdot a\cdot c_{eo} + D\cdot\eta\cdot a\cdot c_{eo} + \left[\sum_j\left(c_{ef,j}\cdot d_j\cdot\sum_i n_i + c_{ev,j}\cdot d_j\cdot DP_k\right)\right]\cdot\frac{D}{Q}$$

(84

$$E_{sup}(Q) = \frac{1}{2} \cdot c_{eh\,s}(Q \cdot b)\left(\frac{d'}{i'}\right) + D \cdot r \cdot t$$

(85

According to a generic Pareto design optimization problem (Pareto 1964, 1971), involving the two conflicting objective functions introduced above, it can be concisely stated:

$$Minimize\ \{f_1(Q), f_2(Q)\ \}$$

(86

A Pareto-optimal solution is also defined "Pareto-efficient solution", and the set of all the efficient points is called the Pareto Frontier. Generally, it is not possible to express with an analytical expression the Pareto Frontier; however, it is possible to assert that:

"Q is a Pareto-optimal solution to the problem set by Eq. (72) and Eq. (83), if there does not exist any other design Q such that* $f_1(Q) \leq f_1(Q^*)$ *and* $f_2(Q) \leq f_2(Q^*)$ *simultaneously."*

The number of Pareto-efficient solutions Q* can be wide, for this reason it is necessary to select the best compromise design(s) among them. In the sustainable lot sizing problem here proposed, a sustainable purchasing choice normally increases $f_1(Q)$, while decreases $f_2(Q)$, since the two objective functions are competitive in nature.

If *Q*c* is the single optimal solution of the objective function $f_1(Q)$ and *Q*e* is the single optimal solution of $f_2(Q)$, *EF* can be defined as the Efficient Frontier of the sustainable lot sizing problem here proposed and EF^c its image in the criterion space, then:

$$EF = [Q_c^*, Q_e^*]$$

(87

EF_+^c is convex and there exists $Q_{min} < Q_{max}$ such that $Q^* \in [Q_{min}, Q_{max}]$.

As a consequence, the shape of the EF strongly affects the possibility to move from a cost-optimal solution to an emission-optimal one.

6.3.3 S-JELS model numerical application and discussion

Now a numerical application of the S-JELS model presented in the previous paragraph is developed. The objective is to compare the Efficient Frontiers of the Domestic and Far East finished leather sourcing options presented at the beginning of 6.3; considering the average annual cost and the annual emissions related not only to the buyer replenishment, but also to the supplier activities. Moreover, the Cap and Trade regulation is applied to the buyer emissions.

As already explained, the case study considered regards the Finished Leather industry, and all the information and data are taken from the literature or inspired by experiential knowledge of the industrial sector. The buyer company is assumed located in Vicenza, in the north-east of Italy and could purchase material through a domestic sourcing, or a Far East sourcing.

The finished leather is transported rolled up into boxes with the following dimensions: 150 cm width, 30 cm height and 30 cm depth. We consider that a box of this dimension can transport in average 15 m^2 of finished leather.

As in 6.3.1 it is considered a domestic supplier located in the province of Naples, while the international supplier is located in Taiwan, in New Taipei City. The two different shipping routes are illustrated in Figure 6.4 and Figure 6.5, while the travelled distances are reported in Table 6.1.

As indicated in paragraph 4.2, transportation costs are obtained from (Battini et al., 2014) and carbon footprint coefficients are calculated using the Ecoinvent database in SimaPro Software (www.simapro.co.uk). The cost and emission functions, described in previous paragraph formulas, are computed considering the set of discontinuity points DP_i determined according to the different handling units adopted in the purchasing network (container 1: ISO 20 feet and container 2: ISO 40 feet).

Let us consider some hypothesis and suggestions:

- HP1 – the Buyer's emissions are subject to Cap and Trade regulation.
- HP2 – It is considered a buyer demand rate d' equal to the supplier inventory (production) rate i'.
- HP3 – In the present numerical application the Carbon Average Price *P* is fixed at 22 €/tCO2e, that is the EU ETS Carbon Price registered on October 10^{th}, 2018 (www.markets.businessinsider.com/commodities/co2-emissionsrechte).

- HP4 – the buyer generates emissions during the following steps:
    - Warehousing;
    - Waste collection and treatment of the obsolete stock;
    - Disposal of waste from defective finished leather and cutting process;
    - Order transportation.
- HP5 – the finished leather produced by the two alternative suppliers (one in Italy and the other in Taiwan) have different quality standard, so different average annual waste rate from cutting process.
- HP6 – The purchasing annual demand D is subject to the average annual waste rate from cutting process η. Therefore, to higher waste rate corresponds and higher annual demand D.
- HP7 – the two alternative suppliers have different production processes and technologies, therefore the carbon footprint generated during the finished leather production process is different (Chen et al., 2014; EPD DANI S.p.A., 2015).

All constant input parameters used for running the S-JELS model are summarized in Table 6.6, while the variable input parameters are presented in Table 6.7. Table 6.8 lists all the dependent variables in the model, describing their relation to the input data.

Table 6.6 - Constant Input data

Constant Input Data	**Value**
D_n *[leather boxes/year]*	4,800
O [€/order]	400
Inner volume container1 [m3]	33.2
Load Capacity container1 [tons]	21.75
Inner volume container2 [m3]	67.2
Load Capacity container2 [tons]	26.70
v_{road} *[km/year]*	525,600
v_{rail} *[km/year]*	788,400
v_{ship} *[km/year]*	219,000
$c_{f,road}$ *[€/km]*	0.8
$c_{v,road}$ *[€/km·m³]*	0.01
$c_{f,rail}$ *[€/km]*	0.6

Constant Input Data	**Value**
$c_{eh\ b}$ *[kgCO₂e/ m3·year]*	24
$c_{eh\ s}$ *[kgCO₂e/ m3·year]*	24
c_{eo} *[kgCO₂e/ ton]*	77.004
$c_{ef,\ road}$ *[kgCO₂e/km]*	2.20017
$c_{ev,\ road}$ *[kgCO2e/ton·km]*	0.154398
$c_{ef,\ rail}$ *[kgCO₂e/km]*	1.28017
$c_{ev,\ rail}$ *[kgCO2e/ton·km]*	0.0392892
$c_{ef,\ ship}$ *[kgCO₂e/km]*	0.06443
$c_{ev,\ ship}$ *[kgCO2e/ton·km]*	0.0088875
a [kg/box]	15
ρ *[kg/m3]*	111.1
β *[%]*	30

$c_{v,rail}$ *[€/km·m^3]*	0.007		K_{sc} *[€/setup] (Banerjee, 1988)*	400
$c_{f,ship}$ *[€/km]*	0.48		*δ [€/kg leather]*	0.21
$c_{v,ship}$ *[€/km·m^3]*	0.003		*r [m^2 of leather/box]*	15

Table 6.7 - Variable Input Data for the Domestic and the Far East sourcing

Variable Input Data	**Domestic sourcing Value**	**Far East sourcing Value**
p [€/box]	1,200	900
$\Delta E_{cap\ b}\%$ *[%]*	10	10
P [€/tCO2e]	22 (Carbon Price value on October 10th, 2018)	22 (Carbon Price value on October 10th, 2018)
d [km on road]	709	81
d [km by train]	0	0
d [km by ship]	0	15090
η [%]	25	35
t [kgCO2e/m^2 of leather]	43.06	73

Table 6.8 - Dependent Variables

Dependent Variables	**Value**
D *[leather boxes]*	$D_n \cdot (1+\eta)$
b [m3/box]	$a/(\rho \cdot 1000)$
p' [€/box]	0.5·*p*
h_b *[€/unit]*	0.25·*p*
h_s *[€/unit]*	0.25·(*p/2)*
y_1*[units/container1]*	Min (Inner volume container1/*b*; Load Capacity container1/*a*)
y_2 *[units/container2]*	Min (Inner volume container2/*b*; Load Capacity container2/*a*)
CAP_b *[tCO2e]*	$E(Q'_c{}^*{}_{buy})\cdot(1-\Delta E_{cap\ b}\%)$

Figure 6.8 shows the trend of the Pareto Frontiers for the two different sourcing options. At a first glance, we immediately notice that Taiwan frontier is located in the right lower part of the Cartesian plane, so it is dominant in costs but not in emissions. Analyzing the results,

it is evident that for both Cost optimal solution ***Q*c*** and Emission optimal solution ***Q*e,*** the supplier located in Taiwan is convenient on the average annual costs, but not on the annual total emissions (see Table 6.9).

For example, considering the Emission optimal solutions ***Q*e***, the Italian option produces average annual costs 20.9% higher, but emits the 45.16% less of CO2e compared to the sourcing in Taiwan. So these results, in contrast with the one illustrated in 6.3.1, demonstrate that, considering both buyer's and supplier's average annual cost and total quantity of emissions generated during the annual activity related to the buyer replenishment, the international sourcing option cannot be considered the most sustainable. Therefore, the paradox "far International suppliers are more sustainable than the Domestic closer ones" is no longer verified. As illustrated in 6.3.1, the International sourcing option results more sustainable if the emissions related to the supplier's production activities are not taken into account. Only under these conditions, International suppliers that do not have to observe certain strict production process regulations, result more sustainable, even if more far. In these far sourcing options more sustainable transportation modes are indeed involved.

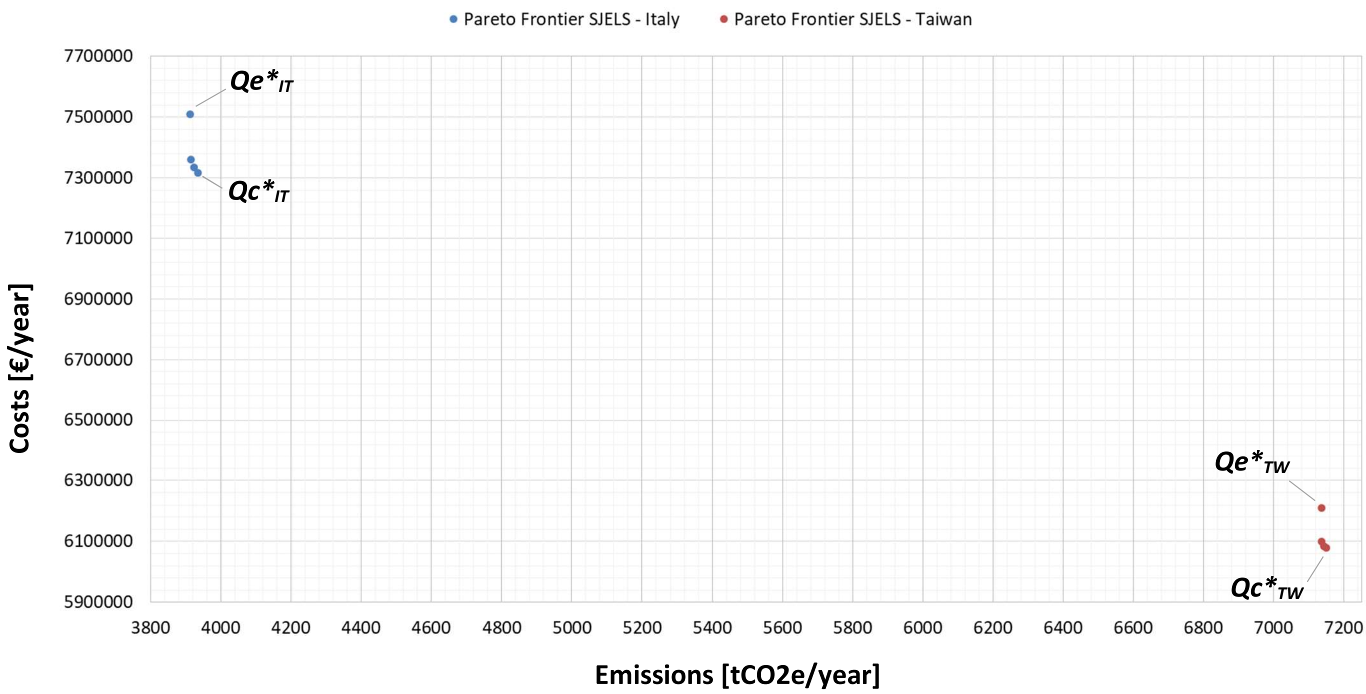


Figure 6.8 - S-JELS Pareto Frontiers: Sourcing in Italy vs in Taiwan

Table 6.9 – S-JELS Results Summary: Sourcing in Italy vs in Taiwan

		ITALY	TAIWAN	Δ IT vs TW	Δ% IT vs TW
Qe*	**C(Q) – Costs [€/year]**	€ 7,508,926	€ 6,209,653	€ 1,299,273	20.92%
	E(Q) - Emissions [tCO2e/year]	3,913.09	7,135.34	-3,222.25	-45.16%
	Q - Lot size [items/lot]	900	900	-	-
Qc*	**C(Q) – Costs [€/year]**	€ 7,317,041	€ 6,078,999	€ 1,238,042	20.37%
	E(Q) - Emissions [tCO2e/year]	3,934.46	7,150.43	-3,215.97	-44.98%
	Q - Lot size [items/lot]	200	200	-	-

6.3.4 S-JELS model to Support a Sustainable Supplier Selection in a Leather Industry case study

As explained in 6.2, the S-JELS model presented can be integrated into a procedure for Sustainable Supplier Selection.
Indeed, the S-JELS model results obtained in paragraph 6.3.3 can be exploited as numerical KPIs and user-friendly graphs, useful for evaluating the costs and emissions criteria for each sourcing option.
In order to identify the effective best supplier between the Italian and the Taiwanese sourcing, the steps illustrated in 6.2 have been followed.

1. The two potential suppliers are identified, one is a Domestic sourcing, located in the province of Naples, while the other is an International supplier located in Taiwan, in New Taipei City.

2. The relevant criteria for the supplier selection are identified by the company DMs: C1 represents the cost criterion, C2 the environmental criterion and C3 the supplier reliability criterion.

3. and 4. C(Q*e) and E(Q*e) are defined as KPIs for C1 (Total annual costs) and C2 (Total annual emissions) respectively, while C3 criterion is provided with other quantitative and qualitative KPIs.

5. It is identified a tool for making decisions using AHP methodology, and four decision makers, by using pairwise comparisons, determine the relative importance of the criteria and calculate their weights.

6. 7. and 8. The S-JELS model is run for each sourcing option in order to build the Pareto Frontiers for each supplier and calculate the emission optimal solution Q*e for both the Domestic sourcing and the Far East sourcing (see Figure 6.9).

9. The Total annual cost C(Q*e) and Total annual emissions E(Q*e) correspondent to the optimal emission lot size Q*e are calculated.

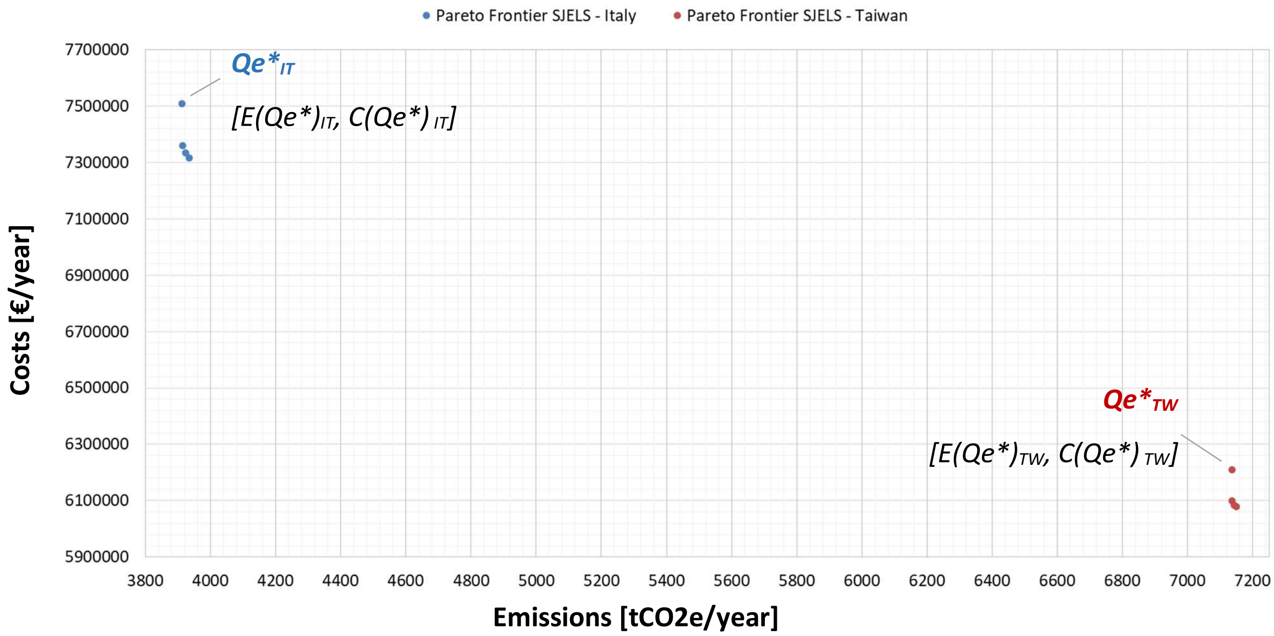


Figure 6.9 - S-JELS Pareto Frontiers: KPIs for domestic and Far East sourcing

10. The Decision Makers analyze quantitative and qualitative KPIs data for each supplier: in particular C(Q*e) and E(Q*e) are defined as KPIs for C1 (costs) and C2 (emissions), together with the comparison of the Pareto Frontier graphs of the alternative suppliers. The Supplier reliability (C3 criterion) is evaluated by DMs through other quantitative and qualitative KPIs outside the proposed S-JELS model.

11. After the KPIs analysis, the DMs evaluate each supplier according to the selected criteria (see Figure 6.10).

12. The AHP tool calculates the final scores of the suppliers, creating the Suppliers' final ranking (see Figure 6.11).

13. As shown in Figure 6.11, the Domestic supplier has the best final score; therefore, it is the best sourcing option considering the criteria selected and the weight applied by the Decision Makers.

Result

	Total annual costs 0.28	Total annual emissions 0.17	Supplier reliability 0.55	RESULT
S1 - Italian Supplier	0.2	0.86	0.83	**0.66**
S2 - Taiwanese Supplier	0.8	0.14	0.17	**0.34**

	Total annual costs 0.63	Total annual emissions 0.11	Supplier reliability 0.26	RESULT
S1 - Italian Supplier	0.2	0.89	0.89	**0.45**
S2 - Taiwanese Supplier	0.8	0.11	0.11	**0.55**

	Total annual costs 0.29	Total annual emissions 0.14	Supplier reliability 0.57	RESULT
S1 - Italian Supplier	0.14	0.86	0.83	**0.64**
S2 - Taiwanese Supplier	0.86	0.14	0.17	**0.36**

	Total annual costs 0.21	Total annual emissions 0.07	Supplier reliability 0.72	RESULT
S1 - Italian Supplier	0.13	0.89	0.89	**0.73**
S2 - Taiwanese Supplier	0.87	0.11	0.11	**0.27**

Figure 6.10 - DMs suppliers' evaluation matrix

	Result
S1 - Italian Supplier	0.62
S2 - Taiwanese Supplier	0.38

Figure 6.11 - Suppliers' final ranking

In light of the outcome obtained running the S-JELS model, the company DMs have exploited the results as numerical KPIs and user-friendly graphs for evaluating two of the

three selection criteria of the AHP procedure (Total annual costs and Total annual emissions) for each potential supplier in an easier, faster, more analytical and correct way.
At the end, the result of the Sustainable Supplier Selection procedure points out the Domestic sourcing as the best sourcing option considering the selected criteria, the weight applied by the Decision Makers and the DMs final evaluation of the sourcing options according to the selected criteria.

7 CONCLUSIONS

As discussed in this research work, it is clear that global warming poses a grave threat to the world's ecological system and the human race, and it is very likely caused by increasing concentrations of carbon emissions, which mainly results from such human activities as fossil fuel burning and deforestation (IPCC, 2007).

Mr. Peter Thompson, President of the UN General Assembly, during the COP22 (Conference of the Parties), required the transformation of the global economy in order to achieve a resilient and low emissions global economy (www.unfccc.int).

Global measures are actually needed in order to avoid irreversible and catastrophic changes, involving many countries with a common objective. A cooperative solution has indeed to be reached; otherwise without an effective global climate agreement no result will be accomplished (Stavins, 2008). As illustrated in the present work, many countries have introduced policies and mechanisms to contain the total amount of greenhouse gas emissions, but it is still missing an effective global cooperative solution. Some countries still consider the efforts to mitigate global warming as obstacles to striving for economic growth. However, without a comprehensive engagement, some actors are advantaged and more competitive in the global economy. Some others, involved in emission saving policies, have to face stronger investments and restrictions, with the risk of suffering economic disadvantages and becoming therefore less competitive in the global economy.

As declared by the European Parliament resolution on the 2017 UN Climate Change Conference in Bonn, the efforts to avoid global warming should not be seen as an obstacle to economic growth but should, differently, be seen as a driving force for developing new and sustainable growth and employment: a valid climate mitigation policy can produce growth and jobs. However, giving that some specific sectors with a high carbon intensity and high trade intensity could suffer from carbon leakage, a suitable protection against carbon leakage is therefore needed to protect jobs in these specific sectors.

Since the emissions released by companies' operational activities into the air are one of the main causes of global climate change (He et al. 2015), businesses are becoming increasingly conscious of their carbon footprint and have begun to incorporate environmental thinking into their business strategy and supply chain management, making efforts to be more environmentally friendly.

Therefore, it is clear that there is an increasing trend among firms to set up more environmental friendly manufacturing systems introducing new technologies, optimizing their production and inventory decisions by integrating environmental factors that can help on reducing GHG emissions (Kazemi et al. 2016). As stated by (Miemczyk et al., 2012), Sustainable Purchasing means considering social, environmental and financial factors in taking goods procurement decisions. Many managers are now looking beyond the traditional economic parameters and are starting to take decisions based on the whole life cost, the associated risks, measures of success and impacts on society and environment.
Following this research field, the main objective of this research work was to develop multi-objective lot sizing models together with useful tools and graphs for supporting managers in making sustainable purchasing decisions and assessing a Sustainable Supplier Selection.
This comprehensive aim has been fulfilled, as illustrated in the next paragraph, where the three Research Questions results and insights are reported.

7.1 Research Questions results and insights

1st Research Question

Support companies in making sustainable and efficient purchasing decisions through a multi-objective Sustainable Economic Order Quantity (S-EOQ) Model.

In Chapter 4 it is presented a multi-objective optimization approach (Pareto, 1964) in which the optimal lot-sizing decision depends on a bi-objective model with two different objective functions (costs and emissions) and transportation capacity constraints.
The bi-objective S-EOQ model introduced is born as a conceptual evolution of the sustainable EOQ model by Battini et al. (2014) and tries to capture economic and environmental trade-offs in material purchasing lot sizing under a Cap and Trade policy, in order to help managers driving companies towards sustainable and efficient purchasing decisions.
The model is useful in practice to support managers in understanding the Pareto frontier shape linked to a specific purchasing problem, defining the cost-optimal and emission-

optimal solutions and identifying a sustainable quantity to purchase when a Cap and Trade mitigation policy is present.

Total purchasing costs and total CO_2 equivalent emissions are taken into account to build the Pareto Frontier as a tool to support managers' decision making in an interactive way. The model is applied to a simple set of numerical scenarios, where a number of input data are fixed and inspired to a real case, while other product features (weight and product purchase price) assume various values.

Moreover, it is introduced the parameter φ in order to better support managers in understanding the economical convenience in reducing carbon emissions by taking a sustainable purchasing choice. The parameter is the rate between the marginal increment in total annual costs, the Marginal Logistic Cost (MLC), and the market carbon price P, that represents the allowance that helps the company to fit and go under the defined carbon limit (the carbon cap). Only with $\varphi<1$, the company will be economically motivated to reduce emissions by consolidating transportations and increasing purchasing lot size, otherwise, until the φ parameter will be higher than 1, the company will need to autonomously sustain an extra cost in order to reduce its emissions under the cap value.

The sensitivity analysis and the graphical results provided in Chapter 4 permit to summarize the following main conclusions:

a. By a practical point of view, the analysis of the Pareto frontier is useful to address managers towards the correct comprehension of the sustainable purchasing problem, by identifying the cost-optimal and the emission-optimal solutions, while having an immediate comprehensive visualisation of Pareto frontier shape.
b. The purchasing manager can then be driven to decide the material purchasing quantity to order when a Cap and Trade mitigation policy is present, with an immediate comprehension of the effects of his/her choice in terms of emissions and costs.
c. The Carbon Trading system currently applied by Governments in order to mitigate the emission production in some critical sectors, is a promising tool to be applied also in the field of freight transportation and material purchasing when ship/train/road transportation modes are considered.
d. Assuming a constant apparent density of products, the company investment required for the emission reduction in order to respect the cap increases with the product purchasing price, as well as the product weight.
e. This research work demonstrates that today's carbon prices (i.e. 22 €/tCO2e in October 2018 in the EU ETS trading system) are still too low to sustain and economically

motivate a feasible extension of the Cap and Trade policy to the freight transportation sector and to the sustainable purchasing problem under analysis. By considering the current carbon price of 22 €/tCO2e (October 10th, 2018), there is still a gap of 78% in order to reach a φ value equal to 1.

f. The current positive trend in worldwide carbon price values is quite encouraging: if the carbon price will reach in the near future the threshold of 100 €/tCO2e, the Cap and Trade mechanism will start acting as an economic incentive for company managers and buyers towards more sustainable purchasing choices.

2nd Research Question

Support managers in making sustainable and efficient purchasing and logistics decisions into a supply-chain context, through a multi-objective Sustainable Joint Economic Lot Size (S-JELS) Model.

In Chapter 5 of this research work, new innovative multi-objective Sustainable Joint Economic Lot Size Models (S-JELS) under a Cap and Trade policy have been developed (applying the Cap and Trade regulation only to the buyer or on both buyer and supplier), in order to consider costs and emissions related to a two-echelon supply chain, not only to the buyer.

