Influence of Lead Time and Emission Policies on the Design of Supply Chains – Insights from Supply Chain Design Models

Inaugural Dissertation

to obtain the academic degree Dr. rer. pol.
from the faculty for economics
of the Julius-Maximilians-University Würzburg

Benjamin Siller
Master of Science

Würzburg 2021

First Supervisor:

PROF. DR. RONALD BOGASCHEWSKY

Chair of Industrial Management

Julius-Maximilians-Universität Würzburg

Second Supervisor:

PROF. DR. UDO BUSCHER

Chair of Business Management, esp. Industrial Management

Technische Universität Dresden

Acknowledgements

This dissertation would not have been possible without the continued support and encouragement by many people over the last few years.

First, I want to thank my first supervisor, Prof. Dr. Ronald Bogaschewsky, who supported my research during every step. I am extremely grateful for the academic and personal freedom he provided. Additionally, I want to thank my second supervisor, Prof. Dr. Udo Buscher, for the fast preparation of the second opinion on this thesis.

Furthermore, I want to give a thank you to a former colleague and friend at the chair for business management and industrial management. Many thank you also to Felix Blank who offered tremendous support and was available for any discussion at any time, not always necessarily on optimization topics.

A further special thanks to Giacomo Welsch for all the interesting discussions around various topics. Additionally, I want to thank my close friends Stephan Hardt, Thomas Renz, and Peter Worell for all your emotional support during the time, especially in the last stages of this work.

Last, but not least, I want to express my gratefulness to my parents, Josef and Beate. Thank you so much for the endless support, enabling my whole education, and for always standing by my side. I dedicate this work to you!

German Summary

Der Bereich des Supply Chain Management ist einem ständigen Wandel unterworfen. Von den Unternehmen wird erwartet, dass sie als internationale Akteure agieren und ihre Fähigkeiten nutzen, um maßgeschneiderte Produkte und Dienstleistungen schnell und effizient bereitzustellen. Dieses Wettbewerbsumfeld führt zu Komplexität und erhöht die Vielfalt der Managemententscheidungen. Viele frühe Beiträge zur Gestaltung von Supply Chains konzentrierten sich nur auf die Minimierung der Gesamtkosten. Aufgrund der zunehmenden Komplexität und der steigenden Kundenerwartungen haben mehrere Autoren jedoch die Notwendigkeit festgestellt, zusätzliche Leistungskennzahlen in die Modelle aufzunehmen. Solche Leistungskennzahlen können z. B. die Lieferzeit oder Nachhaltigkeitskennzahlen sein.

Heutzutage erwarten die Verbraucher, dass ihre Anforderungen innerhalb kurzer Zeit und zu einem günstigen Preis erfüllt werden. Die Lieferzeit hat bei den Konsumenten immer mehr an Bedeutung gewonnen. Darüber hinaus kann eine effiziente Nutzung der Lieferzeit Vorteile für den Kundenservice bringen und die Kosten senken. Generell können zeitbezogene Merkmale von Produkten und Dienstleistungen eine Quelle der Differenzierung sein. Da die Verkürzung der Lieferzeit als ein wichtiger Wettbewerbsfaktor gilt, haben viele Unternehmen dies zu einer Wettbewerbsstrategie gemacht. Maßgeschneiderte und spezialisierte Produkte, die in kleinen Chargen hergestellt und schnell geliefert werden können, sind notwendig, um auf modernen Märkten wettbewerbsfähig zu sein. Außerdem haben Lieferzeiten einen starken Einfluss auf Entscheidungen über den Standort von Produktionsstätten und Lagern. Um eine wettbewerbsfähige Lieferkette zu gestalten, sollten die Entscheidungsträger die Lieferzeiten bereits in der Planungsphase einer Lieferkette berücksichtigen.