By considering two different objective functions (costs and emissions), both economic and sustainable issues are equally considered and integrated in the contest of a supply chain.

The S-JELS model is useful in practice to support managers in understanding the Pareto Frontier shape linked to a specific supply chain purchasing problem, defining the cost-optimal and emission-optimal solutions and identifying a sustainable quantity to purchase when a Cap and Trade mitigation policy is present. In this way, the model leads the Decision Makers to more sustainable and efficient logistic and purchasing solutions, considering a supply chain point of view.

With the purpose of helping companies analyzing the trade-offs among different supplies, the S-JELS model can be run iteratively for many sourcing options, in order to build the Pareto Frontiers for each supplier and compare then the Frontier shapes, the cost-optimal solutions and the emission-optimal ones. In this way, the model can be useful to evaluate which sourcing option is the most sustainable, efficient or economical.

With this aim, the bi-objective S-EOQ model (introduced in Chapter 4) and the bi-objective S-JELS model have been applied to a leather industry case study, where two different sourcing options need to be compared, respectively a Domestic and an International sourcing, in order to help a company on analyzing the trade-offs.

The numerical and graphical results provided in Chapter 6 permit to summarize the following main conclusions and managerial insights:

a. By running the bi-objective S-EOQ model, the outcome is that the International sourcing Pareto Frontier is dominant in costs and in emissions. Therefore, the International supplier results both more economical and sustainable, compared to the Domestic one. These results are in line with the outcome of Lee at al. (2017).
b. By running the bi-objective S-JELS model for the same case study, the International sourcing Pareto Frontier is dominant in costs but not in emissions. Therefore, the International supplier results more economical, but not more sustainable.
c. The outcome obtained running the S-JELS model is in contrast with the one yielded by the S-EOQ model and demonstrates that, considering both buyer’s and supplier’s average annual costs and total quantity of emissions generated during the annual activity related to the buyer replenishment, the International supplier cannot be considered the most sustainable.
d. Therefore, the outcome of the bi-objective S-EOQ model is a shortsighted result, because it only considers the emissions generated for the purchasing and transportation activity by the buyer, it is not evaluated the total amount of emissions generated by the two-echelon supply chain for the purchasing activity.
e. The paradox "far International suppliers are more sustainable than the Domestic closer ones" is no longer verified. International sourcing options result more sustainable if the emissions related to the supplier's production activities and plants management are not taken into account. Only under these conditions, International sourcing options that do not have to observe certain strict production process regulations, result more sustainable, even if more far. In these far sourcing options, more sustainable transportation modes are indeed involved.

3rd Research Question

Support managers in Sustainable Supplier Selection procedures with numerical KPIs and user-friendly graphs.

In Chapter 6, the S-JELS model presented has been integrated into a procedure for assessing the Sustainable Supplier Selection among several sourcing options, providing the following conclusions and managerial insights:

a. The developed S-JELS model has been exploited in order to provide a company Decision Makers with the tools for selecting the best sourcing option. The DMs by iterating the solution process can obtain and compare the Pareto Frontiers of the different sourcing options.

b. In light of the outcomes obtained running the S-JELS model, the company DMs can exploit the results as numerical KPIs and user-friendly graphs for evaluating the selection criteria of the Sustainable Supplier Selection procedure for each potential supplier.

   Specifically, in paragraph 6.2 it is proposed an AHP selection procedure, where the numerical results obtained running the S-JELS model, together with the comparison of the Pareto Frontier graphs of the alternative suppliers, are identified as quantitative KPIs to be used for evaluating two out of three selection criteria, the Total annual costs and the Total annual emissions.

c. In this way, the Decision Makers are helped on analysing the trade-offs among different supplies and on evaluating the selection criteria for each potential supplier in an easier, faster, more analytical and correct manner.

   Thanks to these KPIs and user-friendly graphs, The DMs are supported in making the more efficient and sustainable supplier selection being able to consider trade-offs before taking a purchasing strategy decision, choosing then the best supplier and the optimal lot sizing. Moreover, by exploiting the results of the S-JELS model, they keep a supply chain point of view, considering also the presence of a Cap and Trade mitigation policy.

d. In Paragraph 6.3.4 the S-JELS model integrated in the Sustainable Supplier Selection procedure has been applied to a leather industry case study with the objective of supporting managers during a supplier selection between a Domestic and a Far East sourcing. The already described KPIs and user-friendly graphs have been exploited as useful and effective tools for evaluating the selection criteria for each potential supplier.

They can indeed support managers on analysing the trade-offs between the two supply options and help on identifying the more efficient and sustainable supplier.

In this particular case study, the result of the Sustainable Supplier Selection procedure points out the Domestic sourcing as the best sourcing option considering the chosen selection criteria, the weights applied by the Decision Makers and the DMs final evaluation of the sourcing options according to the criteria.

7.2 Improvements and Future Research

In conclusions, some recommendations must be done: first of all, the bi-objective S-JELS model presented has only been applied to a specific numeric case study. To improve the research, it could be applied to other industrial sectors and contexts, developing also a sensitivity analysis of the Pareto Frontiers according to variations in the purchased products' characteristics.

Moreover, it could be interesting to properly consider in the S-JELS model the costs and emissions related to reverse logistics activities on defective and obsolete items.

Since, Sustainable Purchasing means considering social, environmental and financial factors in taking goods procurement decisions (Miemczyk et al., 2012), this multi-objective S-JELS model could be improved taking into account the social impacts related to transportation, for instance the impact of transportation on traffic and driveability.

Moreover, it could be interesting to integrate the social impacts related to opt for International sourcing options, instead of the Domestic ones; producing a negative effect on the European suppliers' production and sales volume.

At the moment, the S-JELS model only takes into account the impact of GHG emissions; the GHG pollution has indeed a negative effect not only on the environment, but also on the human race health.

Furthermore, future research in this field should extend this work, enhancing the S-JELS model: the scope of the supply chain could be expanded beyond two stages to a supply chain network of multiple buyers and suppliers.

In the end, the presented Sustainable Supplier Selection procedure could be enhanced, by introducing for instance more than three selection criteria in the AHP selection process. Moreover, the Analytic Hierarchy Process method, with its weaknesses, can be overcome by applying the outranking multi-criteria decision-making (MCDM) methods and taking inspirations from the recent literature progress. For example, an interesting hybrid method is introduced by Govindan K. et al. (2018) for the selection of a sustainable third-party reverse logistics provider. Also, Govindan K. et al. (2017) studied the evaluation and selection of the green supplier considering several tangible and intangible criteria. They introduced a hybrid approach that combines the revised Simos procedure, PROMETHEE methods, algorithms for constructing a group compromise ranking, and robustness analysis. Furthermore, in order to balance the unexpected turbulence in Supply Chain, Costa et al. (2018) integrated resilience issues into the classification of suppliers, contributing to the decision process of Supplier Selection. The suggested ELECTRE TRI-nC method leads to robust conclusions with respect to the classification of suppliers, considering risk and resilience criteria rather than solely traditional criteria.

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10 PAPERS COLLECTION

"Sustainable purchasing and transportation in a global supply chain scenario under a Cap and Trade system" submitted to the 19th International Working Seminar on Production Economics, February 22-26, 2016, Innsbruck, Austria

Sustainable purchasing and transportation in a global supply chain scenario under a Cap and Trade system

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Abstract

Material purchasing decisions are strongly affected by material handling equipment, transportation path flows, modes of transportation, vehicle routing, vehicle capacities and related technical constraints. Within a global sourcing context, companies experience that the cost of transportation is a significant part of total purchasing cost. More recently, sustainability and environmental impact assessment have become key requirements for materials purchasing and transportation decisions. Global warming is a rising concern both in academia and industrial researches, and now it is well known that the freight transport industry is responsible for large amounts of carbon emissions contributing to global warming. In this paper, we initially analyse and compare the environmental economic policies established by the International Governments in relation to the carbon trading systems adopted. Then, we develop a multi-objective lot sizing approach useful in practice to define the sustainable quantity to purchase when a long distance transportation is required and a Cap and Trade system is present. We further analyze the model behavior according to variations in product size and weight, purchasing price and different carbon price values. Most of the results presented here are part of the **REINVEST** research project, which is financed by the European Union Europe-Aid funding scheme.

Keywords: multi-objective optimization, sustainability, transportation, purchasing strategy, lot sizing, Cap and Trade

1. Introduction

The international increasing concern on environmental problems stresses the need to treat inventory management and material purchasing decisions by integrating economic and environmental objectives. In particular, the present work is the conceptual evolution of the previous (Battini et al. 2014) in which the authors provided a "sustainable EOQ model" that from an economic point of view incorporates the environmental impact of transportation and inventory holding in the total cost function. Here, as a second step of the research, the authors investigate the material purchasing strategy by applying a multi-objective optimization approach (Pareto 1964) in which the optimal lot-sizing decision depends on a bi-objective model with two different objective functions (costs and

emissions) and transportation capacity constraints. A Cap and Trade system approach is integrated in the model in order to understand if it could be successful to incentive the reduction of emissions in material purchasing and transportation decisions. The Trading system used here is inspired to the current EU ETS system (www.ec.europa.eu) and on the carbon cap evolution forecasted in the medium term. An increasing number of works have been published in the last years with the aim of incorporating sustainability issue in the traditional Inventory Management and Lot Sizing theory. In particular, there are some recent studies closely related to our work, that couple the EOQ theory with the cap and trade mechanism. The EOQ model is integrated with a cap and trade system by Arslan et al. (2013): here the authors analyse different environmental policies like carbon tax, direct cap, carbon offsets and cap and trade, taking into account a single item and a single location. Hua et al. (2011) extend the EOQ model to take carbon emissions into account under the cap and trade system. Analytical and numerical results are presented and managerial insights are derived. In Chen et al. (2013) is discussed what are the factors that affect the cost increase and the reduction of emissions in a EOQ considering a cap and price system (price are not decided in a market mechanism) considering what changes can be made without increasing costs. Benjaafar et al. (2013) incorporate carbon emission constraints on single and multi-stage lot-sizing models with a cost minimization objective. Four regulatory policy settings are considered, based respectively on a strict carbon cap, a tax on the amount of emissions, the cap-and-trade system and the possibility to invest in carbon offsets to mitigate carbon caps. Insights are derived from an extensive numerical study. In the recent research agenda proposed by Andriolo et al. (2014), the authors discuss the significance of transportation cost modelling and emissions computation in order to develop a fully sustainable lot sizing approach.
Thus, the present work, focusing on a multi-objective optimization of the purchasing material lot size under a cap and trade regulation, is complementary to the existing literature: it aims to better reflect real cost and emission functions arising when a company needs to purchase materials in a global supply chain environment.

2. Cap and Trade System and EU carbon price value trend

Cap-and-Trade is already the policy instrument of many EU, US States and New Zealand. Keohane (2009) argues that C&T has a number of important advantages compared to carbon tax, such as political feasibility, cost effectiveness, broad participation, equity in the international context, and control on the cumulative quantity of emissions. The International Emissions Trading Association (IETA, www.ieta.org) describes some of the emissions trading advantages:
Cap-and-trade is designed to fulfil an environmental outcome, in that the cap must be met.
This trading scheme will deliver its environmental objective at lowest cost to the economy.
It can be fundamental for setting a global agreement to reduce emissions: national trading systems can be linked with other similar systems, driving to a global carbon market.
C&T offers to business both compliance and policy flexibility, it delivers an incentive to the companies able to innovate and find more effective ways of reducing emissions.
Cap-and-trade has proven effectiveness: for example in the US acid rain program it quickly reduced pollution levels at lower cost than expected.
The Emission Trading System is a cost-effective way of the European Union's policy to combat climate change and to reduce industrial greenhouse gas emissions (GHG). It has been launched in 2005 and it works on the ”cap and trade” principle (Jaber et al, 2013): a cap is set on the total amount of certain GHG that can be emitted by factories, power plants and other installations. The cap is reduced over time, in this way the total emissions fall. The target for 2020 is a reduction of 20% of GHG emissions compared to 1990 levels. The EU ETS regards in particular power plants, a wide range of energy-intensive industry sectors and operators of flights to and from the EU, Iceland, Liechtenstein and Norway. The companies involved into this system sell or buy emission allowances which they can trade with one another as needed. Each allowance corresponds to the right to emit 1 tonne of CO_2. Businesses must report their EU ETS emissions every year and provide enough allowances to cover them by 30 April of the following year. If a business does not surrender enough

allowances to cover its emissions, it must buy allowances to make up the shortfall; its name is published, and has to pay a fine for each excess tonne of greenhouse gas emitted (www.ec.europa.eu). This policy, by putting a price on carbon, implies some interesting consequences: each tonne of emissions saved has a financial and commercial value and a sufficiently high carbon price can promote investment in clean, low-carbon technologies. The price of carbon allowances (the so-called carbon price) is determined by supply and demand according to a market-oriented mechanism. During the first phase of EU ETS (2005–2007), the price of allowances increased up to a peak level of about €30/tCO_2 in April 2006 (www.publications.parliament.uk). Nevertheless the excess of allowances led to a trading price of € 0.10 in September 2007. The estimated needs were excessive; this is way the allowances price falls to zero (www.ec.europa.eu). During the Phase II (2008–2012) the carbon price increased to over €20/tCO_2 in the first half of 2008, but the 2012 closed with a price around 6.67 €/tCO_2. One main reason for this fall in prices was that the economic downturn led to a reduced output in energy-intensive sectors, therefore less abatement has been required to respect the cap and the market has been oversupplied with permits, leading to the downfall of the price. For Phase III (2013-2020) the European Commission has proposed a number of changes that during the first three quarters of 2015 conducted the allowances price trend to rise. The allowances average price for the third quarter of 2015 was between €7.90 (EEX-DE platform) and €7.92 (EU t-CAP platform). This positive trend is considered from some mayor analysts an indicator for a long-term growing trend (www.gse.it).

3. Theoretical formulation

The mathematical formulation that follows tries to capture economic and environmental trade-offs of lot sizing in material purchasing. The authors consider the single-product replenishment problem and apply a bi-objective optimization approach by modelling the lot sizing problem for incoming goods to be purchased by a company in accordance with two distinctive objective functions: the total annual cost function and the total emission cost function. We suppose that the product demand is deterministic, the product price is exogenous and the buyer decides only the order size.
First, we introduce the notations used in the model as follows:

INDICES:
i container/vehicle type
j transportation mode

DECISION VARIABLES AND COST FUNCTIONS:

Q decision variable [units/purchasing order]

$C(Q)$ total average annual cost of replenishment [€/year]

$E(Q)$ total annual emission generated by the replenishment [CO2 eq/year]

Q_c* optimal order quantity for the cost function [units/purchasing order]

Q_e* optimal order quantity for the emission function [units/purchasing order]

INPUT PARAMETERS:

D annual demand [units/year]

p unit purchase cost [€/unit]

p' unitary scrap price [€/unit]

b space occupied by a product unit with sale packaging [m3/unit]

a weight of a unit stored in the warehouse [ton/unit]

O fixed ordering cost per order [€/order]

h holding cost [€/unit]

β average inventory obsolescence annual rate [%]

y full load-vehicle/container capacity [units or m3]

v average freight vehicle speed [km/year]

d_j distance travelled by transportation mode j [km]

$c_{f,j}$ fixed transportation cost coefficient for transportation mode j [€/km]

$c_{v,j}$ variable transportation cost coefficient for transportation mode j [€/km m3]

$c_{ef,j}$ fixed transportation emission coefficient for transportation mode j [kgCO2 eq/km]

$c_{ev,j}$ variable transportation emission coefficient for transportation mode j [kgCO2 eq/km m3]

c_{eh} warehouse emission coefficient [kgCO2 eq/m3]

c_{eo} waste collection and recycling emission coefficient [kgCO2 eq/ton]

n_i number of full load-vehicle/container i [units]

y_i full load-vehicle/container i capacity [units]

k range of order quantity Q_s between the two discontinuity points DP_k and DP_{k+1}

DP_k Discontinuity Point for range k, defined as $\sum_i n_i * y_i$

S freight vehicle utilization ratio in %

C value of carbon price quoted in the market [€/tonCO2 eq]

cap carbon cap according to a cap and trade system[tonCO2 eq]

ΔE_{cap} emission reduction by reaching the cap value

ΔC_{cap} cost increment by reaching the cap value

Unlike prior models already discussed in section 1, transportation and obsolescence cost are here considered explicitly and modelled according to their true discontinuity nature.
Let us introduce the first objective function $f_1(Q)$ that quantifies the average annual cost of replenishment and it is expressed as follows:

$$f_1(Q) = C(Q) = p \cdot D + C_o(Q) + C_h(Q) + C_{obs}(Q) + C_t(Q) \tag{1}$$

In detail, the terms included in this formulation are defined as follows (from Battini et al, 2014). The ordering cost, associated only to the buyer fixed cost of processing the order, and the holding cost are calculated according to traditional models:

$$C_o(Q) = \frac{D}{Q} \cdot O \tag{2}$$

Holding cost now considers both the traditional holding cost of carrying inventory in the warehouse and the cost associated to hold inventory during the transportation activity that is not as function of Q, as expressed by the following formula (derived from Axsäter and Grubbström ,1979):

$$C_h(Q)=\frac{Q}{2}h+Q\left(\frac{d}{v}\right)\left(\frac{D}{Q}\right)h \tag{3}$$

Where v is the freight vehicle speed expressed in km/year. To make the application of this formulation less time-consuming, a simple but plausible formulation for obsolescence cost is here applied. An obsolete event comes from a specific cause(i.e. a change in the product design or in product technical specification) and makes immediately unusable the inventory on hand. We here apply the obsolescence annual risk rate β according to Battini et al. (2014). At the end of each year, the remaining stocks are sold by the buyer to a specific waste treatment company for disposal at the unitary scrap price p', lower than p. In some cases, p' could also become negative if the owner has to pay the waste treatment company for the disposal service.

$$C_{obs}(Q)=\frac{Q}{2}(p-p')\cdot\beta \tag{4}$$

Due to the relevance of transportation cost on the optimization of the order quantity (Zhao et al, 2004), its formulation includes both fixed and variable costs and it presents Discontinuity Points DP_k when the vehicle capacity is saturated. Thus, we express the transportation costs with the sum of a fixed portion (expressed in €/km since it doesn't increase with the order quantity but only with the travelled distance) and a variable portion, which depend on the quantity transported and on the vehicle saturation:

The vehicle saturation S_j depends on the quantity transported, on vehicle capacity y_i and on the number of vehicle used in the order cycle n_i:

$$S_j=\frac{Q}{\sum_i n_i y_i} \tag{5}$$

Under the following constraint:

$$\sum_i n_i y_i \geq Q \tag{6}$$

As discussed in previous studies (Zhao et al, 2004, Battini et al, 2014), the transportation cost is not a continuous function and it cannot be differentiated during the whole interval. Moreover, the value n depends on the number of different vehicle types used in the transportation (for example different containers with different capacities). In practice, in a global supply chain scenario, more types of vehicle are available with different capacities and different costs, hence it is necessary to accurately evaluate all discontinuity points and ranges between them and apply a step by step approach, as already adopted in literature. To simplify the problem, when DP_k is the Discontinuity Point k, obtained after the accurate evaluation of all capacity saturation ranges of different kind of container i are applied in the same purchasing cycle, we can assert that, in general:

$$S_j=\frac{Q}{\sum_i n_i y_i}=\frac{Q}{DP_k} \tag{7}$$

And then express the transportation cost for each kind of transportation mode j used, as follows (Battini et al, 2013):

$$C_t\left(Q,d_j,S_j\right)_j=\left[\left(c_{f,j}\cdot d_j\cdot\sum_i n_i\right)+\left(c_{v,j}\cdot d_j\cdot DP_k\right)\right]\cdot\frac{D}{Q} \tag{8}$$

Concluding, the first function to optimize is finally expressed as follows (considering the whole mix of transportation modes used in the material supply from vendor to buyer):

$$f_1(Q) = C(Q) = p \cdot D + \frac{D}{Q_s} \cdot O + \frac{Q}{2} \cdot h + \left(\frac{d}{v}\right) \cdot D \cdot h + \frac{Q}{2}(p - p') \cdot \beta + \left[\sum_j \left(c_{f,j} \cdot d_j \cdot \sum_i n_i + c_{v,j} \cdot d_j \cdot DP_k\right)\right] \cdot \frac{D}{Q} \tag{9}$$

The second objective function $f_2(Q)$ is the average total quantity of emission generated during the annual purchasing activity and it can be expressed by the sum of the emissions generated in the following three steps: material order transportation, warehousing and waste collection and treatment of the obsolete items. Thus, by an environmental point of view, only 3 terms must be considered and homogeneously expressed in tons of CO2 eq.

$$f_2(Q) = E(Q) = E_h(Q) + E_{obs}(Q) + E_t(Q) \tag{10}$$

The first term compute the average quantity of equivalent carbon emissions generated by warehousing during the time unit of one year:

$$E_h(Q) = c_{eh}\left(\frac{Q}{2} \cdot b\right) \tag{11}$$

c_{eh} is the average emission cost coefficient of a warehouse expressed in € per cube meter of warehouse space occupied by inventory (this coefficient differs in case we use or not a temperature controlled warehouse), and b measures the cube meters occupied by a product unit stored in the warehouse (considering also packaging materials).
The inventory stored in the warehouse present a risk of obsolescence at the end of the year, expressed by the obsolescence annual risk rate β. Obsolescence goods at the end of the year are sold by the buyer to a specific waste treatment company for recycling at the disposal price *p'*, lower then *p*. Anyway, in this case we only consider the emissions generated during the waste collection and treatment process. Therefore:

$$E_{obs}(Q) = \frac{Q}{2} \cdot \beta \cdot a \cdot c_{eo} \tag{12}$$

c_{eo} is the carbon emission cost coefficient for obsolete inventory waste collection and recycling, expressed in €/ton and a is the weight of an obsolete unit stored in the warehouse in tons/unit. Finally, due to the reasons described above and to the discontinuity nature of the transportation cost function, also the emission function linked to the transportation activity will be described by a discontinuous function as follows:

$$E_t(Q, d_j, S_j)_j = \left[\left(c_{ef,j} \cdot d_j \cdot \sum_i n_i\right) + \left(c_{ev,j} \cdot d_j \cdot DP_k\right)\right] \cdot \frac{D}{Q} \tag{13}$$

Thus, the second objective function to optimize is finally expressed as follows (considering the whole mix of transportation modes used in the material supply from vendor to buyer):

$$f_2(Q) = E(Q) = c_{eh}\left(\frac{Q}{2} \cdot b\right) + \frac{Q}{2} \cdot \beta \cdot a \cdot c_{eo} + \left[\sum_j \left(c_{ef,j} \cdot d_j \cdot \sum_i n_i + c_{ev,j} \cdot d_j \cdot DP_k\right)\right] \cdot \frac{D}{Q} \tag{14}$$

According to a generic Pareto design optimization problem (Pareto 1964, 1971), involving the two conflicting objective functions introduced above, can be concisely stated as

$$Minimize\ \{f_1(Q), f_2(Q)\ \} \tag{15}$$

A Pareto-optimal solution is also defined "Pareto-efficient solution", and the set of all efficient points is called the Efficient Pareto Frontier. It is generally impossible to come up with an analytical expression of the Pareto frontier, however, a basic requirement for Pareto optimality is expressed in the following: Q* is a Pareto-optimal solution to the problem posed by Eq. (9) and Eq. (14), if there does not exist any other design Q such that $f_1(Q) \le f_1(Q^*)$ and $f_2(Q) \le f_2(Q^*)$ simultaneously.
The number of Pareto-efficient solutions Q* can be quite large, and it is yet necessary to select the best compromise design(s) among them. Thus, a sustainable purchasing choice normally increases $f_1(Q)$,while decreases $f_2(Q)$, since the two objective functions are competitive in nature.
If Q_c^* is the single optimal solution of the objective function $f_1(Q)$ and Q_e^* is the single optimal solution of $f_2(Q)$ we can call EF the Efficient Frontier of the lot sizing problem here proposed and EF^c its image in the criterion space, then:

$$EF = \left[Q_c^*, Q_e^*\right] \tag{16}$$

EF_+^c is convex and exist $Q_{\min} < Q_{\max}$ such that $Q^* \in \left[Q_{\min,} Q_{\max}\right]$.
As a consequence, the shape of the EF strongly affect the possibility to move from a cost-optimal to an emission-optimal solution.
We can now define the following three measures, all related to the EF shape:

$$\Delta Q = Q_{\max} - Q_{\min} = \left|Q_c^* - Q_e^*\right| \tag{17}$$

$$\Delta C = f_1(Q_{\max}) - f_1(Q_{\min}) \tag{18}$$

$$\Delta E = f_2(Q_{\max}) - f_2(Q_{\min}) \tag{19}$$

The first one expresses by a quantitative point of view the extension of the efficient frontier curve in the space and in other words the distance between the emission-optimal solution and the cost-optimal solution in term of purchasing units. By computing the rate $\Delta C / \Delta E$ we can express the expected marginal increment in annual logistic cost per ton CO2 eq. in order to move towards an emission optimal solution instead of a cost optimal solution. The solution of the multi-objective problem under consideration, can be achieved using the concept of indifference band (Passy and Levanon, 1984). An indifferent band is the area on the Cartesian coordinate plane where the feasible solutions are all equally desirable to the decision maker. Between any two solutions in the indifference curve there is a trade-off, so that a decrement in the value of one objective function f_i inevitably determines an increment in the other objective function f_j.
When a carbon cap is set according to a Cap and Trade regulatory policy a company needs to reduce the total emissions below the cap in order to respect the governmental constraint.
By a traditional cost-oriented optimization approach, a company prefer to apply a cost-optimal solution in order to minimize the total annual purchasing cost, so that the costs are at minimum but consequently the emissions are maximized (Q_C^*) .
In order to reduce the total annual emissions below the cap value, the company has to move in the Pareto Frontier from right to left until it is possible to define a discrete transportation quantity that is applicable as a purchasing lot size.
In doing this, the company will inevitably increase its annual costs. We here define this marginal increment in total annual costs as the Marginal Logistic Cost (*MLC*) defined as follows:

$$MLC = \frac{\Delta C_{cap}}{\Delta E_{cap}} \tag{20}$$

The concept of *MLC* is shown in Figure 1 on the right.
The *MLC* value varies according to different shape of the Pareto frontier, that in some industrial sector could be steep or on the contrary more flat. When a carbon cap is coupled with a carbon allowance in a cap and trade system, the market carbon price C represents the allowance that helps the company to fit and go under the defined carbon limit (the cap).
By introducing the parameter $\varphi = \frac{MLC}{C}$, two different situations could be identified in practice:

a) $\varphi > 1$: the *MLC* is major than the carbon price and the company has to autonomously sustain an extra cost in order to reduce its emissions under the cap value equal to: $MLC - C$

b) $0 < \varphi \leq 1$: the *MLC* is less or at least equal to *C* and the company could earn by the emission reduction an extra saving equal to: $C - MLC$. For this reason, the company is fully economically supported in increasing the purchasing quantity of incoming materials while saturating vehicles.

In the next paragraph a numerical application of the model with a parametrical analysis is reported in order to understand how the Pareto Frontier shape specifically built for each industrial case could affect the value of the parameter φ and the consequent emission reduction.

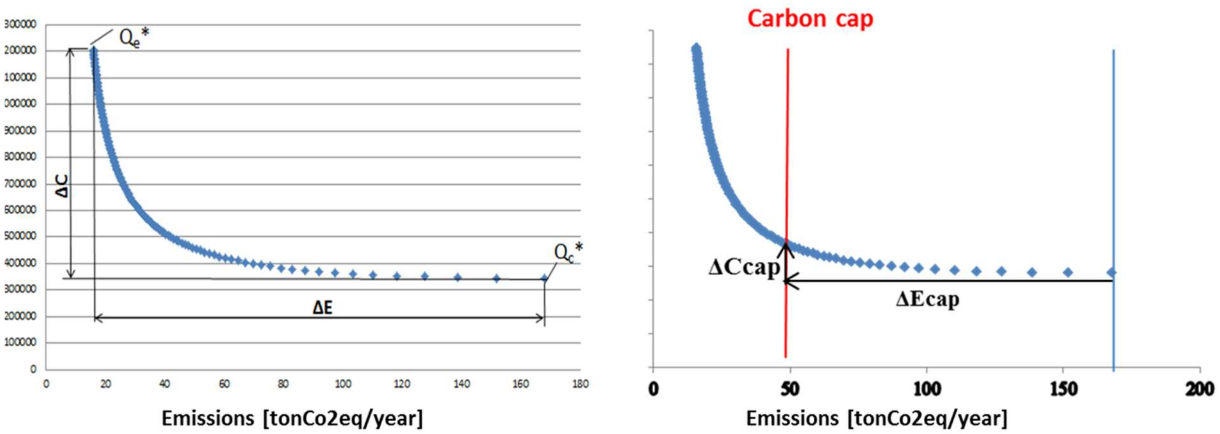

Figure 1. Pareto Efficient Frontier (left) and carbon cap effect in the Pareto Frontier (right)

4. Parametric analysis and discussion

In this section we present a parametric analysis, directly inspired by real industrial cases, to illustrate the above analytical model and provide some observations of the Cap and Trade system applied to the material purchasing and transportation setting.
Let consider a set of different purchasing material purchased and transported in 4 type of logistic load unit (i.e. stock keeping unit, box, etc), each of them with a different weight and volume. The product purchasing price changes in order to provide results suitable for a wide range of real situations. The products considered in the following example can be easily assimilated to different industrial sectors (i.e. electrical equipment, fashion items, metal parts, etc.). Let's suppose that the buyer company is located in the North-East part of Italy and closed to intermodal terminals and the vendor is located overseas (i.e. in Hong Kong). Transportation are made by adopting a rail-ship intermodal transport with only a final short handling by truck. Transportation costs are derived from the Italian Ministry of Transport report (2014) and carbon footprinting coefficient are calculated using the Ecoinvent database in SimaPro Software (www.simapro.co.uk). The cost and emission functions reported in formula (9) and (14) are computed in relation to the set of discontinuity points DP_i identified according to the different handling units used in the purchasing network (container 1: ISO

20 feet and container 2: ISO 40 feet). All constant input parameters used in the analysis are summed up in table 1, while the input parameters subject to variations are reported in table 2. Table 3 lists all the dependent variables in the model, with relation to the input data. The saturation of the two types of containers can be achieved by volume or by weight, depending on the characteristics of the product (see Table3). From the table 2, firstly, notice that the Apparent Density ρ has been introduced and in the present numerical application is fixed to 500 kg/m^3, in order to generate plausible situations for the type of products under consideration.

Constant Input Data	*Value*	*Constant Input Data*	*Value*
D	40,000	$c_{v,road}$ *[€/km*m³]*	0.01
O [€/order]	400	$c_{f,rail}$ *[€/km]*	0.6
d [km on road]	100	$c_{v,rail}$ *[€/km*m³]*	0.007
d [km by train]	500	$c_{f,ship}$ *[€/km]*	0.48
d [km by ship]	14,000	$c_{v,ship}$ *[€/km*m³]*	0.003
Inner volume container1 [m³]	33.2	c_{eh} *[kgCO₂eq/ m³*year]*	24
Load Capacity container1 [tons]	21.75	c_{eo} *[kgCO₂eq / ton]*	77.004
Inner volume container2 [m³]	67.2	$c_{ef,road}$ *[kgCO₂eq/km]*	2.20017
Load Capacity container2[tons]	26.70	$c_{ev,road}$*[kgCO₂eq /ton*km]*	0.154398
v_{road} *[km/year]*	525,600	$c_{ef,rail}$ *[kgCO₂eq /km]*	1.28017
v_{rail} *[km/year]*	788,400	$c_{ev,rail}$ *[kgCO₂eq /ton*km]*	0.0392892
v_{ship} *[km/year]*	219,000	$c_{ef,ship}$*[kgCO₂eq /km]*	0.06443
$c_{f,road}$ *[€/km]*	0.8	$c_{ev,ship}$*[kgCO₂eq /ton*km]*	0.0088875

Table 1. Constant Input data

Variable Input Data	*Set of values*
p [€/unit]	[1 ; 10 ; 20 ; 40 ; 70 ; 110 ; 160 ; 220 ; 290 ; 370]
a [kg/unit]	[0.5 ; 1 ; 5 ; 10 ; 20]

Table 2. Variable Input data

Dependent Variables	*Relation with variable Input Data*
b [m³/unit]	a/ (ρ*1000)
p' [€/unit]	0.5* p
h [€/unit]	0.25* p
y_1 *[units/contanier1]*	Min (Inner volume container1/b; Load Capacity container1/a)
y_2 *[units/container2]*	Min (Inner volume container2/b; Load Capacity container2/a)

Table 3. Dependent Variables

Figure 2 shows the trend of the Pareto efficient frontiers for the 5 different values of product weight reported in Table 2. Note that the scales are the same for all the graphs, in order to facilitate a visual comparison. From a first glance, we immediately notice that as the product weight increases, the width of the frontiers decreases, then the number of Pareto optimal solutions belonging to the Efficient Frontier decreases. Moreover, the efficient frontiers move from lower to higher values of the total emissions but at the same time the total annual costs decrease. Consequently, they move towards the right lower part of the Cartesian plane. At equal weight instead, as the product price increases, the efficient solutions move towards higher values for both costs and emissions.
By comparing the different Pareto Frontier shapes we can summarize the following:
-each material purchasing decision has a specific Pareto Frontier associated which is capable to drive the decision maker to the final choice according to an interactive approach;
-more the frontier is large and flat around the cost-optimal solution more possibilities exist to increase the purchasing lot sizing quantity wirh a consistent reduction in emission and a limited increment in costs.

-when the product weight is low and the product purchasing price is high, the Frontier is large and flat around the cost-optimal solution, leaving possibilities to optimize the choice and reduce the emission.
-when the product weight is higher and product price is lower, ΔC and ΔE are reduced and the frontier is shorter and constituted only by some points. This happens since the vehicles are faster saturated;
-the trend of the outputs in relation to the price p is evident in fig.2: for the same value of the product weight, low values of the product price p determine lower values of ΔC and ΔE, but when it increases also the gap between the two optimal lot sizing solution Q_c^* and Q_e^* increases and thus ΔC and ΔE become higher.
Finally in Table 5 is then reported a parametric analysis of the parameter φ introduced in the previous paragraph according to the simple testing set of variable data (in table 4), in order to understand the incidence of the marginal logistic cost respect to the carbon price applied by the Cap and Trade approach:

Variable Input Data	***Set of values***
p [€/unit]	[1 ; 10 ; 100 ; 1000]
a [kg/unit]	[0.5 ; 1 ; 5 ; 10 ; 20]
Logistic cube side [in mm] with an apparent density ρ =500[kg/m³]	[100; 126; 215; 271; 342]

Table 4. Variable Input data

The simple parametric analysis reported in table 5 clearly show that a cap and trade regulatory policy when applied to the material purchasing problem is largely affected by the type of product purchased/transported, that means in other wards by the industrial sector under analysis. In particular the product physical characteristics (weight and volume) and its purchasing price strongly affect the feasibility in practice of the Cap and Trade mechanism when it is applied to inventory management and purchasing decisions. Starting in table 5 with a carbon average price equal to €7.92 (according to the third quarter of 2015, EU t-CAP platform) is evident that the company: 1) has large possibilities to improve its purchasing policy in order to be more sustainable and reduce emissions for all the cases reported by coloured cells, 2) needs to sustain an extra cost in order to reduce its emissions under the fixed cap. This extra cost ranges from 4.18 to 96.96 times the carbon price value, that is the φ values reported in table 5. More the product price increases, more the value of φ increases (in table 5 this effect is depicted by the colours changing from green to red): this means that always larger extra cost and profit sacrifices are necessary for the company in order to reduce its annual emissions under the cap. By considering a long-term growing trend (www.gse.it) of the carbon price value and by applying 3 tentative carbon prices equal to 15, 30 and 60 €/ton of Co2eq saved at the end of the year, only with a carbon price equal to 60 €/ton it starts to become convenient ($\varphi \leq 1$) for the purchasing company to better optimize and saturate the transportation system by purchasing greater product quantities and by selling its carbon allowances in the market instead of apply a traditional cost-oriented approach. In the other cases depicted with grey cells in table 5, the transportation system is already fully saturated and optimized by using a cost-oriented approach and no other savings in emission could be achieved: the only way to reduce under the cap the transportation system emissions in these cases is by cutting the delivery distance, thus purchasing materials near the buyer premises instead in the overseas market. Thus, a Cap and Trade system applied to the material purchasing and transportation sector should be carefully adapted to each industrial sector and should also provide a higher value of the carbon price value in order to sustain companies towards sustainable choices.

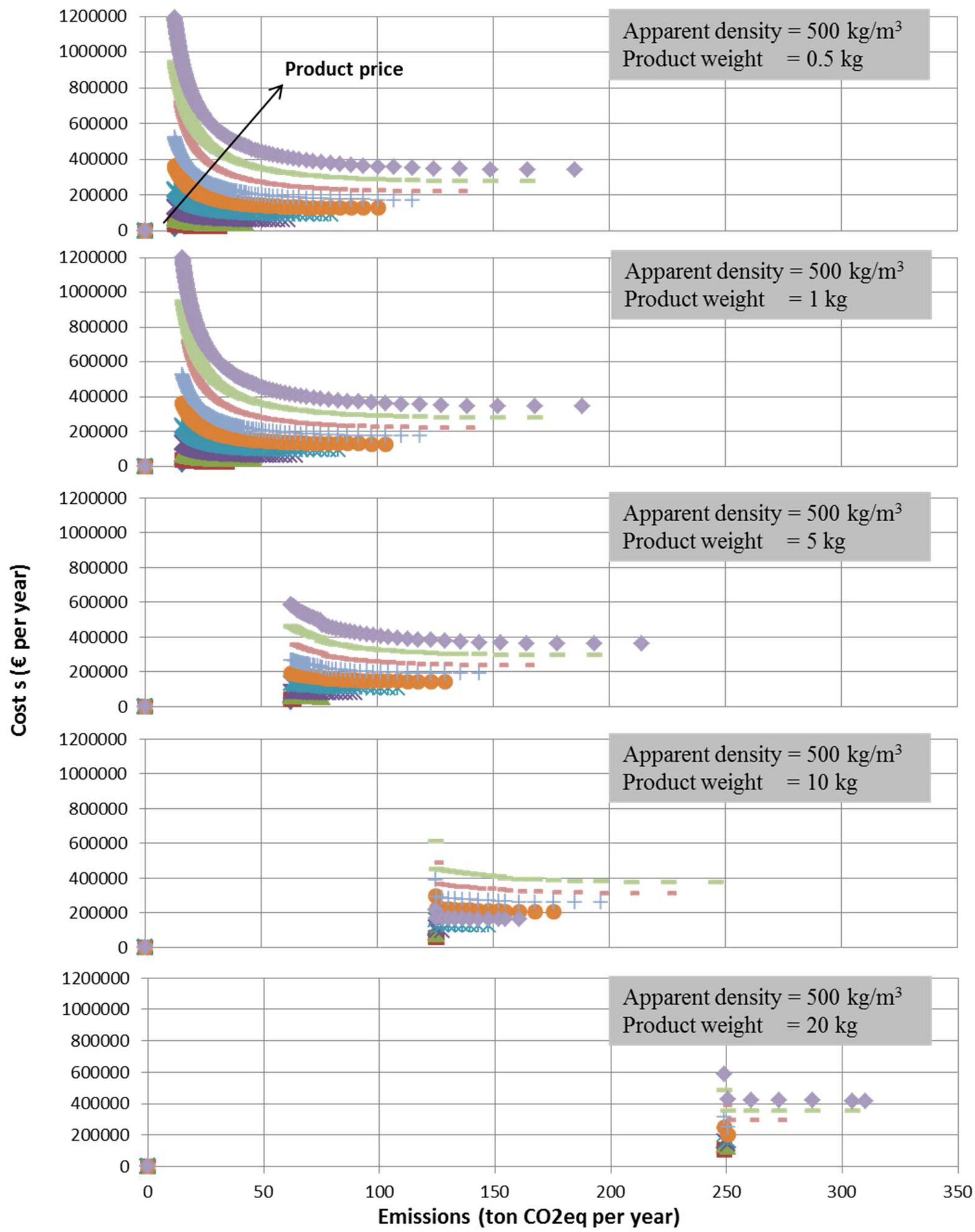

Figure 2. Sensitivity analysis of the Efficient Frontier according to variations in the product unitary price (with different colours) and in the product weight (from top to down).

5. Conclusions

The paper develops a bi-objective lot sizing model that considers a typical global supply chain purchasing problem with a long distance freight transportation. Total logistics costs and total CO2 equivalent emissions are taken into account and calculated by a numerical example. The model is applied to a simple set of numerical scenarios, where a number of input data are fixed and inspired to a real case while other product features (weight, volume and purchase price) assume different values. The parametric analysis here developed, permits to analyze the different shapes of the Pareto efficient frontiers according to variations in these key parameters and to conclude that the effect of a Cap and Trade policy could be largely different respect to the industrial sector in which is applied. Higher the product purchasing price and the product weight and higher the economic sacrifice in order to reduce the emission under the cap. However, the current EU carbon price value (7.92 €/ton in 2015) is too low to sustain and practically motivate a feasible extension of the Cap and Trade policy to the material transportation and inventory management problems. Higher carbon price values could better incentive the company managers towards a responsible and sustainable material purchasing.

				Carbon price= 7.92 €/ton					Carbon price= 15 €/ton					Carbon price= 30 €/ton					Carbon price= 60 €/ton				
				cap (emission reduction %)					cap (emission reduction %)					cap (emission reduction %)					cap (emission reduction %)				
p [€/item]	a [kg/item]	b [m3/unit]	cube side [mm]	10%	20%	30%	40%	50%	10%	20%	30%	40%	50%	10%	20%	30%	40%	50%	10%	20%	30%	40%	50%
1	0,5	0,001	100	TRANSPORTATION SYSTEM ALREADY OPTIMIZED					TRANSPORTATION SYSTEM ALREADY OPTIMIZED					TRANSPORTATION SYSTEM ALREADY OPTIMIZED					TRANSPORTATION SYSTEM ALREADY OPTIMIZED				
1	1	0,002	126																				
1	5	0,010	215																				
1	10	0,020	271																				
1	20	0,040	342																				
10	0,5	0,001	100	4,18	10,77	18,69	29,91	47,12	2,21	5,69	9,87	15,79	24,88	1,10	2,84	4,93	7,90	12,44	0,55	1,42	2,47	3,95	6,22
10	1	0,002	126	4,86	12,14	22,08	36,73	62,85	2,57	6,41	11,66	19,39	33,18	1,28	3,20	5,83	9,70	16,59	0,64	1,60	2,92	4,85	8,30
10	5	0,010	215																				
10	10	0,020	271																				
10	20	0,040	342																				
100	0,5	0,001	100	8,59	12,89	21,48	30,08	45,13	4,54	6,80	11,34	15,88	23,83	2,27	3,40	5,67	7,94	11,91	1,13	1,70	2,84	3,97	5,96
100	1	0,002	126	8,59	12,89	21,49	32,25	49,46	4,54	6,81	11,35	17,03	26,11	2,27	3,40	5,67	8,51	13,06	1,13	1,70	2,84	4,26	6,53
100	5	0,010	215	8,62	19,41	32,38	64,53		4,55	10,25	17,10	34,07		2,27	5,12	8,55	17,03		1,14	2,56	4,27	8,52	
100	10	0,020	271	9,90					5,23					2,61					1,31				
100	20	0,040	342																				
1000	0,5	0,001	100	13,60	20,76	27,92	42,24	56,56	7,18	10,96	14,74	22,30	29,86	3,59	5,48	7,37	11,15	14,93	1,80	2,74	3,69	5,58	7,47
1000	1	0,002	126	13,60	20,76	27,92	42,24	56,56	7,18	10,96	14,74	22,30	29,86	3,59	5,48	7,37	11,15	14,93	1,80	2,74	3,69	5,58	7,47
1000	5	0,010	215	13,60	20,77	35,09	42,26	63,76	7,18	10,96	18,53	22,31	33,67	3,59	5,48	9,26	11,16	16,83	1,80	2,74	4,63	5,58	8,42
1000	10	0,020	271	13,61	27,94	35,11	56,63	96,96	7,19	14,75	18,54	29,90	51,20	3,59	7,38	9,27	14,95	25,60	1,80	3,69	4,63	7,48	12,80
1000	20	0,040	342	20,79	40,74	61,54			10,98	21,51	32,49			5,49	10,76	16,25			2,74	5,38	8,12		

Table 5. Sensitivity analysis of the parameter φ according to different product unitary price, weight and volume and with variations in the carbon price applied.

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Carbon Trading Systems in the international setting: analysis and critical comparison

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Topic(s): low carbon freight transportation, cap-and-trade system analysis, freight modelling methods

Abstract

The Intergovernmental Panel on Climate Change (IPCC) reports that global warming poses a grave threat to the world's ecological system and the human race, and it is very likely caused by increasing concentrations of carbon emissions, which mainly results from such human activities as fossil fuel burning and deforestation (IPCC, 2007). A powerful action is needed to stabilize the rising temperatures, in order to avoid irreversible and catastrophic changes. Global measures are actually needed, involving many countries with a common objective. A cooperative solution has indeed to be reached; otherwise without an effective global climate agreement no result will be accomplished (Stavins, 2008). This work, jointly developed by the some of the partners involved in the EU Reinvest project, aims to deeply analyse and compare the most relevant Emission Trading Schemes developed by the different countries with a particular interest to Europe, USA and China/India position and to investigate if there actually is cooperation and a global-level agreement. After an initial overview of the systems developed by these countries, a comparison between them is provided according to the following factors: involved area, involved sectors, reduction targets, treated pollutant emissions.

Then, three different cap and trade schemes are deeply investigated and critically compared in relation to: 1. The auction system; 2. The allowances price / carbon cost and 3. Phases and trends.

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) reports that global warming poses a grave threat to the world's ecological system and the human race, and it is very likely caused by increasing concentrations of carbon emissions, which mainly results from such human activities as fossil fuel burning and deforestation (IPCC, 2007).
Several Climate Change Conferences have been organized by the United Nations to talk over countermeasures aiming to face and solve the environmental problems caused by climate change (Liu et al., 2015).
The COP22 (COP, Conference of the Parties) was held in Marrakech, in the North-African country of Morocco, on 7–18 November 2016 and faced two focal issues, at first water scarcity, water cleanliness, and water-related sustainability. This topic represents indeed a major issue for developing world, including many African states. The other focal issue was the need to reduce greenhouse gas emissions (GHG) and enhance the use of low-carbon energy resources.
Mr. Peter Thompson, President of the UN General Assembly, required the transformation of the global economy in order to achieve a resilient and low emissions global economy (www.unfccc.int).
A powerful action is needed to stabilize the rising temperatures, in order to avoid irreversible and catastrophic changes. Global measures are actually needed, involving many countries with a common objective. A cooperative solution has indeed to be reached; otherwise, without an effective global climate agreement no result will be accomplished (Stavins, 2008).
In order to mitigate global warming, the United Nations (UN), the European Union (EU), and many countries have introduced some policies and mechanisms to contain the total amount of greenhouse gas emissions. Among these, one of the primary legislation is the European Union Emission Trading System (EU-ETS). It has been launched in 2005 and it works on the "cap and trade" principle: a cap is set on the total amount of certain GHG that can be emitted by factories, power plants and other installations. The cap is reduced over time, in this way the total emissions fall.
This policy is by far the largest international GHG emission trading scheme with the purpose of mitigating climate change (Shen B. et al., 2014): it covers more than 11.000 power stations and manufacturing plants in the 28 EU member states plus Iceland, Liechtenstein and Norway.
The carbon emission trading is generally considered as one of the most effective market-based mechanisms. It has been introduced in UN, EU, and many other governments (Hua et al., 2011).
In the United States there currently is little action on climate change policy at the Congressional level, but such policy is being driven by the U.S Environmental Protection Agency under the Clean Air Act (L. H. Goulder and A. Schein, 2013).
In addition, in the United States it is anyway possible to identify some regional and federal initiatives, for instance: RGGI, AB 32 in California, WCI between some US states and Canadian provinces.
Shen B. et al. (2014) describe California's emissions trading programme as the most ambitious cap-and-trade scheme at the individual state level. The goals of this cap-and-trade program are to achieve a reduction in GHG emissions to 1990 levels by 2020, and ultimately to achieve an 80% reduction from the 1990 level by 2050. Moreover, in April 2015, Gov. Jerry Brown issued an additional emissions reductions target of 40% below 1990 levels by 2030 (http://www.arb.ca.gov/).
China, India and other developing countries were exempt from the requirements of the Kyoto Protocol, adopted in Kyoto, Japan, on 11 December 1997 (http://unfccc.int/kyoto_protocol). They were not part of the major emitters of GHG during the period of industrialization, which is believed caused climate change.

Nevertheless, now these fast growing economies (China, India, Thailand, Indonesia, Egypt, and Iran) have GHG emissions rapidly increasing and their pollution is becoming a global issue.
China and India will probably achieve more than 35% of total CO_2 emissions by 2030.
This emission increase is primarily due to higher coal consumption. The development of industrialization and urbanization requires for fast energy growth, which leads the growth of energy related carbon dioxide emissions (Liu L. et al., 2015).
In order to reduce the emissions growth, China has developed a national policy program, which included the closure of old, less efficient coal-fired power plants and more investments on green energy. Moreover, by the end of 2014, seven cap-and-trade pilot programs had been officially opened in Beijing, Shanghai, Shenzhen, Tianjin, Guangdong, Hubei and Chongqing (Liu L. et al., 2015).
This work, jointly developed by the some of the partners involved in the EU Reinvest project, aims to provide a review and a critical comparison between the most relevant Emission Trading Schemes developed by the different countries, with a particular interest to Europe, USA and China/India position and to investigate if there actually is cooperation and a global-level agreement. After an initial overview of the systems developed by these countries, a comparison between them is provided according to the following factors: involved area, involved sectors, reduction targets, treated pollutant emissions. Then, three different cap and trade schemes are deeply investigated and critically compared in relation to: 1. The auction system; 2. The allowances price / carbon cost and 3. Phases and trends.
The remainder of our paper is organized as follows: Section 2 deeply analyses and compares the environmental economics policies developed by some key countries, with particular attention to Europe, USA and China/India. In section 3 three different cap and trade schemes are deeply investigated and critically compared in relation to: 1. The auction system; 2. The allowances price / carbon cost and 3. Phases and trends. Section 4 presents the conclusions of the present work and insights for the future researches.

2. National and International commitments

The Intergovernmental Panel on Climate Change (IPCC) reports that global warming poses a grave threat to the world's ecological system and the human race, and it is very likely caused by increasing concentrations of carbon emissions, which mainly results from such human activities as fossil fuel burning and deforestation (IPCC, 2007).
A powerful action is needed to stabilize the rising temperatures, in order to avoid irreversible and catastrophic changes.
It is fundamental to:

- Drastically cut CO_2 and other greenhouse gasses emissions;
- Change the production and use of energy (more efficiency is needed)
- Promote renewable energy and innovative technologies.

Global measures are actually needed, involving many countries with a common objective.
A cooperative solution has indeed to be reached; otherwise without an effective global climate agreement no result will be accomplished (Stavins, 2008).
In order to mitigate global warming, the United Nations (UN), the European Union (EU), and many countries have introduced some policies and mechanisms to contain the total amount of greenhouse gas emissions.