Darüber hinaus gewinnen Maßnahmen zur Verbesserung ihrer Nachhaltigkeitsleistung für Unternehmen zunehmend an Bedeutung. Im ABKOMMEN VON PARIS von 2015 haben sich die Regierungen weltweit darauf geeinigt, die globale Erwärmung auf weniger als 2°C zu begrenzen. Viele Länder haben jedoch angedeutet, dass sie dieses Ziel wahrscheinlich nicht erreichen werden. Verschiedene Gruppen, wie z. B. FRIDAYS FOR FUTURE, haben die Regierungen aufgefordert, ihre Anstrengungen zur Einhaltung der Ziele zu verstärken. Unter anderem diese Proteste haben den Druck auf die Regierungen weltweit erhöht, die Treibhausgasemissionen global zu reduzieren.

Regierungen können verschiedene emissionspolitische Maßnahmen ergreifen, um Unternehmen und Kunden zu zwingen, ihre Treibhausgasemissionen zu reduzieren. Emissionssteuern, Emissionsobergrenzen und Emissionshandel sind bereits in mehreren Ländern eingeführt worden. Es gibt auch freiwillige Ansätze zur Kompensation von Emissionen, aber in vielen Fällen sehen sich die Unternehmen mit gesetzlichen Auflagen wie dem Emissionshandelssystem der Europäischen Union konfrontiert. Diese Gesetze zwingen die Unternehmen dazu, sich mit dem Problem der erzeugten Treibhausgasemissionen auseinanderzusetzen. In Ermangelung globaler Regelungen zur Vermeidung von Treibhausgasemissionen sehen sich die Entscheidungsträger jedoch häufig mit länderspezifischen Vorschriften konfrontiert.

In dieser Arbeit wird der Einfluss der Vorlaufzeit von der Bestellung bis zur Auslieferung und verschiedener Emissionsstrategien auf die Gestaltung einer Lieferkette untersucht. Es werden mathematische Modelle entwickelt, um diese Einflüsse darzustellen und zu bewerten. Die folgenden Forschungsfragen werden in dieser Arbeit behandelt:

> *Wie wirkt sich der Zielkonflikt zwischen Lieferzeit und Gesamtkosten auf die Gestaltung der Supply Chain aus, und wie beeinflussen unterschiedliche Emissionspolitiken diesen Konflikt?*
>
> *Wie beeinflussen Lieferzeitsensible Kunden die Gestaltung einer Supply Chain, und welchen Einfluss haben unterschiedliche Emissionspolitiken?*
>
> *Wie beeinflusst Lieferzeit die Gestaltung der Supply Chain in Bezug auf Unsicherheiten der Nachfrage und in der Gestaltung der Emissionspolitik?*
>
> *Wie beeinflusst Lieferzeit die Gestaltung einer Supply Chain, und welchen Einfluss haben länderspezifische Emissionspolitiken auf die Gestaltung dieser?*

Kapitel 1 bietet eine knappe Einführung in das Thema, stellt die Forschungsfragen vor und skizziert die Struktur der Arbeit. Kapitel 2 gibt einen kurzen, aber detaillierten Überblick über die Grundlagen des Supply Chain Management und des Supply Chain Design. Außerdem wird die Bedeutung von Lieferzeiten im Zusammenhang mit der Lieferkette erörtert. In Kapitel 3 wird kurz auf die Rolle der Treibhausgasemissionen und des Treibhauseffekts eingegangen, und es werden die Quellen solcher Emissionen in Supply Chains beschrieben. Das Kapitel schließt mit einem Überblick über die aktuelle Emissionspolitik. Kapitel 4 bietet einen Literaturüberblick. Zunächst wird die Literatur beschrieben, die sich mit der Integration von Durchlaufzeiten in Modelle zur Gestaltung von Lieferketten befasst. Darüber hinaus werden Modelle für die Gestaltung von Versorgungsketten diskutiert, die verschiedene Emissionspolitiken einbeziehen. Abschließend werden die Ergebnisse der Untersuchung zusammengefasst und Forschungslücken aufgezeigt.