2.1 EU Position EU – Emission Trading System (ETS)

The Emission Trading System is a cost-effective way of the European Union's policy to combat climate change and to reduce industrial greenhouse gas emissions (GHG).
It has been launched in 2005 and it works on the ”cap and trade” principle: a cap is set on the total amount of certain GHG that can be emitted by factories, power plants and other installations. The cap is reduced over time, in this way the total emissions fall.
This policy covers more than 11.000 power stations, manufacturing plants and aviation activities in the 28 EU member states plus Iceland, Liechtenstein and Norway.
Moreover, the ETS allows also buying limited amounts of international allowances from emission-saving projects around the world. These projects must be recognised under the Kyoto Protocol's Clean Development Mechanism or Joint Implementation mechanism as producing real and genuine emission reductions. In this way EU ETS promotes many investments on clean technologies and low-carbon solutions in developing countries and economies (www.ec.europa.eu/clima/policies/ets).
The EU ETS regards in particular power plants, a wide range of energy-intensive industry sectors and operators of flights to and from the EU, Iceland, Liechtenstein and Norway. Under these conditions, around 45% of the EU's greenhouse gas emissions are covered.
Covering also the aviation in the EU Emissions Trading System (EU ETS) represents one of the policies required to reduce greenhouse gas emissions for a range of transport modes.
The transport industry causes around the 25% of EU greenhouse gas emissions and while emissions from other sectors are generally falling, those from transport have increased until 2007, starting then a decrease mostly due to the growth of oil prices, to a stronger efficiency of passenger cars and to a slower growth in mobility (Figure 2).

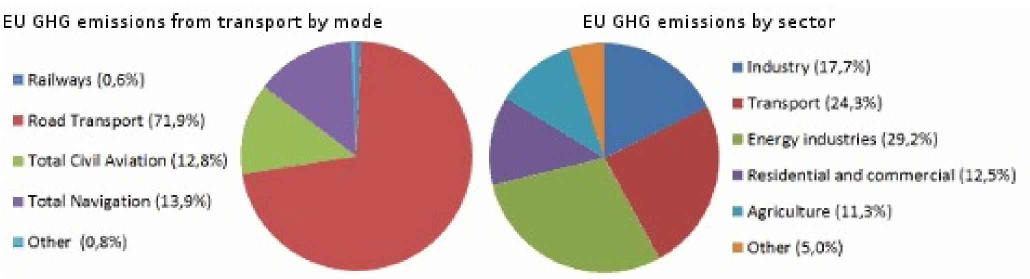
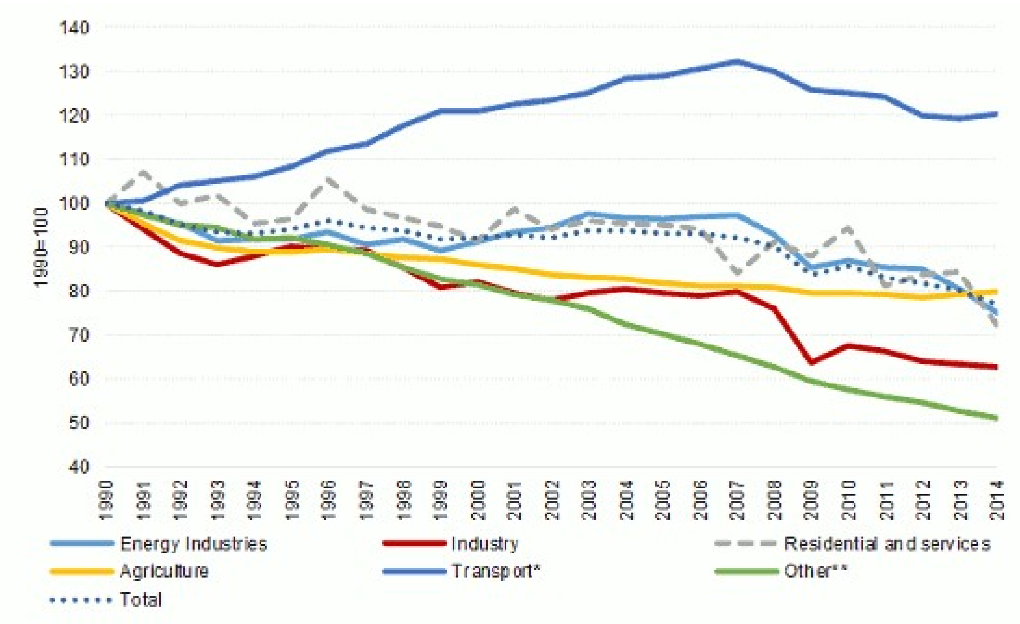


Figure 1 – EU28 greenhouse gas emissions by sector and mode of transport, 2012 (https://ec.europa.eu/clima/policies/transport_en)



Note: * Transport includes international aviation but excludes international maritime;
** Other include fugitive emissions from fuels, waste management and indirect CO2 emissions

Figure 2 – Percentage Increase/Decrease of emissions according to sector (EU28), 1990-2014 (https://ec.europa.eu/clima/policies/transport_en)

The companies involved into the EU ETS system receive or buy emission allowances, which they can trade with one another as needed. Each allowance corresponds to the right to emit 1 tonne of CO_2. Therefore, by putting a price on carbon this policy implies some interesting consequences:

- Each tonne of emissions saved has financial and commercial value (see Figure 3);
- A sufficiently high carbon price promotes investment in clean, low-carbon technologies;
- The price of allowances is determined by supply and demand.

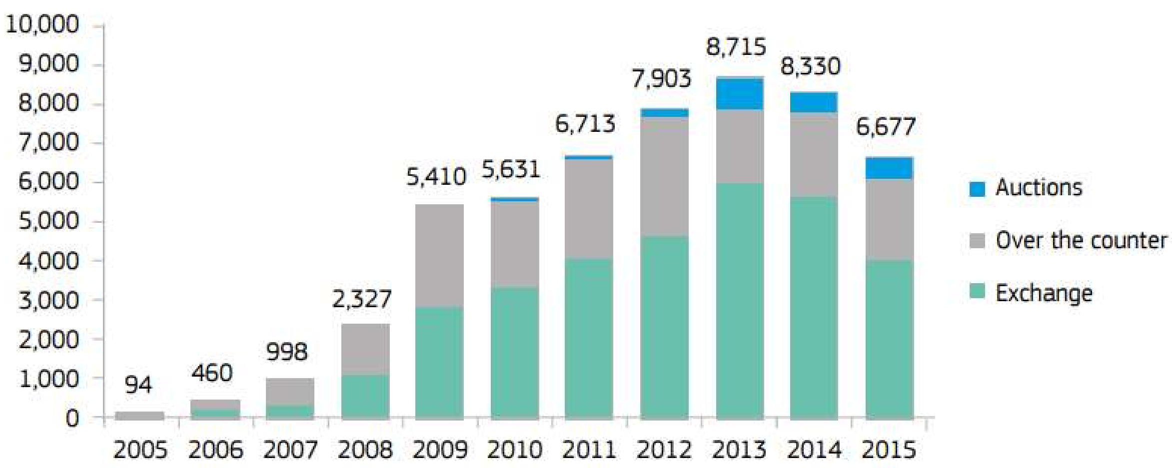


Figure 3 - The trading volumes in EU emission allowances (https://ec.europa.eu/clima/policies/ets)

Businesses must monitor and report their EU ETS emissions for each calendar year; these have then to be checked by an accredited verifier. After that, companies must provide enough allowances to cover their total emissions by 30 April of the following year.
If a business does not surrender enough allowances to cover its emissions, it must buy allowances to make up the shortfall; its name is published, and has to pay a fine for each excess tonne of greenhouse gas emitted. The fine in 2013 was €100 per tonne of CO_2 (www.ec.europa.eu).

2.1.1 How EU ETS is different

M. Grubb and K. Neuhoff (2006) have been able to clarify and emphasize five features that make the EU ETS different from previous emissions trading systems:

1. In terms of economic scale, the European emission trading scheme is still the biggest scheme in the world. The economic size of the EU ETS causes strong lobbying around allocation and competitiveness concern. At the same time, this system represents a source of profit-making incentives without precedents in the history of environmental policy. Due to its scale, the EU ETS could affect the costs of key industrial sectors more than any previous environmental policy.

2. The difficulty of reducing CO_2 emissions (compared to many other pollutants), combined with the large-scale of the EU ETS led to two outcomes: cutbacks imposed in the first stages have been quite small; and prices have been volatile. Cutbacks during the 1st phase of EU ETS amounted to about 1% of projected needs. Conversely, the US SO_2 programme required at the beginning cutbacks over 50% of historical emissions, with more additional reductions later. The difference between the EU ETS and other trading schemes is that during first phases the negotiated cutbacks have been within the range of projection uncertainty. Therefore, if emissions turn out to be lower than the projections, it is inevitable the price volatility. The allowances price uncertainty delays investment decisions: by waiting, a company can obtain more knowledge about future CO_2 prices, and thereby make better decisions. Therefore, in the presence of price uncertainty, risk aversion is also likely to cut investment.

3. A third characteristic is the tendency towards ‘overcompensation’. CO_2 costs feed into production costs; therefore in order to compensate, higher input costs cause the raise of product prices. In economic terms, free allocation represents an alternative way of compensating and protecting companies from the carbon cost. Firms, usually, in competitive markets maximize profits by defining prices relative to marginal cost of production. These marginal costs now include opportunity costs of CO_2 allowances. Therefore, if the allowances are received for free, there is potential ‘double compensation’. This creates the opportunity to make considerable profits. Smale et al. (2006) well explained this topic in their studies; Sijm et al. (2006) analysed it more for the electricity industry and Demailly and Quirion (2006) studied it with a focus on the cement industry.

4. By having negotiations of allocations for successive period, CO_2 budgets and allowance allocations are defined for a limited time period, initially of only 3 and 5 years. Therefore, uncertainty about the future leads to a cost.

5. Finally, one more characteristic that makes EU ETS different from many other trading programs is the decentralization of allocation responsibilities to its Member States. They would never have left to the European Commission the power to assign valuable assets to their companies. Moreover devolving powers of assignment is typical of some US systems.

2.1.2 EU – International network

The European Commission has the aim to exploit the EU ETS for developing an **international network** of **emission trading systems**, by linking compatible domestic cap-and-trade systems.
For instance, national or sub-national systems are already operating in Japan, New Zeeland, Switzerland and United States.

"Linking the EU ETS with other cap-and-trade systems offers several potential benefits, including reducing the cost of cutting emissions, increasing market liquidity, making the carbon price more stable, leveling the international playing field and supporting global cooperation on climate change." (European Commission, 2013a).

For instance, the EU and Switzerland signed in November 2017 (www.ec.europa.eu/clima) an agreement to link their emissions trading systems. Thanks to this link, the participants in the EU's Emissions Trading System will be able to use allowances from the Swiss system for compliance, and vice versa. This is the first agreement of this kind for the EU and between two Parties to the Paris Agreement on climate change.
National or sub-national systems are already operating also in Japan, New Zealand, South Korea and the United States, therefore a linkage between these cap-and-trade systems could be very convenient.

2.2 US Position

The US signed the Kyoto Protocol on 12 November 1998 but it has never been submitted to the Senate for ratification. Likewise, by May 2012 US had indicated they would not sign up to the second Kyoto commitment period.
In the United States there currently is little action on climate change policy at the Congressional level, but such policy is being driven by the U.S Environmental Protection Agency under the Clean Air Act (L. H. Goulder and A. Schein, 2013).
The Clean Air Act is one of the United States' most important modern environmental federal laws. It has been introduced to control air pollution on a national level (www3.epa.gov) and it is one of the most exhaustive air quality laws in the world (www.nrdc.org). It is managed by the U.S. Environmental Protection Agency (EPA), in collaboration with state, local, and tribal governments.
In addition, in the United States it is anyway possible to identify some regional and federal initiatives, for instance: RGGI, AB 32 in California, WCI between some US states and Canadian provinces.

REGIONAL GREENHOUSE GAS INITIATIVE (RGGI)

The Regional Greenhouse Gas Initiative (RGGI) has been adopted in 2009 (Murray et al., 2015).
This system caps emissions from power generation in 9 US states: Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New York, Rhode Island and Vermont.
The 2020 target of this cap-and-trade program is to achieve a reduction of more than 45% in CO2 emissions from the power sector compared to 2005 emissions.
To reduce emissions of greenhouse gases, the RGGI States use a market-based cap-and-trade approach defining a multi-state CO2 emissions budget ("cap") and the CO2 allowances are allocated through quarterly, regional auctions. The proceeds from the CO2 allowance auctions have then to be invested in consumer benefit programs to improve energy efficiency and accelerate the deployment of renewable energy technologies. The RGGI initiative also includes requirements for fossil fuel-fired electric power generators with a capacity of 25 megawatts (MW) or greater. Moreover, an emissions and allowance tracking system has been introduced in order to record and track RGGI

market and program data, including CO2 emissions from regulated power plants and CO2 allowance transactions among market participants (http://www.rggi.org/).

EMISSIONS TRADING IN CALIFORNIA (AB 32)

Shen B. et al. (2014) describe California's emissions trading programme as the most ambitious cap-and-trade scheme at the individual state level. The goals of this cap-and-trade program are to achieve a reduction in GHG emissions to 1990 levels by 2020, and ultimately to achieve an 80% reduction from the 1990 level by 2050. Moreover, in April 2015, Gov. Jerry Brown issued an additional emissions reductions target of 40% below 1990 levels by 2030 (http://www.arb.ca.gov/).
The program started on January 1, 2012, with an enforceable compliance obligation began on January 1, 2013, for greenhouse gas (GHG) emissions. This cap-and-trade program covers the power and industrial sectors, and moreover the natural gas and transportation fuels. The program imposes a greenhouse gas emission limit that will decrease by two percent each year through 2015, and by three percent annually from 2015 through 2020. Emission allowances are distributed by a mix of free allocation and quarterly auctions. The number of free allowances will gradually be reduced over time and an increasing number will be auctioned. Freely allocated allowances are mostly provided to vulnerable industries that might move from California.
A distinguishing feature of the Californian cap-and-trade program is that law enabled it: the enactment of the Assembly Bill 32 (AB 32), also known as the California Global Warming Solutions Act of 2006, established the legal framework for leading the state's actions in reducing GHG emissions (Shen B. et al., 2014).
Jeffery B. Greenblatt (2015) developed four potential policy and technology scenarios in California using CALGAPS, a new model simulating GHG and criteria pollutant emissions in California from 2010 to 2050 (see Figure 4). The first simulated scenario Committed Policies (S1) includes all policies either underway or extremely likely by 2020; while all the financial commitments were considered achievable. S2, Uncommitted Policies, includes existing policies and targets that lack of precise implementation plans, financial commitments or supports. S3, Potential Policy and Technology Futures, includes speculative policies, considering extensions of S1 or S2 policies and targets proposed by non-governmental organizations. This scenario may not represent the maximum feasible level of GHG reductions. Finally, the Counterfactual scenario (S0) was constructed by disabling all policies included in S1.

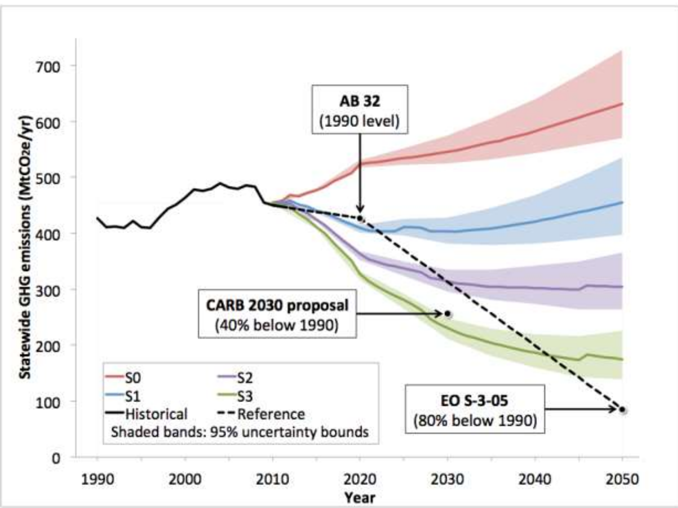


Figure 4 - GHG Emissions by scenario, with historical emissions and straight-line reference pathway between 2020 and 2050 GHG policy targets (Jeffery B. Greenblatt, 2015).

THE WESTERN CLIMATE INITIATIVE (WCI)

This scheme consists in a collective commitment, agreed between seven U.S. states and four Canadian provinces to identify, evaluate, and implement measures to reduce greenhouse gas (GHG) emissions (www.westernclimateinitiative.org).
This non-profit corporation has the goal of developing a multi-sector, market-based program to reduce greenhouse gas emissions (http://www.wci-inc.org/).
The WCI began in February 2007 when the Governors of Arizona, California, New Mexico, Oregon, and Washington signed an agreement in order to take part to a multi-state registry to track and manage GHG emissions in their regions, defining regional target for reducing greenhouse gas emissions and developing a market-based scheme to reach the objective. In November, 2011, the Western Climate Initiative formed Western Climate Initiative, Inc., in order to provide administrative and technical services to support the implementation of state and provincial greenhouse gas emissions trading programs. This cap-and-trade program was scheduled to start in January 2012, covering six greenhouse gases (carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulphur hexafluoride). Actually Québec and California were the first systems to have started their compliance periods, in January 2013.
The WCI, in accordance with all the partners' individual goals, set a target of a 15 % reduction from 2005 levels by 2020. With each partner reaching its own goal, the region is assured of achieving this level of reduction (www.westernclimateinitiative.org).
British Columbia, California, Ontario and Quebec are still working together through the Western Climate Initiative to develop and harmonize their emissions trading program policies (www.wci-inc.org).

2.3 China – India Position

China, India and other developing countries were exempt from the requirements of the Kyoto Protocol. They were not part of the major emitters of GHG during the period of industrialization which is believed caused climate change.
Now, these fast growing economies (China, India, Thailand, Indonesia, Egypt, and Iran) have GHG emissions rapidly increasing and their pollution is also becoming a global issue. As we can see from Figure 7 a large proportion of total CO2 emissions are caused by China. Its emission curve is indeed really steep after 2002, as we can notice from Figure 5.
Therefore, while Europe aims to a continuous reduction according to IPCC, emissions will globally increase in the near future especially in developing countries.
China and India will probably achieve more than 35% of total CO_2 emissions by 2030.
By the fact that these fast growing economies have GHG emissions rapidly increasing, some more effective systems are now required.

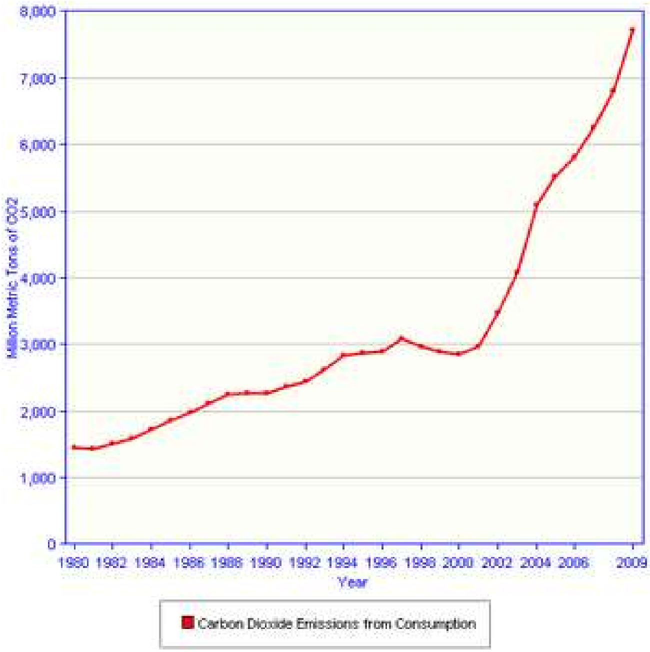


Figure 5 – China CO2 emission per millions of metric tons from 1980 to 2009. (http://www.eia.gov/countries/img/charts_png/CH_co2con_img.png)

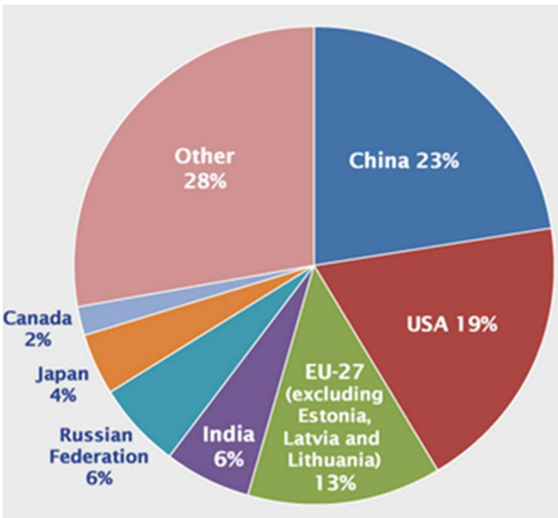


Figure 6 – 2008 Global CO2 Emissions from Fossil Fuel Combustion and some Industrial Processes (million metric tons of CO2), (http://www3.epa.gov/climatechange)

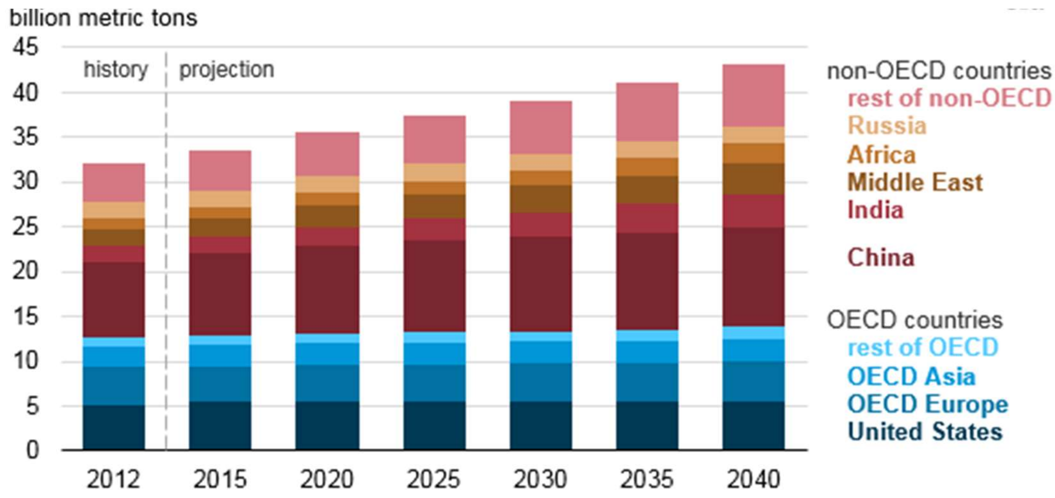


Figure 7 – Energy-related carbon dioxide emissions by country or region (2020 – 2040) (www.eia.gov/todayinenergy)

Liu L. et al. (2015) describe that between 1981 and 2002, China total CO2 emissions rose of 202%: from 1346 MMt to 3623 MMt. China's CO2 emissions additionally increase 50 % in 2006 and in 2011 this country gave the biggest contribution to the global increase, with its emissions rising by 720 million tonnes (Mt). This emission increase is primarily due to higher coal consumption. The development of industrialization and urbanization requires for fast energy growth, which leads the growth of energy related carbon dioxide emissions (Liu L. et al., 2015).

China has had a national policy program to reduce emissions growth, which included the closure of old, less efficient coal-fired power plants and more investments on green energy. Another dominant approach in the Chinese environmental regulation system consists on emissions fees. But this policy is more likely less effective than tradable permits (Zhao, 2014).

In 2009, at the Copenhagen Climate Conference, the Chinese government pledged to reduce carbon-emission intensity per unit of GDP by 40-45% of 2005 levels by 2020.

In order to meet this goal, in October 2011, the NDRC (National Development and Reform Commission of the People's Republic of China) identified 4 municipalities (Beijing, Chongqing, Shanghai and Tianjin), 2 provinces (Guangdong and Hubei) and the special economic zone of Shenzhen City as regions for implementing carbon trading pilots. These 7 pilots are expected to build up the infrastructure needed to start a national system. By the end of 2014, the pilot trading programs had been officially opened in Beijing, Shanghai, Shenzhen, Tianjin, Guangdong, Hubei and Chongqing.

In December 2017, China announced the initial details of its national emissions trading scheme (ETS), its national carbon market will be by far the world's largest one and it will start covering the power sector (www.chinaenergyportal.org/en).

The comparison between the main features of the policies above described are collected in Table 1.

Table 1 - Comparison between the policies above described

	KYOTO PROTOCOL	POLICY	REGULATION TYPE	INITIATIVE TYPE	INVOLVED AREA	INVOLVED SECTORS	START YEAR	REDUCTION TARGET FOR 2020	REDUCTION TARGET FOR 2030	TREATED POLLUTANT EMISSIONS
EU	✓	**EU ETS**	Cap and Trade Sytem	Both Eurpean and National initiative	28 EU member states plus Iceland, Liechtenstein and Norway	power plants, energy-intensive industry sectors , operators of flights , production of certain acids and aluminium production	2005	21% compared to 2005 levels	43% below 2005 levels	CO_2 , N_2O , PFCs
USA	✗	**The Regional Greenhouse Gas Initiative (RGGI)**	Cap and Trade Sytem	Federal - Not at a Congress level	9 US states: Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New York, Rhode Island and Vermont.	Fossil - Fuel Power Plants	2005 (Trading program began 2009)	45 % in the region's annual power-sector CO_2 emissions from 2005 levels	-	CO_2
		AB 32	Cap and Trade Sytem	Federal (Not at a Congress level)	California	The power and industrial sectors, natural gas and transportation fuels	2006 (Cap & Trade in 2013)	1990 levels	40% below 1990	GHGs (CO_2, CH_4, N_2O, HFCs, PFCs, SF_6, NF_3)
		The Western Climate Initiative (WCI)	Cap and Trade Sytem	Federal and Regional	Some US states and Canadian provinces	Electricity generation, industrial and commercial facilities, transportation,residential and commercial fuel use	2007 (WCI's Cap & Trade in 2013)	Regional target of 15 % below 2005 levels	Quebec proposes a target of 37.5% under 1990 levels	GHGs (CO_2, CH_4, N_2O, HFCs, PFCs and SF_6
CHINA	✗	**7 pilot trading programs**	Emission trading system	Regional (Objective: National system by 2017)	China	Electricity and power industries;carbon emissions industries; Iron and steel, cement, chemical and petrochemical industries; manufacturing industry and large buildings (Hotels, airports, ports)	2013	40–45 % of 2005 levels	-	GHGs (CO_2, CH_4, N_2O, HFCs, PFCs, SF_6)

3. Cap and Trade - 3 different key studies

The present work aim is now to analyse and compare three different cap and trade schemes, mainly focusing on 3 key features:

- Auction system;
- Allowances price / carbon cost
- Main phases and trends

3.1 EU key study

3.1.1 EU ETS – Phases

The EU ETS can be described by some phases; each of them with different main features and targets (www.ec.europa.eu/clima/policies/ets).