In Kapitel 5 wird ein Modell zur Gestaltung der Supply Chain entwickelt, das Lieferzeiten und Gesamtkosten einbezieht, und es werden verschiedene Emissionspolitiken implementiert. Die Einflüsse der Lieferzeiten und die Auswirkungen der verschiedenen Emissionsstrategien werden anhand eines Beispieldatensatzes untersucht. In Kapitel 6 wird ein Supply Chain Design Modell vorgestellt, das den Einfluss der Lieferzeitsensitiver Konsumenten abbildet, und es werden wiederum verschiedene Emissionspolitiken implementiert, um ihre Auswirkungen zu untersuchen. Zu diesem Zweck wird eine stückweise lineare Nachfragefunktion angenommen, die eine geringere Nachfrage bei höheren Lieferzeiten widerspiegelt. Die Analyse zeigt, dass der Anteil der Kunden, die auf die Lieferzeit sensibel reagieren, einen erheblichen Einfluss auf die Gestaltung einer Lieferkette hat. Darüber hinaus kann es durch unterschiedliche Emissionspolitiken schwieriger werden, die Bedürfnisse der Verbraucher zu erfüllen.

Die Unsicherheit der Nachfrage und die Unsicherheit bei der Ausgestaltung der verschiedenen Emissionspolitiken werden in Kapitel 7 durch die Entwicklung eines geeigneten mathematischen Optimierungsmodells untersucht. Zu diesem Zweck wird ein Ansatz der robusten Programmierung gewählt, um die verschiedenen Arten der Unsicherheit darzustellen. Es wird deutlich, dass insbesondere Unsicherheiten über die Ausgestaltung einer Emissionspolitik die Gesamtkosten einer Supply Chain erheblich beeinflussen können. Die Auswirkungen von unterschiedlich gestalteten Emissionspolitiken in verschiedenen Ländern werden in Kapitel 8 untersucht. Zu diesem Zweck wird ein geeignetes Modell zur Gestaltung der Supply Chain entwickelt, das die länderspezifischen Emissionspolitiken und Lieferzeiten berücksichtigt. Die Analysen zeigen, dass sowohl Lieferzeiten als auch unterschiedliche Emissionspolitiken die Offshoring- und Nearshoring-Strategien von Unternehmen stark beeinflussen können. Kapitel 9 fasst die Ergebnisse der Studie in Bezug auf die Forschungsfragen zusammen, zeigt die Grenzen der Studie auf und gibt einen Ausblick auf mögliche zukünftige Untersuchungen.

English Summary

The field of supply chain management is subject to constant change. Companies are expected to act as international players and to use their capabilities to provide customized products and services quickly and efficiently. This competitive environment leads to complexity and increases the diversity of management decisions. Many early contributions to supply chain design focused only on minimizing total cost. However, due to increasing complexity and rising customer expectations, several authors have noted the need to incorporate additional performance metrics into models. Such performance metrics can be, for example, order-to-delivery lead times or sustainability metrics.

Today, consumers expect their requirements to be met within a short time and at a favorable price. Order-to-delivery lead time has steadily gained in importance for consumers. In addition, efficient use of lead time can create customer service benefits and reduce costs. In general, time-related features of products and services can be a source of differentiation. Since shortening lead time is considered a key competitive factor, many companies have made this a competitive strategy. Customized and specialized products, produced in small batches and delivered quickly are necessary to compete in modern markets. Furthermore, lead times have a strong influence on decisions about the location of production sites and warehouses. Decision makers should already consider lead times in the planning phase of a supply chain to design a competitive supply chain.