2005 – 2007: 1st TRADING PERIOD

This first period has been characterized by a "learning by doing" process and it made possible to build the infrastructure needed to monitor, report and verify emissions from the covered businesses.
During this 3-years pilot the UE ETS became the world's biggest carbon market, but only CO2 emissions from power generators and energy-intensive industries were covered and almost all the allowances were given to business for free.
Moreover, given the absence of reliable emissions data, the caps of this phase were set on the basis of estimates. As a result, the total amount of allowances issued exceeded emissions.
Therefore, by being the supply higher than the demand, in 2007 the price of allowances fell to zero (during Phase 1 allowances could not be banked for using them in Phase 2) (www.ec.europa.eu/clima/policies/ets/pre2013_en).

2008 – 2012: 2nd TRADING PERIOD

During the second phase the number of allowances has been reduced, but the economic downturn led once again to the surplus of unused allowances. Moreover 3 new countries joined the EU – ETS: Iceland, Liechtenstein and Norway.
An important step forward of this phase is that also the Nitrous oxide emissions from the production of nitric acid started being covered by a number of countries.
Moreover, the proportion of free allocation fell slightly to around 90% and several countries started holding auctions.
During the First Phase the penalty for non-compliance was €40 per tonne, this amount was increased during the Second Phase to €100 per tonne (https://ec.europa.eu/clima/policies/ets/pre2013_en).

2013 – 2020: 3rd TRADING PERIOD

During the third phase the sectors covered by the ETS have to reduce their GHG emissions by 21% compared to 2005 levels.

Therefore, from 2013 onwards, the cap on emissions from power stations and other fixed installations is reduced every year by 1.74% of the average total quantity of allowances issued annually in 2008-2012.
Another major reform is the introduction of a single, EU-wide cap on emissions applies in place of the previous system of national caps and has led the progressive shift from free allocation of allowances to an auctioning system (http://ec.europa.eu/clima/policies/ets_en)

2030 and 2050 TARGETS:

Since the EU target for 2030 is a GHG reduction of 40% compared 1990 levels, the target for the sectors covered by the EU ETS is to reduce their GHG emissions by 43% compared to 2005 levels. In order to achieve this target the cap will need to be lowered by 2.2% per year from 2021, compared with the current 1.74%.
Moreover, the long-term objective for 2050 is a reduction of emissions by around 90% compared to 2005.

3.1.2 EU ETS Auction System

The European Union Emissions Trading Scheme (EU ETS) is the scheme for trading greenhouse gas emission allowances with the aim of reducing the emissions of the European Union. The involved sectors are the energy-intensive ones: electricity, cement, steel, aluminium, brick and ceramics, glass, chemical, aviation, etc.
From 2013, with some exceptions for protecting the international competitiveness of the manufactural sector, the allocation of allowances is done through auction platforms instead of cost-free allocation (GSE Report about the 3rd quarter of 2015 http://www.gse.it/).
In 2013, over 40% of the allowances were auctioned and The European Commission estimates that 57% of the total amount of allowances will be auctioned during the 3rd Period (2013–2020), while the remaining allowances will be available for free allocation (www.ec.europa.eu/clima/policies/ets/auctioning_en).
All the European allowances correspond to the right to emit 1 tonne of CO2. Moreover, it is possible to distinguish two different types of them:

- The EUA: European Union Allowances, they are usable by all the subjects involved in the EU ETS;
- The EUA A: European Union Allowances Aviation, they are valid only for aircraft operators.

The 88% of the allowances to be auctioned are assigned to states with reference to their share of verified emissions from EU ETS installations in 2005. The 10% are allocated to the least wealthy EU member states as an additional source of revenue to invest for reducing the carbon intensity of their economies. The last 2% is given as a ‘ bonus’ to nine EU member states which by 2005 had reduced their GHG emissions by at least 20% of levels in their Kyoto Protocol base year or period (www.ec.europa.eu/clima/policies/ets/auctioning_en).
Most governments use a common ‘platform’ for their auctions, but Germany, Poland and the UK have decided to use their own platforms.
Since 2013 there are four different auction platforms indeed (Figure 8): the temporary common platform (EU t-CAP), the German one (EEX DE) managed by EEX, the Polish one (PL t-CAP) managed by EEX and the United Kingdom one (ICE UK) run by ICE.
25 Member States operate on t-CAP: Austria, Belgium, Bulgaria, Czech Republic, Cyprus, Croatia, Denmark, Estonia, Finland, France, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Portugal, Romania, Slovakia, Slovenia, Spain and Sweden.
During the third quarter of 2015, EUA auctions have been organized on all of the three platforms, while the EUA A ones have been managed only on the EU t-CAP.

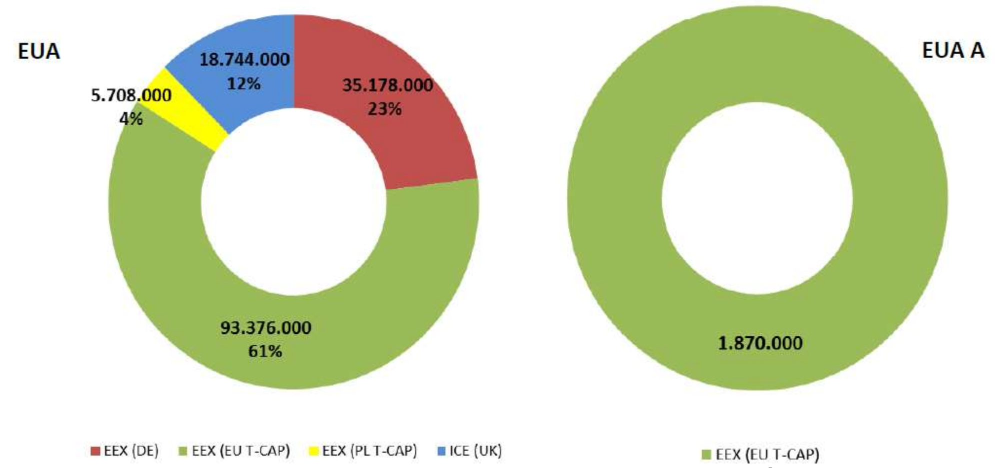


Figure 8 – Allowances allocations among the different platforms (EUA and EUA A) – 3rd quarter of 2015 (Report GSE from EEX and ICE data, http://www.gse.it)

3.1.3 Allowances Price Trends and Forecasts

The price of allowances is determined by supply and demand, therefore it is very floating.
For this reason it is interesting to:

- analyse its trend in the past, from the early 2005 to the 3rd quarter of 2015;
- Forecast how it is going to change in the future.

2005 – 2007: 1st TRADING PERIOD

During the first phase of EU ETS (2005–2007), the price of allowances increased up to a peak level in April 2006 of about €30 per tonne of CO2 (www.publications.parliament.uk). In late April 2006, some EU countries, like Netherlands, Czech Republic, Belgium, France, and Spain; announced that their verified emissions were less than the number of allowances allocated to installations. The spot price for EU allowances dropped 54% from €29.20 to €13.35 in the last week of April 2006. In May 2006, the European Commission confirmed that verified CO2 emissions were 4% lower than the number of allowances distributed to installations for 2005 emissions (http://web.mit.edu/globalchange). Therefore, in May 2006, prices fell to under €10/tonne. The excess of allowances during the first phase of the system continued through 2006 leading to a trading price of € 1.2 per tonne in March 2007 and to € 0.10 in September 2007. In 2007, carbon prices dropped to near zero for most of the year.
The estimated needs were excessive; this is way the allowances price falls to zero in 2007 (www.ec.europa.eu).

2008 – 2012: 2nd TRADING PERIOD

During the Phase II the carbon price increased to over €20/tCO2 in the first half of 2008 (CCC, 2008, p. 149 www.gov.uk/government). But during the first half of 2009 it decreased to €13/tCO2.
Two were the main reasons for this fall in prices (CCC, 2009, p. 67):

- Reduced output in energy-intensive sectors as a result of the economic downturn. This means that less abatement have been required to respect the cap, decreasing the carbon price.
- The market perception of future fossil fuel prices may have been revised downwards.

Prices for EU allowances for December 2010 dropped 8.7% to 12.40 euros a tonne.
In March 2012 the EUA permit price under the EU ETS had been persistently under €10 per tonne. Compared to nearly €30 per tonne in 2008, it was too low to provide incentives for firms to reduce emissions. The market had been oversupplied with permits, leading to the downfall of the price.
In July 2012, Thomson Reuters Point Carbon stated that without intervention to reduce the supply of allowances, the price of allowances would fall to four Euros (http://financial.thomsonreuters.com/).
The 2012 closed with a price around €6.67 a metric tonne (Figure 10).

2013 - 2020: 3nd TRADING PERIOD

For Phase III the European Commission has proposed a number of changes, including (CCC, 2008, p. 149 https://www.theccc.org.uk):

- the setting of EU-wide cap, with allowances then allocated to EU members. This overall cap decreases by 1.74% each year (www.ec.europa.eu);
- tighter limits on the use of offsets;
- limiting banking of allowances between Phases II and III;
- Shift from free allocation of allowances to an auctioning system. In particular the European Commission aim to auction at least 50% of the total permits, with an exception for the energy industry in which permits were already obtained 100% trough auction in 2013.

These changes led to some results: during the first three quarters of 2015 the allowances price trend has been rising (Figure 9 and Figure 10). In a troubled period for the markets, the European carbon market has instead registered the maximum values for the last 3 years (GSE Report about the 3rd quarter of 2015 http://www.gse.it/). The trend for EUA A auctions is in line with the EUA one, although with slightly lower values.
During the third quarter of 2015, the most important event, from a regulatory point of view, is the EU Commission’s proposal for the 4th EU ETS phase. It consists in a strong reduction on allowances free allocations thanks to harder rules on carbon leakage and to the introduction of a linear reduction factor for reducing benchmarks. Moreover, the proposal suggests fixing the percentage of allowances to be auctioned to 57%.
This news gave more vigour to the upward trend of prices and the new mechanism should produce positive results for the revenue of the EU Member States.

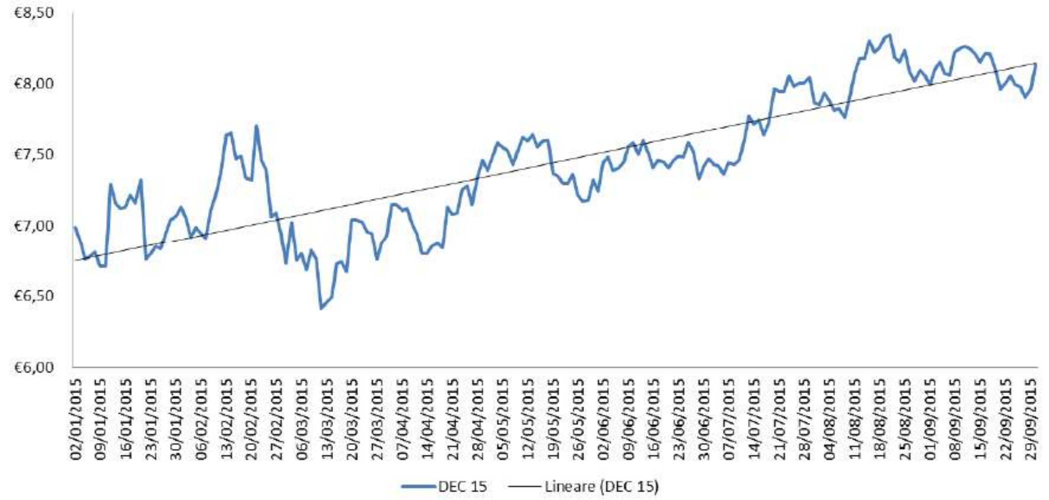
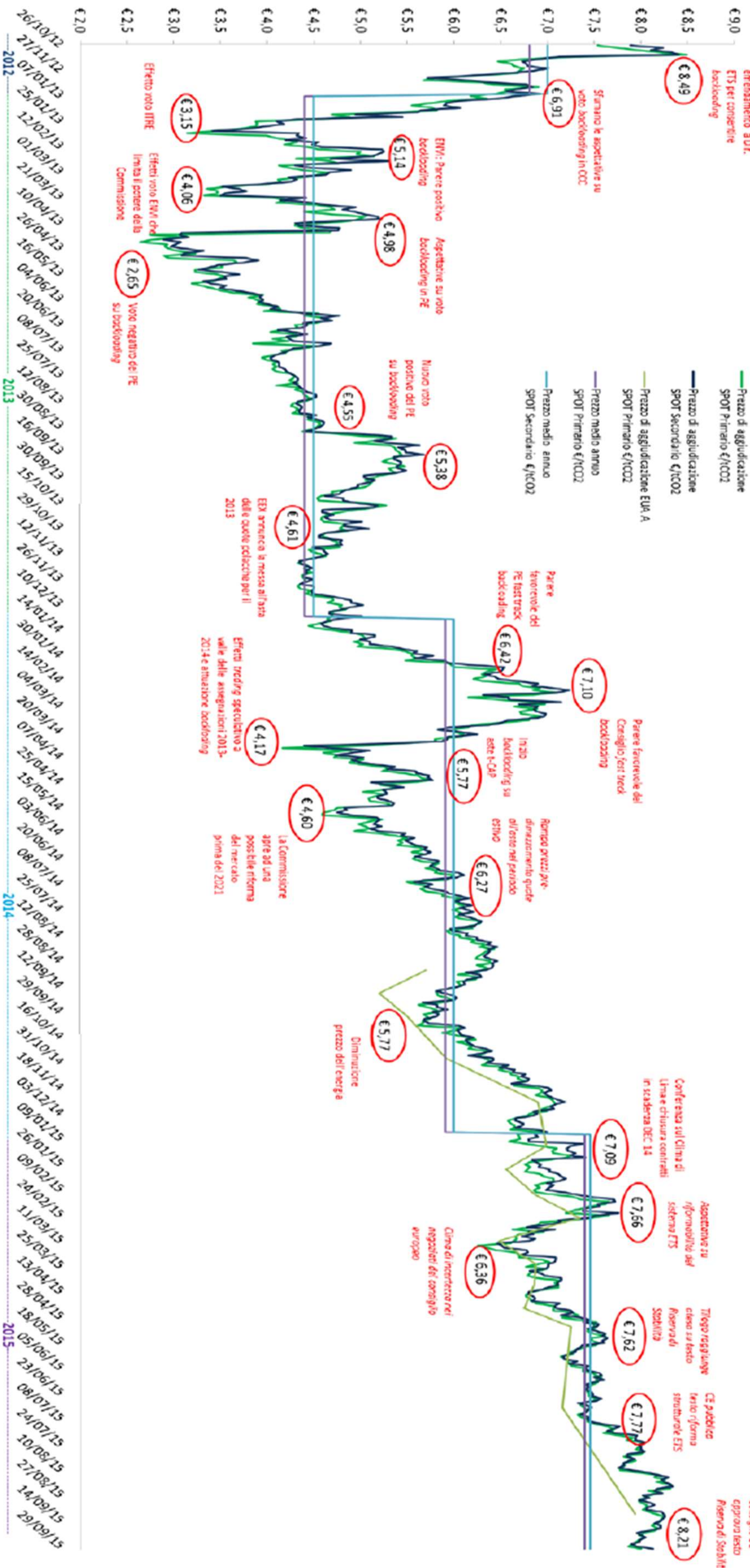


Figure 9 – EUA price trend (Jan. – Sept. 2015) (Source: GSE Report on Thomson Reuters <u>http://www.gse.it</u>)

Figure 10 – Allowances price trend (EUA and EUA A) – November 2012 – September 2015 (Source: GSE Report on EEX and ICE



Some actions introduced during the 3rd trading period, like the backloading of allowances between 2014 and 2016 (a postponement in the global quantity of allowances to be auctioned during a certain year) and the sharp reduction in the use of international credits, contributed to reducing the supply of allowances, giving an effect on the supply and demand balance. Moreover, from 2015 onwards, emission reductions from the the Phase II can no longer be used for compliance (EEA Report No 18/2017 www.eea.europa.eu/publications/trends-and-projections-EU-ETS-2017).
Thanks to these regulations, the EUA price increased in 2015 however, there was a sudden drop at the beginning of 2016 (see Figure 11).
In 2016, despite the surplus of EU ETS allowances declined for the second consecutive year, the average annual carbon prices declined compared to the previous year (fluctuating around a level of EUR 5 per EUA). That drop was probably due to a decline in speculative activity and hedging needs and it suggests that market players expect a surplus of allowances to persist, in the short term at least (EEA Report No 18/2017 www.eea.europa.eu/publications/trends-and-projections-EU-ETS-2017).
In May 2017 an ascendant trend of the carbon price begun, it continued during the summer months, supported by lower auction volumes in August and a strengthened energy sector: the EUA price exceeded the six euros at the end of August and reached a maximum of € 7,42 in September 2017.
The weighted average price of the third quarter of 2017 was 5.91 euro, a sharp rise compared to the same quarter of 2016 (€ 4.48) and the second quarter of 2017 (€ 4.77) (GSE Report on Thomson Reuters http://www.gse.it).

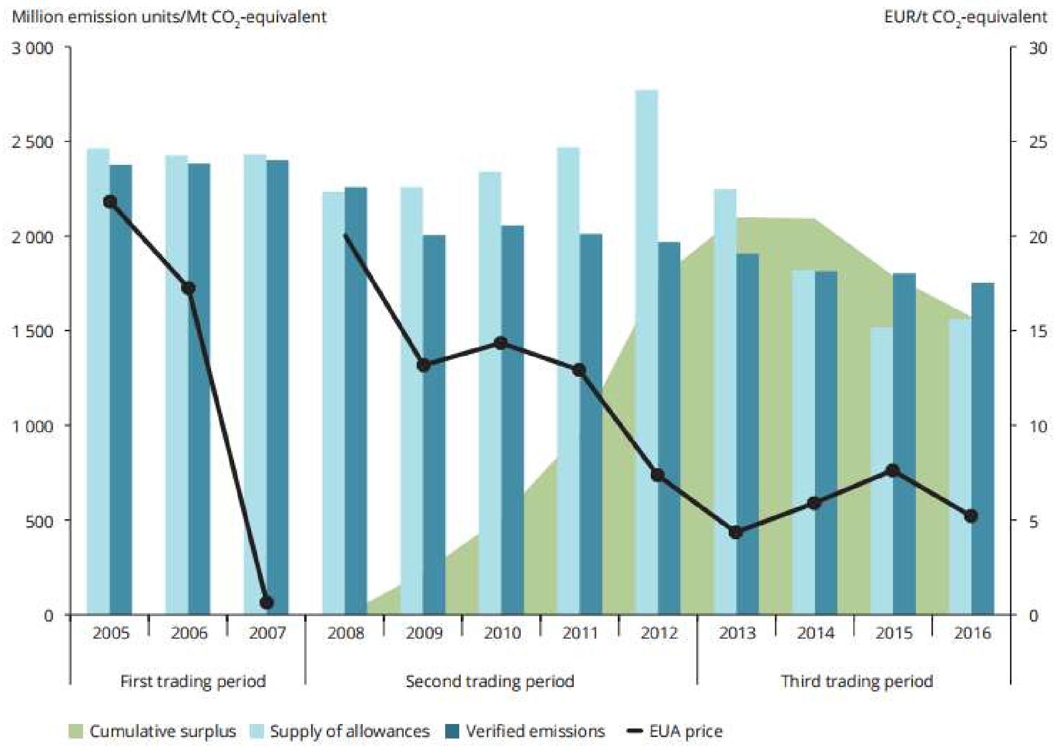


Figure 11 - Emissions, allowances, surplus and prices in the EU ETS, 2005-2016 (Source: www.eea.europa.eu/publications/trends-and-projections-EU-ETS-2017)

3.2 RGGI key study

3.2.1 RGGI – Phases

RGGI has begun in late 2003 in order to face the risks associated with climate change. On December 2005, seven states (Connecticut, Delaware, Maine, New Hampshire, New Jersey, New York and Vermont) released a Memorandum of Understanding (MOU), describing the overall goal of the RGGI initiative: to develop a cap and trade program with the objective of stabilizing and reducing emissions in the involved states, while remaining consistent with overall economic growth and the maintenance of a safe and reliable electric power supply system (www.ieta.org). In 2007 also Massachusetts, Rhode Island and Maryland signed the MOU. The RGGI program is organized in three-year compliance periods. At the end of each period, covered entities must submit one allowance for each ton of CO2 generated during the three-year period.
RGGI's first auction of CO2 allowances was held in 2008, and the first compliance period began on 1 January, 2009 (www.rggi.org/design/history).

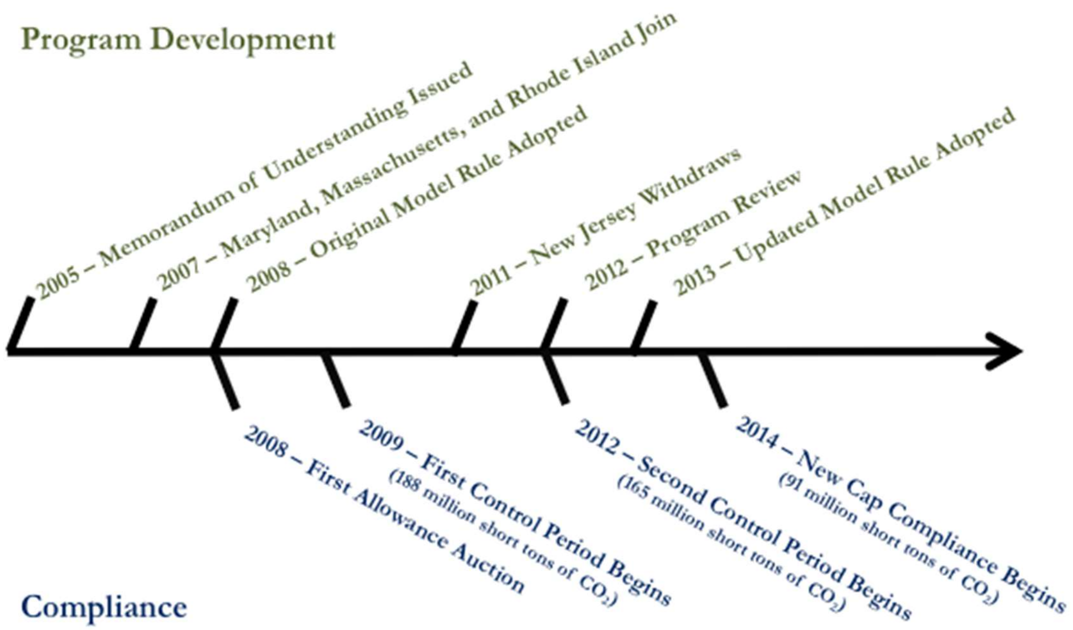


Figure 12 - RGGI Historical Timeline (Source: www.rggi.org/design/history)

In 2006 RGGI established the Model Rule, a framework that allows member states to establish their own cap-and-trade program. The Model Rule regulations set limits on in-state CO2 emissions from electric power plants, issued CO2 allowances, and established state participation in regional CO2 allowance auctions.
In February 2013, RGGI completed its program review with the release of an updated Model Rule. This took effect on 1 January, 2014 and has been adopted by each of the nine involved states.

The RGGI consists of three-year compliance periods; each of them with different main features and targets (www.rggi.org, www.ieta.org).

1st Period (2009-2011): during this first period the MOU set the states' overall emissions cap at 170 million tCO2.

2nd Period (2012–2014): for the second compliance period, the annual emission budget was adjusted down to 150 million tCO2, in order to consider New Jersey's withdrawal from RGGI at the end of 2011. After the 2012 review, the cap decreased to 83 million tCO2. Following the comprehensive 2012 Model Rule review, the cap has been decreased to 83 million tCO2 in 2014 (equal to 2012 emissions levels for the RGGI states). These adjustments have been introduced to account for RGGI allowances that emitters banked during the first and second compliance periods (see Figure 13). After the start of RGGI, it became clear that the allowances supply was higher than actual emissions. Allowance prices consequently fell down, making it particularly inexpensive to purchase allowances and bank them for use in later periods.

3rd Period (2015–2017): During the third compliance period the 2015 cap was 80,49 million tCO2, then adjusted to 60,63 million tCO2 because of allowances banked.
Moreover, the Model Rule stated to maintain the annual cap decline of 2.5% from 2015 to 2020. Therefore, the RGGI cap and RGGI adjusted cap for the years 2018-2020 are as follows (https://www.rggi.org/program-overview-and-design/elements).
2018: RGGI cap is 82,235,598, RGGI adjusted cap is 60,344,190
2019: RGGI cap is 80,179,708, RGGI adjusted cap is 58,288,301
2020: RGGI cap is 78,175,215, RGGI adjusted cap is 56,283,807

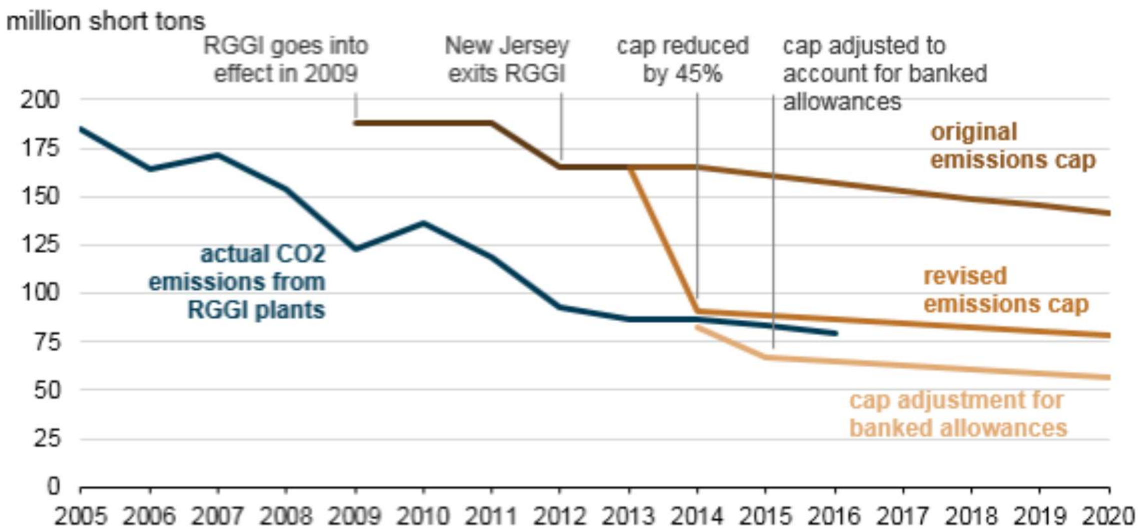


Figure 13 - Regional Greenhouse Gas Initiative CO2 emissions cap vs. actual emissions (Source: www.eia.gov)

3.2.2 RGGI Auction System

RGGI is one of the only cap-and-trade systems that mainly uses auctions to distribute allowances, rather than freely allocating some or all of them. RGGI Inc. coordinates quarterly central auctions on behalf of the RGGI states, for allocating approximately 90% of RGGI CO2 allowances available (www.rggi.org). Each state establishes how to allocate allowances, either via free allocation or

auctions and sells those allowances that are not auctioned off directly to qualifying affected sources or distributes them through set-aside programs.
RGGI auctions are characterized by a single-round, sealed-bid, uniform-price format, in which each bidder may submit multiple confidential bids for a certain quantity of allowances at a specific price. Auctions are open to all the buyers, who meet certain criteria e.g. financial security. However, qualified single buyers or groups of affiliated buyers must respect a purchase limit of no more than 25% of the allowances offered at a single auction.
At the end of the first compliance period (2009-2011), proceeds from auctioned allowances and direct sales were calculated for $952 million, and at the end of 2014, the total auction proceeds were equal to $1.93 billion (www.rggi.org). Table 2 shows cumulative proceeds after the second control period (2012-2014).
Proceeds from the auctions are distributed to states and then disbursed back to economy through: energy efficiency measures, community-based renewable power projects, and assistance to low-income customers to help pay their electricity bills, education and job training programs, etc.

Table 2 – Cumulative Allowances and Proceeds through the Second Period (Source: www.rggi.org/docs/ProceedsReport)

State	Cumulative First Control Period Allowances Sold	Cumulative Second Control Period Allowances Sold	Cumulative Proceeds ($)
Connecticut	24, 343, 412	22, 338, 727	130,554,467.36
Delaware	9, 952, 619	12, 949, 207	67,857,838.33
Maine	11, 797, 376	10, 591, 027	62,221,516.39
Maryland	74, 943, 417	75, 239, 644	418,425,090.90
Massachusetts	62, 024, 346	56, 331, 176	330,779,846.93
New Hampshire	14, 479, 101	14, 435, 469	80,927,555.23
New York	144, 305, 904	128, 764, 643	760,186,645.02
Rhode Island	6, 270, 050	6, 444, 140	38,233,979.59
Vermont	2, 877, 123	2, 565, 272	15,139,597.73
New Jersey (before its withdrawal)	46, 266, 477	2, 217, 293	113,344,551.27

Monitoring and Reporting

On the 30th of January of a compliance year, covered facilities have to submit their previous years CO2 emissions data through the US EPA's Clean Air Markets Division Business System, which then provides the emissions data to the RGGI CO2 tracking system (www.rggi.org).
On 1st of March, covered emitters must surrender allowances equal to 50% of their generated emissions in year-one and year-two of the compliance period, and 100% of all the remaining emissions at the end of the final year of the compliance period.
After the end of a compliance period, from March to June of the next year, Member States are required to check if the covered facilities have provided enough allowances to meet their compliance obligation. After that, on the 4th of June, covered facilities are required to align.
In the case that a covered facility does not follow its annual obligation, the RGGI Member State in which the emitter is located can require the entity to pay a fine, a penalty, or consider another remedy. If a covered facility has not provided enough allowances to meet its three-year compliance obligation, the facility will have to surrender an amount of allowances equal to three times the quantity of

emissions exceeded. In this situation, the RGGI Member State can also impose some specific penalties.

3.2.3 RGGI Allowances Price

Very soon, after RGGI began, it became clear that there was a surplus of supplied CO2 allowances. For this reason, during the initial years of RGGI, the value of these allowances remained close to the program's price floor of $1.93/ton of CO2 allowed in each quarterly auction.

The RGGI auctions during the First Compliance Period reflect this over-allocation: at the first RGGI auction in September 2008, all 12.6 million allowances supplied were sold at a single clearing price of $3.07 per allowance (https://www.rggi.org/docs/Retrospective_Analysis_Draft_White_Paper.pdf). In contrast, at the September 2011 auction, only 18% of the 42.19 million allowances offered for sale were purchased, at the low price of $1.89 per allowance (www.ieta.org/resources).

By analysing the trend of the carbon price in the RGGI system, it is possible to see the impact of the Updated Module Rule on the allowances price (see Figure 14). With the change in legislation and the adjustment to the overall RGGI cap that came into effect in 2013, demand for allowances increased, leading to the increase of the carbon price: the auctioning price continued to increase between March 2013 ($2.80) and March 2015 ($5.41).

In 2016 the total CO2 emissions from member states measured 79.2 million tons of CO2, therefore a total amount lower than the revised cap of 86.5 million tons CO2. Even though RGGI reduced its emissions cap, actual emissions have kept below the cap, leading to a surplus of allowances.

The downward trend in clearing prices since the start of 2016 reflects the excess of RGGI allowances and their relatively low demand (www.eia.gov). In March 2017 the lowest price in more than three years has been reached: more than 14 million allowances were sold at a clearing price of $3.00 per short ton of CO2.

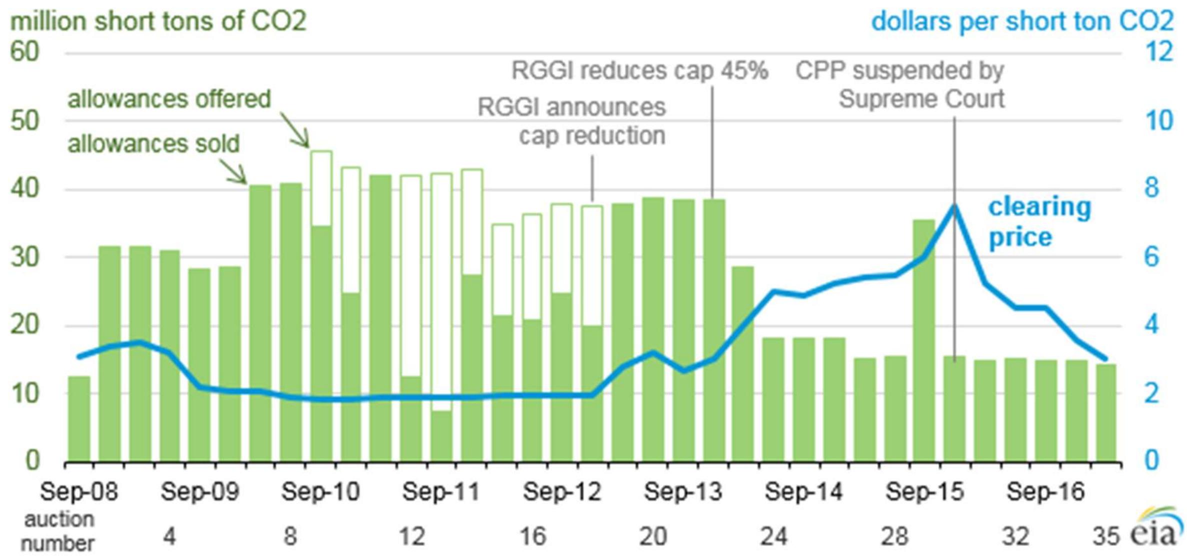


Figure 14 - RGGI Auction Allowances and Carbon Price Development (Source: www.eia.gov, rggi.org)

The current RGGI rules provide several flexibility measures including the use of offsets, banking and price collars like: a Cost Containment Reserve and an auction reserve price.

The **Cost Containment Reserve** consists of a fixed quantity of allowances, beyond the cap, that are held in a reserve. This policy is intended to moderate the increase of price when the allowances demand is higher than expected (www.ieta.org). If bids exceed the CCR trigger price during an auction, the CCR allowances are released and can be purchased by bidders. In 2014, the CCR contained 5 million allowances, and since 2015 onwards it contains 10 million allowances, replenished at the start of each calendar year. The price trigger started at $4/ton of CO2 in 2014, rises to $10/ton of CO2 in 2017, and will thereafter rise by 2.5% per year through 2020. With reference to the 2017 Model Rule, after 2020 the CCR size and trigger price trajectory will change: the CCR trigger price will be $13/ton in 2021 and will increase by 7% per year thereafter. Moreover, the CCR's portion will represent 10% of the regional cap each year (www.rggi.org). The CCR trigger price was first reached in the 2014 March auction, releasing an additional 5 million allowances, all of which were purchased (www.rggi.org/market/market_monitor).
Each auction also has a **reserve price,** the price under which no allowance can be sold. The 2015 auction reserve price was $2.05 per CO2 allowance and each year it increases by 2.5%. The reserve price for 2016 was indeed $2.10 per ton CO2 and the one for 2017 was $2.15 per ton CO2 (www.eia.gov).

3.3 CHINA - CTP (Carbon Trade Pilots) key study

3.3.1 China CTP – Phases

In 2009, at the Copenhagen Climate Conference, the Chinese government pledged to reduce carbon-emission intensity per unit of GDP by 40-45% of 2005 levels by 2020.
In March 2011, China released its **Twelfth Five-Year Plan for National Economic and Social Development (2011-2015)**, in which the establishment of a carbon-emissions trading market was stated for the next five years. Moreover, a set of short and long-term national targets regarding the carbon trade in China were established (L. Liu et al., 2015).

Short-term Targets (Twelfth Five-Year Plan)

1. Set up the carbon trade market and accelerate the implementation of pilot projects of low-carbon cities;
2. 17% reduction in the carbon intensity (carbon dioxide emission per unit GDP) in 2011–2015;
3. 16% reduction energy intensity (energy consumption per unit GDP) in 2011-2015;
4. Increasing the non-fossil energy use to 11.4% of the total energy use by 2015.

Long-term Targets (China’s commitment on Copenhagen Climate Conference in 2009)

1. Reducing carbon intensity by 40-45% of 2005 levels by 2020;
2. At least the 15% of the primary consumption has to come from non-fossil fuel by 2020.

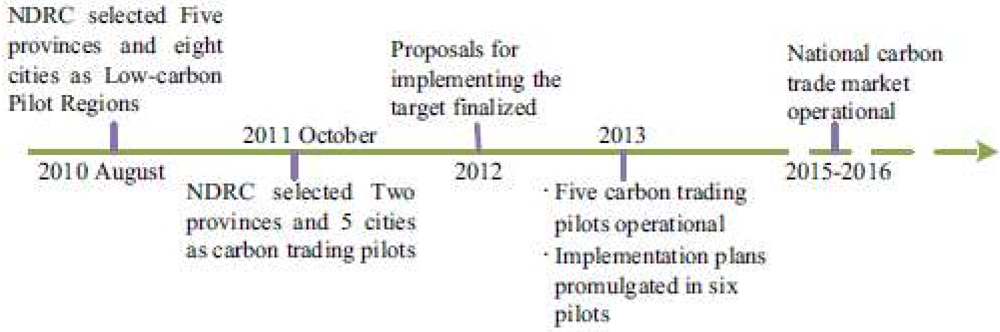


Figure 15 – Timeline in implementation of carbon emission trading schemes in China (Source: L. Liu et al., 2015)

Therefore, China is trying to gradually set-up a national carbon-emission trading market, for this reason the National Development and Reform Commission (NDRC) in August 2010 promoted **"Five provinces and eight cities"** as "Pilot Low-carbon regions" (see Figure 15). The involved areas were: Guangdong Province, Liaoning Province, Hubei Province, Shanxi Province and Yunnan Province, Tianjin, Chongqing, Shenzhen, Xiamen, Hangzhou, Nanchang, Guiyang and Baoding. These regions were expected to work as tests to promote GHG reduction through market mechanisms, by defining their own emission reduction goals and building up their own low-carbon strategies (L. Liu et al., 2015), see Table 3. To obtain more experience, the NDRC announced in October 2011 that carbon-emission trading would be developed in **7 pilot areas** at different stages of economic development and industrial structure. The seven areas involved were 4 municipalities (Tianjin, Beijing, Shanghai and Chongqing) 2 provinces (Guangdong and Hubei Province) and the special economic zone of Shenzhen City (see Figure 16). These 7 pilots are intended as testing grounds for implementing then a national ETS.

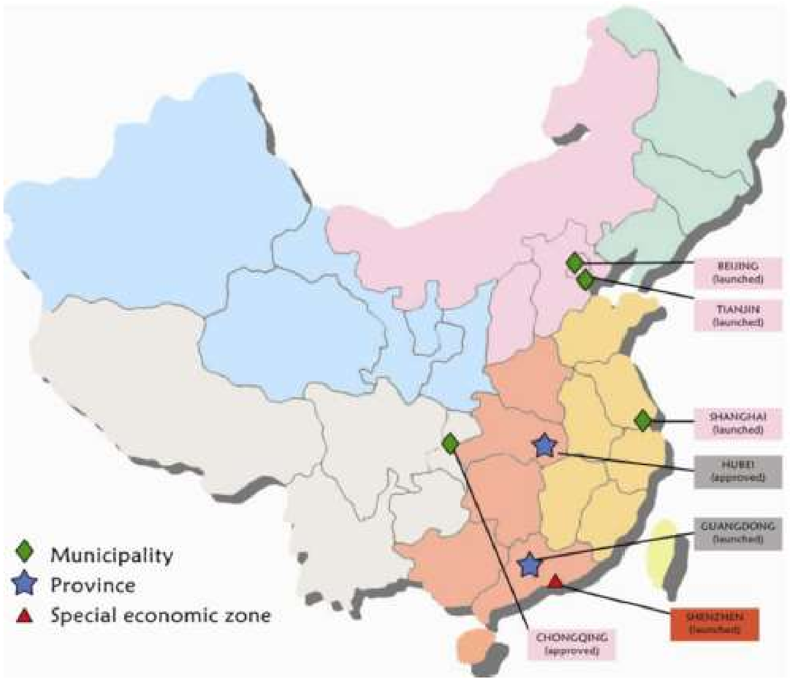


Figure 16 – Map of approved and launched China's carbon trading pilot areas (Source: L. Liu et al., 2015)

Between 2013 and 2014, the five carbon trading pilots became operational; the first pilot lunched was the Shenzhen pilot, while in June 2014 Chongqing is the last pilot starting carbon-emissions trading.

The emitters covered by these projects are those enterprises with high energy consumption and high emissions, and the main traded product is carbon dioxide (L. Liu et al., 2015).
The launch of these 7 carbon trading pilots demonstrates the Chinese government's determination to set up a national carbon-trade market and having taking active part on the international stage of carbon trading.
The objective for the **Thirteen Five-Year plan period (2016-2020)** is to gradually extend the carbon-trading market nation-wide, by creating a unified system of carbon trading (L. Liu et al., 2015).
In December 2017, China announced the initial details of its national emissions trading scheme (ETS), its national carbon market will be by far the world's largest one and it will start with the power sector alone (www.chinaenergyportal.org/en).

Table 3 – The basic features of the seven China's pilots (L. Liu et al., 2015)

Region	Launch Time	Emission Covered *	Industry involved
Shenzhen	6/18/2013	40%	Electricity and other 26 carbon emissions industries
Guangdong	9/11/2013	58%	Iron and steel, cement, power and petrochemical industries
Shanghai	11/26/2013	57%	Iron and steel, Chemical industry, Petroleum chemistry Electric Power, Building including hotel, shopping Aviation, Ports, Airport etc.
Beijing	11/28/2013	40%	Heat supply power, thermal power supply and other industries in the 'direct' field; manufacturing industry and large public buildings.
Tianjin	12/27/2013	50-60%	Iron and steel, chemicals, electricity and heat, petrochemical, oil and gas in the 'indirect' areas,
Hubei	4/2/2014	33%	Electricity, steel, cement, chemicals and other 12 industries
Chongqing	6/19/2014	39.5%	The industrial enterprises over 20,000 t of carbon dioxide emissions.

*: "Emission covered" represents the proportion of A in the B. A= the carbon emissions by the enterprises which are required to participate in the carbon-trading by the local government. B=The total carbon emissions in the specific region.

3.3.2 China CTP Auction System

The majority of allowances in China's CTPs were allocated for free, with very small percentage (3%-5%) of total allowances being auctioned (Figure 17). The Guangdong Province, the world's second largest market just after EU ETS, was the first CTP to hold an auction for allocating carbon allowances (Liu et al., 2015). For 2013 and 2014, 97% of the permits were given for free, while 3% were sold at auction.
The free allocation is useful in order to reduce the compliance cost for covered entities in the initial phase of a carbon trading scheme, but at the same time it reduces the efficiency of China's CTPs, leading to a less carbon reduction and to higher abatement cost resulting from lack of motivation to innovate.
Also, the free allocation cannot provide proceeds to governments, which are essential to support government and community programs in reducing carbon emissions. It is therefore fundamental for China pilots to shift from free allocation to auctioning of permits, at least starting from leakage-prone industries or particular sectors that are characterized by overcapacity (L. Xiong et al., 2015).

Distribution Patterns	China's CTPs						
	BJ	SH	TJ	SZ	CQ	GD	HB
Free distribution	≥ 95%	100%	100%	≤ 95%	100%	≤ 97%	≥ 90%
Competitive auction	< 5%	0%	0%	≥ 3%	0%	≥ 3%	≤ 3%
Fixed price sale	< 5%	0%	0%	≥ 2%	0%	0%	< 7%

Figure 17 – Distribution patterns of allowances in China's pilots (Ling Xiong et al., 2015)

As described by L. Liu et al. (2015), there are several methods for allocating quotas: for example the historical emission method (grandfathering), the public auction and so on. In China's CTPs the Historical emission method was the most used for allocating the carbon allowances, while in some pilots the auction method was also tried. A big issue China has to deal with is that few facilities and enterprises have complete records on what they have emitted, so the accuracy of quota allocation to the emitters is clearly scarce. Moreover, also the emission caps determination cannot be accurate: it is based on historical data from enterprise as well.
L. Liu et al (2015) state that the accuracy of the China's Carbon-Trading Pilots is highly influenced by three factors:

1. Slow response to real-time information, which greatly leads the inaccuracy of the quota allocation. The economic level, economic structure and energy structure vary continuously; therefore a flexible quota allocation mechanism, linking enterprise operation with economic growth in China, might be a better solution; instead of using historical standards to determine future emissions.
2. The verification mechanism differs among the seven carbon-trading pilots. Therefore, the randomness in settings greatly affects the fairness and validity of data.
3. The verification mechanism in operation is not able to satisfy the real-time and high frequency requirements of carbon trading. Enterprises covered by these pilots programs need to know how much they have emitted, how much they have reduced emissions and how many allowances they should purchase. Only in this way the carbon price would be able to link directly with production behaviour. It is clear that with the present verification settings these requirements are not satisfy.

3.3.3 China CTP Allowances Price

As assert before, in China, most allowances were freely allocated, therefore the carbon price equilibrium was difficult to ascertain since it was related to the success or failure of an auction (Zhang et al., 2017).
Moreover, the seven CTP produced seven different carbon prices in China as shown in Table 4. For this reason, allowances and offsets can only be traded on local emissions exchanges in the 7 pilots.
During 2016 prices in China range from €1.75 to €7 per tonne, with a peak to over €15 in the Shenzhen pilot (Swartz J., 2016). During 2013 and 2014, sometimes carbon prices in China's pilots were higher compared to the EU ETS one. The main reasons for these fluctuations in the seven ETS pilots are over allocation of allowances and policy uncertainties about banking/borrowing allowances from the

carbon-trading pilots to the China's national ETS. The lack of transparent market information and the uncertainty about the transition from the regional to the national ETS may have reduced the demand for carbon permits among the 7 ETS pilots. It is quite clear that the total volume of carbon trades by these pilots is quite limited, and the transaction price of carbon is not currently economically based. The carbon prices were indeed formed based on agreement and they almost played no guiding role (L. Liu et al., 2015).

Table 4 – First price of carbon in China's pilots (L. Liu et al., 2015)

Region	First price of carbon
Shenzhen	28 Yuan / ton ($4.57)
Guangdong	61 Yuan/ ton ($9.95)
Shanghai	First transaction prices were 27 Yuan / ton ($4.40), 26 Yuan / ton ($4.24), 25 Yuan / ton ($4.08)
Beijing	50 Yuan / ton ($8.15)
Tianjin	28 Yuan ($4.57) per ton of carbon quota
Hubei	20 Yuan / ton ($3.26)
Chongqing	30–30.15Yuan/ ton ($4.89–5.13)

As asserted by Liu et al. (2015), the enterprises covered by the 7 pilots still cannot completely understand the carbon-trade mechanism because of insufficient publicity, policy and theory explanations of carbon-emissions trading by the Government. Therefore, many of them consider participation in carbon trading just a social responsibility or a way to protect environment, and do not consider the changes or benefits which can be produced by carbon trade.

It is clear that at the moment the legislation for the administrative supervision and control and the operation of trading markets are still inadequate. For instance, among the seven carbon trading pilots, only the one in Shenzhen has legislative power. In particular, by focusing on penalties, the ones which will be imposed if covered emitters exceed their caps yet refuse to pay the resulting fees are still missing. Carbon prices strongly depend on penalties, because they influence the enterprises production behaviour by choosing penalty or carbon reduction. Without standardized rules defining penalties, the carbon price will not be a representative and instructive one.

Carbon price is a significant problem for the China's ETS pilots. It is evident that theory support, market system and mechanism design, scientific quota allocation, verification, a legal system, regulatory authority and potential changes are all important factors influencing carbon price. They all need to be developed and improved to build a representative carbon price that is fundamental for future integration of local markets into a national one.

The comparison between the 3 analysed cap and trade schemes is reported in Table 5.

Table 5 - Comparison between the cap and trade schemes above described

POLICY	REDUCTION TARGET FOR 2020	ETS PHASES	AUCTION SYSTEM	ALLOWANCES PRICE	INITIATIVE TYPE
EU - ETS	21% compared to 2005 levels	**1st Period (2005–2007)**: 3-year **pilot**, the total amount of allowances issued exceeded emissions **2nd Period (2008–2012)**: **Lower cap** on allowances; 3 new countries joined - Iceland, Liechtenstein, Norway **3rd Period (2013–2020)**: introduced a single, EU-wide cap; the cap on emissions from power stations and other fixed installations is reduced every year by 1.74%	**1st and 2nd period**: almost all allowances given to businesses for free **3rd period: > 50%** of total permits distributed through auctions	**1st Period (2005–2007)**: peak level of about 30€/tCO_2 (2006), the **excess** of allowances led to a price near to zero in 2007 **2nd Period (2008–20012)**: peak level of about 20€/tCO_2 (2008). During 2009 the price fell down, one of the causes: the economic recession. 2012 closed with a price of 6,67€/tCO_2 **3rd Period (20013–2020)**: adjustment on the allowances supply and limits on allowances banking led to a rising price trend in 2014 and 2015 (Dec 2015 around 8 €/tCO_2) but there was a sudden drop at the beginning of 2016. However, a strengthened energy sector led to an ascendent trend in 2017 (€ 7,42 in September 2017)	Both Eurpean and National initiative
RGGI	45 % in the region's annual power-sector CO_2 emissions from 2005 levels	**1st Period (2009-2011)**: annual states' overall emission budget set at 170 million tCO_2 **2nd Period (2012–2014)**: annual emission budget ajusted down to 150 milliom tCO_2 (New Jersey's withdrawal). Afeter the 2012 review, the cap decreased to 83 million tCO_2. **3rd Period (2015–2017)**: Introduced an annual cap decline of 2.5% from 2015 to 2020. 2015 cap was 80,49 million tCO_2, adjusted to 60,63 million tCO_2 because of allowances banked.	Approximately **90%** of RGGI CO_2 allowances are available on central **auctions**	**1st Period (2009-2011)**: first RGGI auction in Sep. 2008 all the allowances supplied were sold at $3.07 per allowance. Since the program was over-allocated with CO_2 allowances, in Sep. 2011 only 18% of the offered permits were sold at a lower price of $1.89 per allowance. **2nd Period (2012-2014):** in 2013, with the cap adjustemts, the deman for allowances increased as well as the price ($2,80 Q1 2013 and $5.41 Q1 2015). **3rd Period (2015-2017)**: the auctioning price continued to increase between 2013 and 2015 (March 2015 $5.41), however in 2016 a surplus of allowances led to a downward price trend (In March 2017 $3.00, the lowest price in more than three years)	Federal - Not at a Congress level
CHINA - CTP (Carbon Trade Pilots)	40–45 % of 2005 levels	**"Twelfth Five-Year Plan"period (2011-2015):** in 2013 carbon-trading pilots have been lunched in 4 municipalities, 2 provinces and the special economic zone of Shenzhen City. **"Thirteen Five-Year plan" period (2016-2020):** the carbon-trading market will be gradually extended nation wide	The majority of allowances is currently **free** with very small percentage **(3%-5%)** of total allowances being auctioned	The 7 CTP produced **7 different carbon prices** in China. Allowances and offsets can only be traded on local emissions exchanges in the 7 pilots. 2016 prices in China range from €1.75 to €7 per tonne, with a peak to over €15 in the Shenzhen pilot. The **price fluctuations** are due to overallocation of allowances and policy uncertainties.	Regional (Objective: National system gradually from 2017)

4. Conclusion and future steps

As discussed in this paper, it is clear that global warming poses a grave threat to the world's ecological system and the human race, and it is very likely caused by increasing concentrations of carbon emissions, which mainly results from such human activities as fossil fuel burning and deforestation (IPCC, 2007).
Mr. Peter Thompson, President of the UN General Assembly, during the COP22 (Conference of the Parties), required the transformation of the global economy in order to achieve a resilient and low emissions global economy (www.unfccc.int).
Global measures are actually needed in order to avoid irreversible and catastrophic changes, involving many countries with a common objective. A cooperative solution has indeed to be reached; otherwise without an effective global climate agreement no result will be accomplished (Stavins, 2008).
Therefore, the purposes of this work were to deeply study the most relevant international policies to combat climate change, in order to develop a comparison between them and to investigate if there actually is cooperation and a global-level agreement.
As presented in the paper, in order to mitigate global warming, the United Nations (UN), the European Union (EU), and many countries have introduced some policies and mechanisms to contain the total amount of greenhouse gas emissions.
Among these policies, one of the primary legislation is the European Union Emission Trading System (EU-ETS) that is by far the largest international GHG emission trading scheme with the purpose of mitigating climate change (Shen B. et al., 2014).
China, India and other developing countries were exempt from the requirements of the Kyoto Protocol, adopted in Kyoto, Japan, on 11 December 1997 (http://unfccc.int/kyoto_protocol). Nevertheless, now these fast growing economies (China, India, Thailand, Indonesia, Egypt, and Iran) have GHG emissions rapidly increasing and their pollution is also becoming a global issue. China and India will probably achieve more than 35% of total CO_2 emissions by 2030.
In order to reduce the emissions growth, China has developed a national policy program, which included the closure of old, less efficient coal-fired power plants and more investments on green energy. Moreover by the end of 2014, seven cap-and-trade pilot programs had been officially opened in Beijing, Shanghai, Shenzhen, Tianjin, Guangdong, Hubei and Chongqing (Liu L. et al., 2015) and in December 2017, China announced the initial details of its national emissions trading scheme
In the United States there currently is little action on climate change policy at the Congressional level: the Trump administration has recently decided to withdraw the US from the Paris climate accord and US officials declared at the COP23 in Bonn to promote coal-fired power and nuclear energy.
It is anyway possible to identify some regional and federal initiatives, for instance: RGGI, AB 32 in California, WCI between some US states and Canadian provinces.
During the COP23, has been underlined that non-state actors are becoming a driving force in adaptation and mitigation climate change (www.europarl.europa.eu). Therefore, California represents an example of how non-state actors are providing leadership where is missing the national governments one. Shen B. et al. (2014) describe California's emissions trading programme as the most ambitious cap-and-trade scheme at the individual state level.
Moreover, California Governor Jerry Brown and former New York Mayor Michael Bloomberg published during COP23 the first progress report from America's Pledge, a coalition of states, cities and businesses representing more than half of the population and the economy US.
It is possible to conclude that many countries have introduced policies and mechanisms to contain the total amount of greenhouse gas emissions but it is still missing an effective global cooperative solution. Some countries still consider the efforts to mitigate global warming as obstacles to striving for economic growth. However, without a comprehensive engagement, some actors are advantaged and more competitive in the global economy. Some others, involved in emission saving policies, have

to face stronger investments and restrictions, with the risk of suffering economic disadvantages and becoming therefore less competitive in the global economy.

As declared by the European Parliament resolution on the 2017 UN Climate Change Conference in Bonn, the efforts to avoid global warming should not be seen as an obstacle to economic growth but should, differently, be seen as a driving force for developing new and sustainable growth and employment: a valid climate mitigation policy can produce growth and jobs.

However, giving that some specific sectors with a high carbon intensity and high trade intensity could suffer from carbon leakage, a suitable protection against carbon leakage is therefore needed to protect jobs in these specific sectors.

The most serious effects of climate change will be felt in developing countries, particularly in those least developed, that have insufficient resources to adapt to the effects of climate change. Moreover, climate change can increase competition for resources such as food, water and intensify economic hardship and political instability (www.europarl.europa.eu).

The next step of this research can be to develop a mathematical model to face sustainability problems in real transportations and logistics scenario, in which the analysed Cap and Trade approaches are applied in order to lead managers towards sustainable and economic purchasing solutions.

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Sustainability in Material Purchasing: A Multi-Objective Economic Order Quantity Model under Carbon Trading

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Abstract: Sustainability in material purchasing is a growing area of research. Goods purchasing decisions strongly affect transportation path flows, vehicle consolidation, inventory levels, and related obsolescence costs. These choices have an economic impact on the supply chain, in terms of different logistic costs, and an environmental impact, in terms of the carbon emissions produced during goods transportation, storage and final recovery. In this paper, we initially analyze and compare the environmental economic policies established by the International Governments in relation to the carbon trading systems adopted. Then, we overcome a traditional single objective formulation, by developing a bi-objective lot-sizing model in which costs and emissions are kept separated and analyzed by using a Pareto frontier subject to a Cap and Trade mitigation policy. The model is useful in practice to support managers in understanding the Pareto frontier shape linked to a specific purchasing problem, defining the cost-optimal and emission-optimal solutions and identifying a sustainable quantity to purchase when a Cap and Trade mitigation policy is present. We further analyze the model behavior according to variation in market carbon price and we finally analytically demonstrate that today carbon prices are still far too low to motivate managers towards sustainable purchasing choices: there is still a gap of about 79%.

Keywords: multi-objective approach; sustainable purchasing; lot sizing; Cap and Trade; Economic Order Quantity; carbon price

1. Introduction and Background

The international increasing concern on environmental problems stresses the need to treat inventory management and goods purchasing decisions by integrating economic, environmental and social objectives. Sustainable Purchasing [1] means taking social, environmental and financial factors into consideration in making goods procurement decisions. Several managers are now looking beyond the traditional economic parameters and are starting to make decisions based on the whole life cost, the associated risks, measures of success and impacts on society and environment. Making decisions in this way requires taking into account a number of factors linked with goods procurement:

- economic measures (such as product price, inventory costs, ordering and transportation costs),
- the entire product life cycle (i.e., [2–4]),
- environmental aspects (i.e., [5]),
- social aspects, as the effects on issues such as poverty eradication, inequality in the distribution of resources, labor conditions, human rights, fair-trade, as well as social consequences of air pollution due to goods transportation (i.e., [6,7]),

- use of recycled materials and product remanufacturing (i.e., [8]).

Recently, Andriolo et al. [9] claimed that the international increasing concern on sustainable purchasing policies stresses the need to treat inventory management decisions as a whole by integrating economic, environmental, and social objectives. As described by Andriolo et al. [9], an increasing number of works have been published from 2011 with the aim of incorporating sustainability criteria in the traditional Economic Order Quantity (EOQ) theory.

In the research agenda proposed by Bonney and Jaber [5], the authors briefly present an illustrative model that includes vehicle emissions cost into the traditional EOQ formulation. Hua et al. [10] extend the EOQ model to take carbon emissions into account under the cap and trade system. Analytical and numerical results are presented, and managerial insights are derived. Benjaafar et al. [11] incorporate carbon emission constraints on single and multi-stage lot-sizing models with a cost minimization objective. Four regulatory policy settings are considered, based respectively on a strict carbon cap, a tax on the amount of emissions, the cap-and-trade system and the possibility to invest in carbon offsets to mitigate carbon caps. Insights are derived from an extensive numerical study. An interactive procedure that allows the company to quickly identify the most preferred option is proposed by the authors, while Jaber et al. [2] include emissions from manufacturing processes into a two-echelon supply chain model. Arslan and Turkay [12] propose EOQ models for a number of different policies in order to show how the triple bottom line considerations of sustainability can be appended to traditional cost accounting in EOQ model. Toptal et al. [13] extend the traditional EOQ model to consider total cost and emission reduction investment under three emission regulation policies. He et al. [14] examine the production lot-sizing issues of a firm under the Cap and Trade and Carbon Tax regulations, respectively. Recently, Shu et al. [15] extend the classical EOQ model, considering carbon emissions in (re)manufacturing activities and product transportation and provide an inventory cost model with carbon constraints, while Lee et al. [16] examine a sustainable economic order quantity (S-EOQ) problem with a stochastic lead-time and multi-modal transportation options. By applying the model to various numerical scenarios, they show the effects of incorporating sustainability considerations into the traditional inventory model on operational decisions.

However, all these works apply a direct-accounting method with a single cost objective function by transforming CO_2 emissions or social effects in economic measures. Since in most cases the cost and the emission functions yield different optimal solutions, the cost trade-offs are different from the emission trade-offs [9]. The limits of a direct accounting method when externalities need to be quantified are becoming evident in the recent literature (as also discussed by Battini et al. and Bouchery et al. [4,17]), asking for future efforts in keeping separated cost and emission functions, for instance according to a multi-objective optimisation approach.

A different way to include sustainability criteria into inventory models is proposed for the first time in the paper developed by Bouchery et al. [17], in which the authors apply a multi-objective formulation of the EOQ model abandoning the traditional approach of using a single objective function. However, in this work the authors simplify the reality by considering continuous transportation costs. Then, Andriolo et al. [18] focus the attention on the lot sizing theory when horizontal cooperation is established by supply chain partners, developing the sustainable EOQ model when two partners are cooperating in sharing transportation paths and handling units, by a multi-objective approach.

In order to follow the research agenda described by Andriolo et al. [9] and to make a step forward respect to the literature just described, the present work provides a new multi-objective Economic Order Quantity model for supporting managers in taking sustainable purchasing decisions. The model is the conceptual evolution of the previous [4] in which the authors provide a "sustainable EOQ model" that from an economic point of view incorporates the environmental impact of transportation and inventory holding in the total cost function, by a direct accounting approach. Here, as a second step of the research, the authors investigate the material purchasing strategy by applying a multi-objective optimization approach [19] in which the optimal lot-sizing decision depends on a bi-objective model with two different objective functions (costs and emissions) and transportation capacity constraints.

Costs and emissions are kept separated to better reflect the effect of the lot sizing problem under analysis by also providing managers with a new decision-support tool: the Pareto frontier associated to a specific material purchasing choice. The shape of the frontier (that could be flat or steep around the cost-optimal solution) reflects the real cost and emission increments, which a manager who decides to move from a cost-optimal lot sizing solution to a more sustainable solution has to face, by better consolidating transportations.

Moreover, the Cap and Trade system approach is integrated in the multi-objective model in order to understand the impact of economic incentives (the so-called carbon allowances) on taking sustainable-oriented purchasing decisions. The Trading system used here is inspired to the current EU ETS (Emission Trading System) system (www.ec.europa.eu) and on the carbon cap evolution forecasted in the medium term. In particular, the multi-objective model here presented differs from the one developed by Bouchery et al. [17]. In this case, the transportation cost function and transportation emission function are modelled according to their real nature: piecewise convex function of the ordering levels with discontinuities at the cost breaks (the transportation vehicles' saturation points), unlike the traditional model where the total cost is convex over the entire range of ordering levels [17]. This formulation is essential to better understand and quantify the benefit of transportation consolidation when deciding goods purchasing lot sizes. Finally, the model behavior is investigated according to variation in market carbon price, analytically demonstrating that current carbon prices are still far too low to motivate managers towards sustainable purchasing choices: there is still a gap of about 79%.

This paper is organised as follows. In Section 2 we present a brief overview of the Cap and Trade mitigation policy and the effects of the carbon trading market. In Section 3 the multi-objective EOQ model formulation is presented and the interactive decision making approach is explained. A parametric analysis is provided in Section 4 to better discuss the effect of Cap and Trade mechanism on buyers' decisions, according to variation in the carbon market price. Finally, Section 5 discusses the conclusions.

2. Cap-and-Trade System and EU Carbon Price Value Trend

Cap-and-trade (C&T) and carbon tax are two emission regulations widely used to curb the carbon emissions generated from firms and air-transportations in EU, US States, and New Zealand [20]. Reference [21] argues that C&T has a number of important advantages compared to carbon tax, such as political feasibility, cost effectiveness, broad participation, equity in the international context, and control on the cumulative quantity of emissions.

The Emission Trading System (ETS) is a cost-effective way of the European Union's policy to combat climate change and to reduce industrial greenhouse gas emissions (GHG). It has been launched in 2005 and it works on the "cap and trade" principle [2]: a cap is set on the total amount of a certain GHG that can be emitted by factories, power plants, and other installations. The cap is reduced over time, in this way the total emissions decrease. The target for 2020 is a reduction of 20% of GHG emissions compared to 1990 levels. The EU ETS regards, in particular, power plants, a wide range of energy-intensive industry sectors and operators of flights to and from the EU, Iceland, Liechtenstein, and Norway. The companies involved into this system sell or buy emission allowances, which they can trade with one another as needed. Each allowance corresponds to the right to emit 1 tonne of CO_2. Businesses must report their EU ETS emissions every year and provide enough allowances to cover them by 30 April of the following year. If a business does not surrender enough allowances to cover its emissions, it must buy allowances to make up the shortfall; its name is published, and has to pay a fine for each excess tonne of greenhouse gas emitted (www.ec.europa.eu). This policy, by putting a price on carbon, implies some interesting consequences: each tonne of emissions saved has a financial and commercial value and a sufficiently high carbon price can promote investment in clean, low-carbon technologies. The price of carbon allowances (the so-called carbon price) is determined by supply and demand according to a market-oriented mechanism. During the first phase of EU ETS (2005–2007), the price of allowances increased up to a peak level of about €30/tCO2e in April 2006 (www.publications.parliament.uk). Nevertheless, the excess of allowances led to a trading price of €0.10 in September 2007. The estimated needs were excessive; in this way, the allowances price fell to zero (www.ec.europa.eu). During the Phase II (2008–2012) the carbon price increased to over €20/tCO2e in the first half of 2008, but the 2012 closed with a price of around 6.67 €/tCO2e. One main reasons for this fall in prices was that the economic downturn led to a reduced output in energy-intensive sectors; therefore, less abatement has been required to respect the cap and the market has been oversupplied with permits, leading to the downfall of the price. For Phase III (2013–2020) the European Commission has proposed some changes that during the first three quarters of 2015 conducted the allowances price trend to rise. The allowances average price from the third quarter of 2015 until the first quarter of 2017 was between €7.90 (EEX-DE platform) and €7.92 (EU t-CAP platform). From March 2017 a positive trend is present and at the end of April 2018 the carbon price was around 13.4 €/tCO2e and then it grew again for the entire month of August 2018 to about 21 €/tCO2e (on 27 August 2018): this trend is considered from some major analysts an indicator for a long-term growing trend (www.gse.it).

The International Emissions Trading Association (IETA, www.ieta.org) describes some of the emissions trading advantages:

- Cap-and-trade is designed to fulfil an environmental outcome, in that the cap must be met
- This trading scheme will deliver its environmental objective at lowest cost to the economy.
- It can be fundamental for setting a global agreement to reduce emissions: national trading systems can be linked with other similar systems, driving to a global carbon market.
- Cap-and-Trade offers to business both compliance and policy flexibility, it delivers an economic incentive to the companies able to innovate and find more effective ways of reducing emissions.
- Cap-and-trade has proven effectiveness: for example, in the US acid rain program it quickly reduced pollution levels at a lower cost than expected.

3. Theoretical Formulation

The mathematical formulation that follows tries to capture economic and environmental trade-offs in material purchasing lot sizing. It is considered the single-product replenishment problem and applied a bi-objective optimization approach by modelling the EOQ problem for incoming goods to be purchased by a company, in accordance with two distinctive objective functions: the total annual cost function and the total emission cost function. It is supposed that the product demand is deterministic, the product price is exogenous and the buyer decides only the order size.

First, we introduce the notations used in the model as follows:

Indices

i container/vehicle type
j transportation mode

Decision Variables and Cost Functions

Q decision variable [units/purchasing order]
$C(Q)$ total average annual cost of replenishment [€/year]
$E(Q)$ total annual emission generated by the replenishment [CO2e/year]
Q_c^* optimal order quantity for the cost function [units/purchasing order]
Q_e^* optimal order quantity for the emission function [units/purchasing order]

Input Parameters

D annual demand [units/year]
p unit purchase cost [€/unit]
p' unitary scrap price [€/unit]

b space occupied by a product unit with sale packaging [m^3/unit]
a weight of a unit stored in the warehouse [ton/unit]
O fixed ordering cost per order [€/order]
h holding cost [€/unit]
β average inventory obsolescence annual rate [%]
y full load-vehicle/container capacity [units or m^3]
v average freight vehicle speed [km/year]
d_j distance travelled by transportation mode j [km]
$c_{f,j}$ fixed transportation cost coefficient for transportation mode j [€/km]
$c_{v,j}$ variable transportation cost coefficient for transportation mode j [€/km m^3]
$c_{ef,j}$ fixed transportation emission coefficient for transportation mode j [kgCO2e/km]
$c_{ev,j}$ variable transportation emission coefficient for transportation mode j [kgCO2e/km m^3]
c_{eh} warehouse emission coefficient [kgCO2e/m^3]
c_{eo} waste collection and recycling emission coefficient [kgCO2e/ton]
n_i number of full load-vehicle/container i [units]
y_i full load-vehicle/container i capacity [units]
k range of order quantity Q_s between the two discontinuity points DP_k and DP_{k+1}
DP_k Discontinuity Point for range k, defined as $\sum_i n_i \cdot y_i$
S_j freight vehicle j utilization ratio in %
C value of carbon price quoted in the market [€/tCO2e]
cap carbon cap according to a cap and trade system [tCO2e]f
$cap\%$ emission reduction by reaching the cap value respect to the maximum emission value
ΔE_{cap} emission reduction by reaching the cap value [tCO2e]
ΔC_{cap} cost increment by reaching the cap value [€]

Unlike prior models already discussed in Section 1, transportation costs are here considered explicitly and modeled according to their true discontinuity nature.

Let us introduce the first objective function $f_1(Q)$ that quantifies the average annual cost of replenishment and it is expressed as follows:

$$f_1(Q) = C(Q) = p \cdot D + C_o(Q) + C_h(Q) + C_{obs}(Q) + C_t(Q) \quad (1)$$

In detail, the terms included in this formulation are defined as follows (from [4]). The ordering cost $C_o(Q)$, associated only to the buyer fixed cost of processing the order, and the holding cost $C_h(Q)$ are calculated according to the traditional models:

$$C_o(Q) = \frac{D}{Q} \cdot O \quad (2)$$

Holding cost now considers both the traditional holding cost of carrying inventory in the warehouse and the cost associated to hold inventory during the transportation activity that is not as function of Q, as expressed by the following formula (derived from [22]):

$$C_h(Q) = \frac{Q}{2} \cdot h + Q \cdot \frac{d}{v} \cdot \frac{D}{Q} \cdot h \quad (3)$$

where v is the freight vehicle speed expressed in km/year.

To make the application of this formulation less time-consuming, a simple but plausible formulation for obsolescence cost $C_{obs}(Q)$ is here applied:

$$C_{obs}(Q) = \frac{Q}{2} \cdot (p - p') \cdot \beta \quad (4)$$

An obsolete event comes from a specific cause (i.e., a change in the product design or in product technical specification) and makes immediately unusable the inventory on hand. We here apply the obsolescence annual risk rate β according to [4]. At the end of each year, the remaining stocks are sold by the buyer to a specific waste treatment company for disposal at the unitary scrap price p', lower than p. In some cases, p' could also become negative, for example if the owner has to pay the waste treatment company for the disposal service.

Due to the relevance of transportation cost $C_t(Q)$ on the optimization of the order quantity [23], its formulation includes both fixed and variable costs and it presents Discontinuity Points DP_k when the vehicle capacity is saturated. Thus, we express the transportation costs with the sum of a fixed portion (expressed in €/km since it does not increase with the order quantity but only with the travelled distance) and a variable portion, which depends on the quantity transported and on the vehicle saturation.

The vehicle saturation S_j depends on the quantity transported, on vehicle capacity y_i and on the number of vehicles used in the order cycle n_i:

$$S_j = \frac{Q}{\sum_i n_i \cdot y_i} \tag{5}$$

under the following constraint:

$$\sum_i n_i \cdot y_i \geq Q \tag{6}$$

As discussed in previous studies [4,23], the transportation cost is not a continuous function and it cannot be differentiated during the whole interval. Moreover, the value n depends on the number of different vehicle types used in the transportation (for example different containers with different capacities). In practice, in a global supply chain scenario, more types of vehicle are available with different capacities and different costs. Hence, it is necessary to accurately evaluate all the discontinuity points and ranges between them and apply a step-by-step approach, as already adopted in literature. To simplify the problem, when DP_k is the Discontinuity Point k, obtained after the accurate evaluation of all capacity saturation ranges of different kinds of container i that are applied in the same purchasing cycle, we can assert that, in general:

$$S_j = \frac{Q}{\sum_i n_i \cdot y_i} = \frac{Q}{DP_k} \tag{7}$$

and, then, express the transportation cost $C_t(Q)$ for each kind of transportation mode j used, as follows [4]:

$$C_{tj}(Q, d_j, S_j) = \left(c_{f,j} \cdot d_j \cdot \sum_i n_i + c_{v,j} \cdot d_j \cdot DP_k\right) \cdot \frac{D}{Q} \tag{8}$$

Concluding, the first function to optimize is expressed as follows (considering the whole mix of transportation modes used in the material supply from vendor to buyer):

$$f_1(Q) = C(Q) = p \cdot D + \frac{D}{Q} \cdot O + \frac{Q}{2} \cdot h + \frac{d}{v} \cdot D \cdot h + \frac{Q}{2} \cdot (p - p') \cdot \beta + \sum_j \left(c_{f,j} \cdot d_j \cdot \sum_i n_i + c_{v,j} \cdot d_j \cdot DP_k\right) \cdot \frac{D}{Q} \tag{9}$$

The second objective function $f_2(Q)$ is the average total quantity of emissions generated during the annual purchasing activity and it can be expressed by the sum of the emissions generated in the following three steps: material order transportation, warehousing, and waste collection and treatment of the obsolete items. Thus, by an environmental point of view, only three terms must be considered and homogeneously expressed in tons of CO2e:

$$f_2(Q) = E(Q) = E_h(Q) + E_{obs}(Q) + E_t(Q) \tag{10}$$

The first term computes the average quantity of equivalent carbon emissions generated by warehousing during the time unit of one year:

$$E_h(Q) = c_{eh} \cdot \frac{Q}{2} \cdot b \quad (11)$$

Here, c_{eh} is the average emission cost coefficient of a warehouse expressed in € per cube meter of warehouse space occupied by inventory (this coefficient differs in case we use or not a temperature controlled warehouse), and b measures the cube meters occupied by a product unit stored in the warehouse (considering also packaging materials).

The inventory stored in the warehouse presents a risk of obsolescence at the end of the year, expressed by the obsolescence annual risk rate β. Obsolescence goods at the end of the year are sold by the buyer to a specific waste treatment company for recycling at the disposal price p', lower then p. Anyway, in this case we only consider the emissions generated during the waste collection and treatment process. Therefore:

$$E_{obs}(Q) = \frac{Q}{2} \cdot \beta \cdot a \cdot c_{eo} \quad (12)$$

where c_{eo} is the carbon emission cost coefficient for obsolete inventory waste collection and recycling, expressed in €/ton and a is the weight of an obsolete unit stored in the warehouse in tons/unit. Finally, due to the reasons described above and to the discontinuity nature of the transportation cost function, also the emission function linked to the transportation activity is described by a discontinuous function, as follows:

$$E_{tj}(Q, d_j, S_j) = (c_{ef,j} \cdot d_j \cdot \sum_i n_i + c_{ev,j} \cdot d_j \cdot DP_k) \cdot \frac{D}{Q} \quad (13)$$

Thus, the second objective function to optimize is finally expressed as follows (considering the whole mix of transportation modes used in the material supply from vendor to buyer):

$$f_2(Q) = E(Q) = c_{eh} \cdot \frac{Q}{2} \cdot b + \frac{Q}{2} \cdot \beta \cdot a \cdot c_{eo} + \sum_j \left(c_{ef,j} \cdot d_j \cdot \sum_i n_i + c_{ev,j} \cdot d_j \cdot DP_k \right) \cdot \frac{D}{Q} \quad (14)$$

According to a generic Pareto design optimization problem [19] involving the two conflicting objective functions introduced above, it can be concisely stated:

$$Minimize\{f_1(Q), f_2(Q)\} \quad (15)$$

A Pareto-optimal solution is also defined "Pareto-efficient solution", and the set of all efficient points is called the Pareto Frontier. It is generally impossible to come up with an analytical expression of the Pareto Frontier; however, a basic requirement for Pareto optimality is expressed in the following:

"Q^* is a Pareto-optimal solution to the problem posed by Equations (9) and (14), if there does not exist any other design Q such that $f_1(Q) \leq f_1(Q^*)$ and $f_2(Q) \leq f_2(Q^*)$ simultaneously."

The number of Pareto-efficient solutions Q^* can be quite large, and it is yet necessary to select the best compromise design(s) among them. Thus, a sustainable purchasing choice normally increases $f_1(Q)$, while decreases $f_2(Q)$, since the two objective functions are competitive in nature.

If QQ_c^* is the single optimal solution of the objective function $f_1(Q)$ and QQ_e^* is the single optimal solution of $f_2(Q)$, we can call EF the Efficient Frontier of the lot sizing problem here proposed and EF^c its image in the criterion space, then:

$$EF = \lfloor QQ_c^*, QQ_e^* \rfloor \quad (16)$$

EFQ_+^c is convex and there exists $Q_{min} < Q_{max}$ such that $Q^* \in [Q_{min}, Q_{max}]$.

As a consequence, the shape of the EF strongly affects the possibility to move from a cost-optimal solution to an emission-optimal one.

We can now define the following three measures, all related to the EF shape:

$$\Delta Q = Q_{max} - Q_{min} = |QQ_c^* - QQ_e^*| \quad (17)$$

$$\Delta C = f_1(Q_{max}) - f_1(Q_{min}) \quad (18)$$

$$\Delta E = f_2(Q_{max}) - f_2(Q_{min}) \quad (19)$$

The first one expresses by a quantitative point of view the extension of the efficient frontier curve in the space, that is, the distance between the emission-optimal solution and the cost-optimal solution in term of purchasing units. By computing the rate $\Delta C/\Delta E$ we can express the expected marginal increment in annual logistic cost per ton CO2e, in order to move towards an emission optimal solution instead of a cost optimal solution. The solution of the multi-objective problem under consideration can be achieved using the concept of indifference band [24]. An indifferent band is the area on the Cartesian coordinate plane where the feasible solutions are all equally desirable to the decision maker. Between any two solutions in the indifference curve there is a trade-off, so that a decrement in the value of one objective function f_i inevitably determines an increment in the other objective function f_j.

When a carbon cap is set according to a Cap and Trade regulatory policy, a company can decide to reduce the total emissions below the cap in order to respect the governmental constraint; on the contrary, the company has to buy carbon allowances on the carbon market.

By a traditional cost-oriented optimization approach, a company prefers to apply a cost-optimal solution in order to minimize the total annual purchasing cost, so that the costs are at minimum but, consequently, the emissions are maximized (QQ_c^*).

In order to reduce the total annual emissions below the cap value, the company has to move in the Pareto Frontier from right to left until it is possible to define a transportation quantity that is applicable as a purchasing lot size.

In doing this, the company will inevitably increase its annual costs. We here define this marginal increment in total annual costs as the Marginal Logistic Cost (MLC), defined as follows:

$$MLC = \frac{\Delta C_{cap}}{\Delta E_{cap}} \quad (20)$$

The concept of MLC is shown in Figure 1.

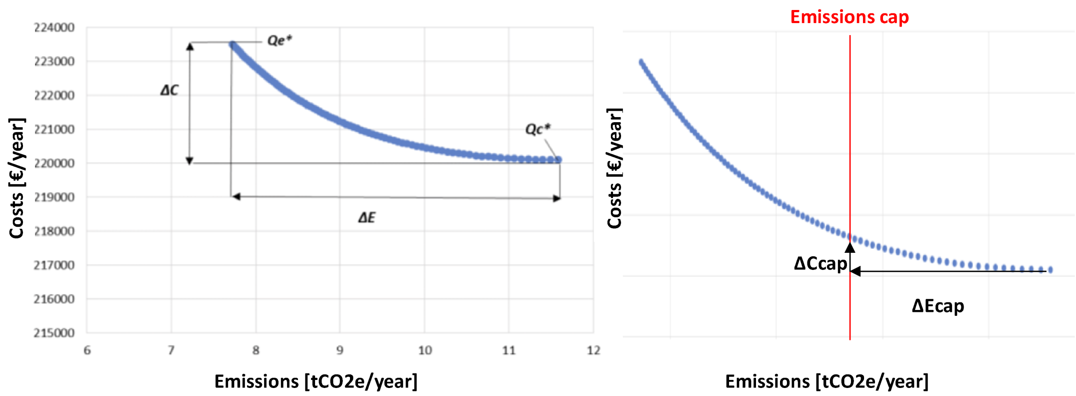

Figure 1. Pareto Frontier (left) and carbon cap effect in the Pareto Frontier (right).

The MLC value varies according to the different shapes of the Pareto Frontier, which in some industrial sectors could be steep or on the contrary more flat. When a carbon cap is coupled with a carbon allowance in a cap and trade system, the market carbon price C represents the allowance that helps the company to fit and go under the defined carbon limit (the cap).

By introducing the parameter φ defined as follows:

$$\varphi = \frac{MLC}{C} \tag{21}$$

Three different situations could be identified in practice:

- $\varphi > 1$: the MLC is major than the carbon price and the company has two options:
    a. buy carbon allowances in the carbon market instead of investing in reducing emissions by transportation consolidation
    b. autonomously sustain an extra cost in order to reduce its emissions under the cap value equal to $MLC - C$
- $0 < \varphi \leq 1$: the MLC is lower or at least equal to C and the company could earn by the reduction of emissions an extra saving equal to $C - MLC$. For this reason, the company is fully economically supported and the company decision maker is motivated in increasing the purchasing quantity of incoming materials while saturating vehicles.
- There is no feasible solution to better consolidate transportation since the cost-optimal solution is equal to the emission-optimal solution: the company could only change the supplier or the transportation modality.

In the next paragraph a numerical application of the model with a parametrical analysis is reported in order to understand how the Pareto Frontier shape specifically built for each industrial case could affect the value of the parameter φ and the consequent emission reduction. The proposed bi-objective model does not aim at finding a single optimal solution at once. The problem could be solved only by an interactive approach during the decision-making [25]. The decision makers (as managers and buyers) by yielding all of the potentially optimal solutions and by understanding the shape of the Pareto Frontier in each specific case, can understand the trade-offs between extra-logistic costs and economic incentives (carbon allowances) and finally define how to improve their purchasing strategy.

4. Parametric Analysis and Discussion

In this section we present a parametric analysis, directly inspired by real industrial cases, to illustrate the above analytical model and provide some observations of the Cap and Trade system applied to the material purchasing and transportation setting.

Let us consider a set of different goods purchased and transported inside logistic load units (i.e., stock keeping unit, box, etc.), each of them with a different weight and volume. The product purchasing price changes in order to provide results suitable for a wide range of real situations. The products considered in the following example can be easily assimilated to different industrial sectors (from small electrical equipment, cellular phones, computers to fashion items and metal parts etc.). The buyer's company is located in the North-East part of Italy and closed to intermodal terminals, while the vendor is located overseas (e.g., in Hong Kong). Transportations are made by adopting a rail-ship intermodal transport with only a final short handling by truck.

Constant input data and fixed transportation costs values reported in Table 1 are derived from [4], while carbon footprint coefficients are calculated using the Ecoinvent database in SimaPro Software (www.simapro.co.uk). The cost and emission functions reported in Formulas (9) and (14) are computed in relation to the set of discontinuity points DP_i identified according to the different handling units used in the purchasing network (container 1: ISO 20 feet and container 2: ISO 40 feet). The input parameters subject to variations are reported in Table 2.

Table 3 lists all the dependent variables in the model, with relation to the input data. The saturation of the two types of containers can be achieved by volume or by weight, depending on the characteristics of the product (see Table 3). From Table 1, it can be noticed that the Apparent Density ρ has been introduced and in the present numerical application it is fixed to 300 kg/m^3, in order to generate plausible situations for the type of products under consideration. The risk of obsolescence of the inventory is supposed fixed and equal to $\beta = 0.15$.

Figure 2 shows the trend of the Pareto Frontiers for the 5 different values of product weight reported in Table 2. Note that the scales are the same for all the graphs, in order to facilitate a visual comparison. At a first glance, we immediately notice that as the product weight increases, the width of the frontiers decreases, then the number of Pareto optimal solutions belonging to the Frontier decreases. Moreover, the frontiers move from lower to higher values of the total emissions, but at the same time, the total annual costs decrease. Consequently, they move towards the right lower part of the Cartesian plane. At equal weight instead, as the product price increases, the efficient solutions move towards higher values for both costs and emissions.

Table 1. Constant Input data.

Constant Input Data	Value	Constant Input Data	Value
D	40,000	$c_{v,road}$ [€/km·m^3]	0.01
O [€/order]	400	$c_{f,rail}$ [€/km]	0.6
d [km on road]	100	$c_{v,rail}$ [€/km·m^3]	0.007
d [km by train]	500	$c_{f,ship}$ [€/km]	0.48
d [km by ship]	14,000	$c_{v,ship}$ [€/km·m^3]	0.003
Inner volume container1 [m^3]	33.2	c_{eh} [kgCO2e/m^3·year]	24
Load Capacity container1 [tons]	21.75	c_{eo} [kgCO2e/ton]	77.004
Inner volume container2 [m^3]	67.2	$c_{ef,road}$ [kgCO2e/km]	2.20017
Load Capacity container2 [tons]	26.70	$c_{ev,road}$ [kgCO2e/ton·km]	0.154398
v_{road} [km/year]	525,600	$c_{ef,rail}$ [kgCO2e/km]	1.28017
v_{rail} [km/year]	788,400	$c_{ev,rail}$ [kgCO2e/ton·km]	0.0392892
v_{ship} [km/year]	219,000	$c_{ef,ship}$ [kgCO2e/km]	0.06443
$c_{f,road}$ [€/km]	0.8	$c_{ev,ship}$ [kgCO2e/ton·km]	0.0088875
ρ [kg/m^3]	300	β[%]	15

Table 2. Variable Input data.

Variable Input Data	Set of Values
p [€/unit]	[1; 10; 20; 40; 70; 110; 160; 220; 290; 370]
a [kg/unit]	[0.5; 1; 5; 10; 20]

Table 3. Dependent Variables.

Dependent Variables	Relation with Variable Input Data
b [m^3/unit]	$a/(\rho \cdot 1000)$
p' [€/unit]	$0.5 \cdot p$
h [€/unit]	$0.25 \cdot p$
y_1 [units/container1]	Min (Inner volume container1/b; Load Capacity container1/a)
y_2 [units/container2]	Min (Inner volume container2/b; Load Capacity container2/a)

By comparing the different Pareto Frontier shapes in Figure 2 we can summarize the following:

- each material purchasing decision has a specific Pareto Frontier associated, which is capable to drive the decision maker to the final choice according to an interactive approach;
- the more the frontier is large and flat around the cost-optimal solution, the more possibilities exist to increase the purchasing lot sizing quantity with a consistent reduction in emission and a limited increment in total costs;
- when the product weight is low and the product purchasing price is high, the Frontier is large and flat around the cost-optimal solution, leaving possibilities to managers to increase the purchasing lot size, saturate vehicles and reduce emissions;

- when the product weight is higher and product price is lower, ΔC and ΔE are reduced, and the frontier is shorter and constituted only by some few points. This happens since the vehicles are saturated faster;
- the trend of the outputs in relation to the price p is also evident: for the same value of the product weight, lower values of the product price p determine lower values of ΔC and ΔE; when it increases, also the gap between the two optimal lot sizing solution QQ_c^* and QQ_e^* increases and, thus, both ΔC and ΔE become higher.

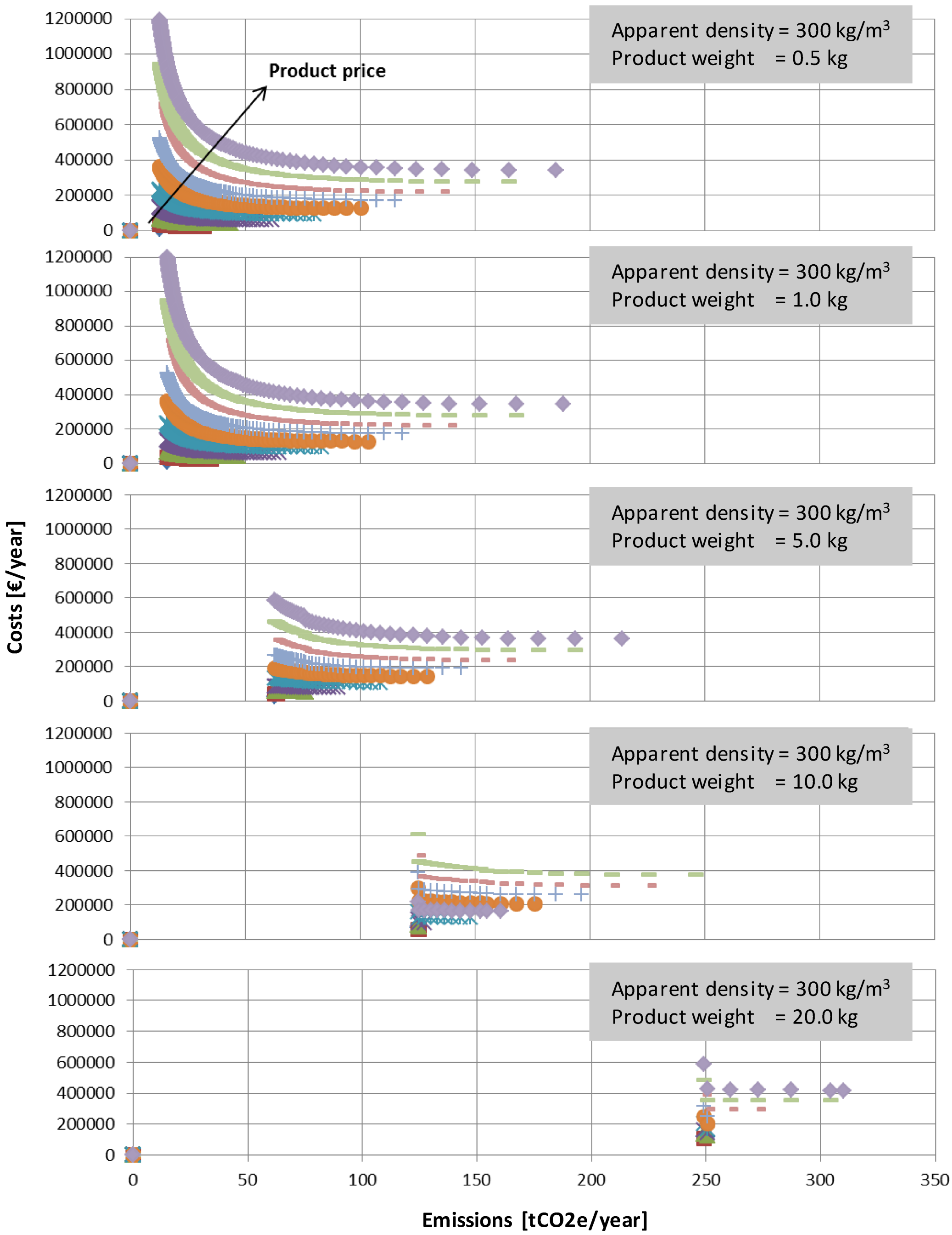

Figure 2. Sensitivity analysis of the Pareto Frontier according to variations in the product unitary price (with different colours) and in the product weight (from top to down).

Finally, a sensitivity analysis of the parameter φ introduced in the previous paragraph is performed, according to variations in product price (from 5 to 1000 €/item) and product weight (from 0.5 to 5 kg/item), in order to understand the incidence of the marginal logistic cost with respect to the market carbon price applied under a Cap and Trade approach. The results are reported in Figures 3 and 4. Figure 3 shows the trend of the parameter φ in relation to the product price. In the case illustrated in the Figure 3, the product weight is set at 0.5 kg/item and it is required an emission reduction to reach the cap of 10% (*cap*%) It is shown that the higher the product price, the higher is the φ value. This means that for a higher product price, larger extra costs and profit sacrifices are required to the company in order to reduce its annual emissions below the cap and to perform an efficient transportation vehicle saturation. Therefore, more expensive products reach φ values equal or lower than 1 for higher carbon price values: the φ value starts to be equal to 1 only with a carbon price major than 100 €/tCO2e when the product price is equal to 5 €/item. By considering the current carbon price of 21 €/tCO2e (28 August 2018), the φ value is close to 5 when the product price is 5 €/item, which means that the company needs to invest 5 times the carbon allowance value in order to reduce emissions of 1 tCO2e.

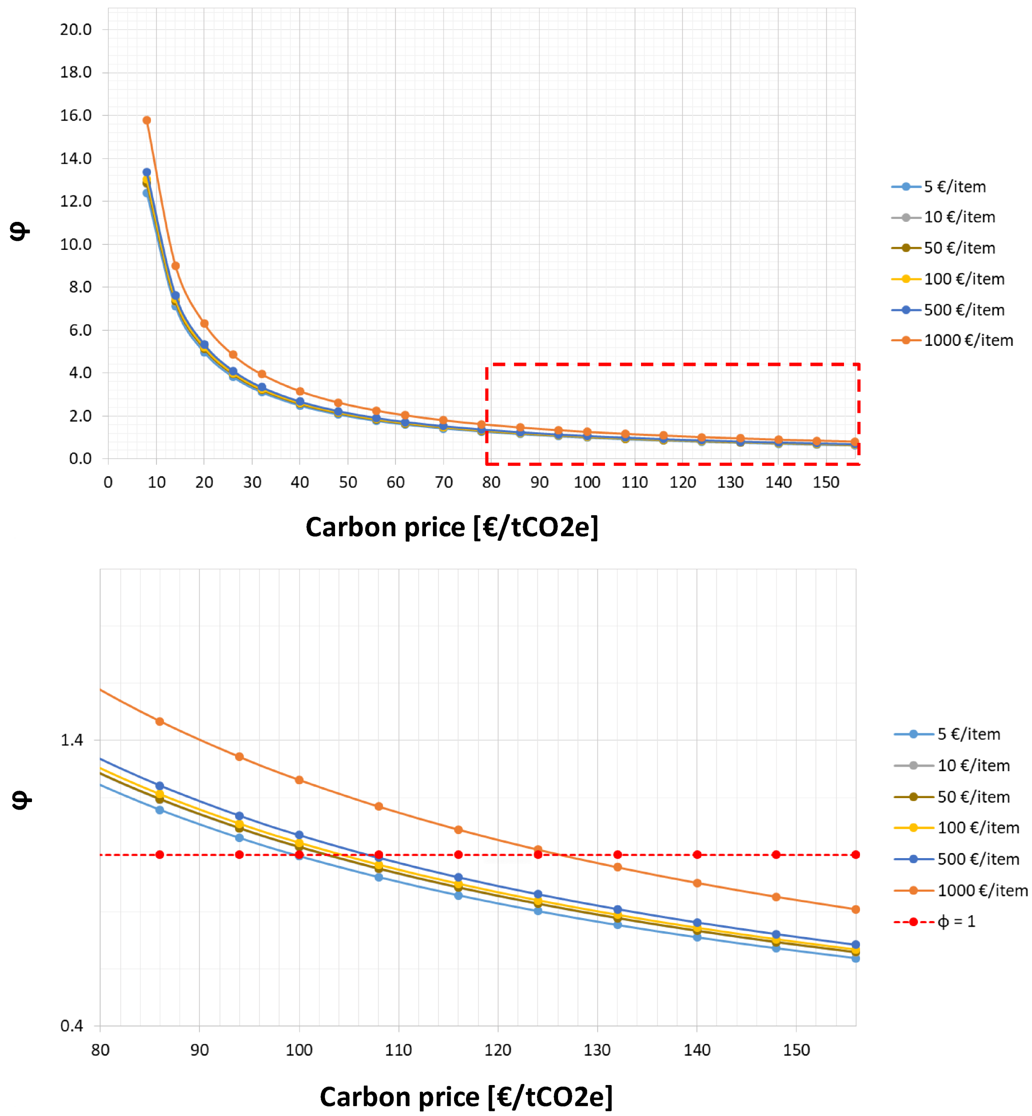

Figure 3. Sensitivity analysis of the parameter φ according to variation in the purchasing item price and in the carbon price (on top) and a zoom to understand when the parameter φ equals to 1 (product weight = 0.5 kg/item).

The same situation is also evident in Figure 4, showing the trend of the parameter φ in relation to the product weight. In the case illustrated the product price is set at 50 €/item and it is required also in this case an emission reduction to reach the cap of 10% (*cap*%) for an item purchasing. It is shown that the higher the product weight, the higher is the φ value. This means that for a higher product weight, bigger extra costs are required to the company in order to reduce its annual emissions under the cap. Therefore, heavier products reach φ values equal or lower than 1 for higher carbon price values, and always with a carbon price major than 100 €/tCO2e. This means that with the current carbon price values (21 €/tCO2e in the ETS system in 27 August 2018) significant extra costs and profit sacrifices are necessary for the company in order to reduce its annual emissions under the cap and there is still a gap of 79% in order to reach a φ value equal to 1.

Thus, a cap-and-trade system if applied to the material purchasing and transportation sector should be carefully adapted to each industrial sector and should also provide a higher value of the carbon price value in order to really incentive companies towards sustainable choices. We demonstrate for the first time, by a mathematical point of view, that current carbon price values are still far too low to motivate managers towards sustainable purchasing choices.

However, managers highly oriented to sustainable choices could always decide to reduce emissions instead of buying carbon allowances by accepting to increase the total purchasing cost and reducing their profit margins.

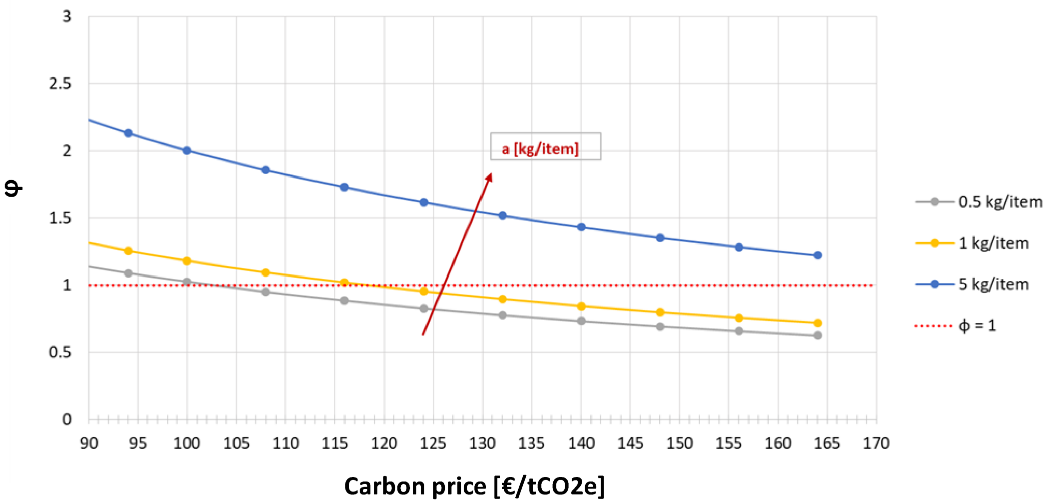

Figure 4. Sensitivity analysis of the parameter φ according to variation in product weight and carbon price (product price = 50 €/item).

5. Conclusions

The paper develops a multi-objective EOQ model that considers a typical global supply-chain purchasing problem with long-distance freight transportation, but it could be also applied to a domestic transportation case. Total purchasing costs and total CO_2 equivalent emissions are taken into account to build the Pareto Frontier as a tool to support managers' decision making in an interactive way. The model is applied to a simple set of numerical scenarios, where a number of input data are fixed and inspired to a real case, while other product features (weight and product purchase price) assume various values. The parametric analysis here developed permits to analyze the different shapes of the Pareto Frontiers according to the variations in these key parameters. Moreover, the model introduces for the first time the parameter φ in order to better support managers in understanding the economical convenience in reducing carbon emissions by taking a sustainable purchasing choice. The parameter is the rate between the marginal increment in total annual costs, the Marginal Logistic Cost (MLC), and the market carbon price C, that represents the allowance that helps the company to fit and go under the defined carbon limit (the carbon cap). Only with $\varphi < 1$, the company is economically motivated to reduce emissions by consolidating transportations and increasing purchasing lot size; otherwise, until the φ parameter is higher than 1, the company needs to autonomously sustain an extra cost in order to reduce its emissions under the cap value.

The graphical results provided in Figures 3 and 4 permit to summarize the following main conclusions:

(a) A bi-objective approach to material purchasing overcomes the limits of a direct cost accounting approach in which emissions are transformed in costs and only a single objective function is considered, as previously highlighted also in [4,9].
(b) By a practical point of view, the analysis of the Pareto frontier is useful to address managers towards the correct comprehension of the sustainable purchasing problem, by identifying the cost-optimal and the emission-optimal solutions, while having an immediate comprehensive visualisation of Pareto frontier shape (Figure 1).
(c) The purchasing manager can be driven to decide the material purchasing quantity to order when a cap and trade mitigation policy is present, with an immediate comprehension of the effects of his/her choice in terms of emissions and costs (Figure 1).
(d) The Carbon Trading systems currently applied by Governments in order to mitigate the emission production in some critical sectors, is a promising tool to be applied also in the field of freight transportation and material purchasing when ship/train/road transportation modes are considered.
(e) In this paper, we analytically demonstrate that the current carbon prices (i.e., 21 €/tCO2e at the end of August 2018 in the ETS trading system) are still too low to sustain and economically motivate a feasible extension of the cap-and-trade policy to the freight transportation sector and to the sustainable purchasing problem under analysis. In fact, Figures 3 and 4 show that, by considering the current carbon price of 21 €/tCO2e (28 August 2018), there is still a gap of 79% in order to reach a φ value equal to 1.
(f) The current positive trend in worldwide carbon price values (especially in Australia and Japan) is quite encouraging: if the carbon price will reach in the near future the threshold of 100 €/tCO2e, the cap and trade mechanism will start acting as an economic incentive for company managers and buyers towards more sustainable purchasing choices.
(g) However, even without the presence of effective carbon mitigation policies, a purchasing manager can always decide to apply a sustainable purchasing quantity to better consolidate transportation, by accepting a profit sacrifice in order to be more sustainable. The higher the profit margin of the item purchased is and the lower the sacrifice asked to the purchasing company will be in order to be more sustainable.

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