Furthermore, measures to improve their sustainability performance are becoming increasingly important for companies. In the 2015 PARIS AGREEMENT, governments worldwide agreed to limit global warming to less than 2°C. However, many countries have indicated that they are unlikely to meet this target. Various groups, such as FRIDAYS FOR FUTURE, have urged governments to step up their efforts to meet the targets. This public outreach has increased pressure on governments worldwide to reduce greenhouse gas emissions globally.

Governments can use various emissions policies to force companies and customers to reduce their greenhouse gas emissions. Emissions taxes, emission caps, and emission trading have already been enacted in several countries. Voluntary approaches to offsetting emissions also exist, but companies face legal requirements such as the European Union Emissions Trading Scheme in many cases. These laws force companies to deal with the problem of greenhouse gas emissions generated. However, in the absence of global

regulations to prevent greenhouse gas emissions, decision makers are often faced with country-specific regulations.

This thesis investigates the influence of order-to-delivery lead time and different emission policies on the design of a supply chain. Mathematical models are developed to represent and evaluate these influences. The following research questions are addressed in this thesis:

> *How does the trade-off between order-to-delivery lead time and total cost influence the design of the supply chain, and how do different emission policies influence this trade-off?*
>
> *How do order-to-delivery lead time sensitive customers influence the design of a supply chain, and what influence do different emission policies have?*
>
> *How does order-to-delivery lead time influence the supply chain design regarding uncertainties in demand and the design of emission policies?*
>
> *How does order-to-delivery lead time influence the design of a supply chain, and what is the impact of country-specific emission policies on supply chain design?*

Chapter 1 provides a concise introduction to the topic, presents the research questions, and outlines the thesis structure. Chapter 2 provides a brief but detailed overview of the fundamentals of supply chain management and supply chain design. It also discusses the importance of lead times in the context of the supply chain. Chapter 3 briefly examines the role of greenhouse gas emissions and the greenhouse gas effect and describes the sources of such emissions in supply chains. The chapter concludes with an overview of current emissions policies. Chapter 4 provides a literature review. First, the literature is described that deals with the integration of lead times into supply chain design models. Furthermore, supply chain design models that incorporate different emission policies are discussed. Finally, the results of the review are summarized, and research gaps are outlined.

In Chapter 5, a supply chain design model is developed that incorporates delivery times and total costs, and various emission policies are implemented. The influences of order-to-delivery lead times and the effects of different emissions policies are examined using a sample data set. In Chapter 6, a supply chain design model is presented that reflects the influence of order-to-delivery lead time sensitive consumers, and different emission policies are implemented to study their impacts. For this purpose, a piecewise linear demand function is assumed to reflect lower demand at higher delivery times. The data set analysis shows that the share of order-to-delivery lead time sensitive consumers has a significant impact on the design of a supply chain. Furthermore, different emission policies can make it more challenging to meet the consumers' needs.

Demand uncertainty and uncertainty in the design of different emission policies are investigated in Chapter 7 by developing an appropriate mathematical optimization model. For this purpose, a Robust Programming Approach is chosen to represent the different types of uncertainty. It becomes clear that especially uncertainties about the design of an emission policy can significantly impact the total cost of a supply chain. The effects of differently designed emission policies in various countries are investigated in Chapter 8. For this purpose, a suitable supply chain design model is developed to incorporate country-specific emission policies and delivery times. The analyses highlight that both delivery times and different emission policies can strongly influence companies' offshoring and nearshoring strategies. Chapter 9 summarizes the thesis results concerning the research questions, highlights the study's limitations, and provides an outlook for possible future research.

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List of Abbreviations

Cap-Opt.	Capacity Option
CFCs	Chlorofluorocarbons
CF_4	Perfluorocarbons
CH_4	Methane
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
EDGAR	Emission Database for Global Atmospheric Research
EU	European Union
EU-ETS	European Union – Emission Trading System
GHG	Greenhouse gas
GWP	Global warming potential
HFC-23	Hydrofluorocarbons
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
MIP	Mixed Integer Programming
MILP	Mixed Integer Linear Programming
MINLP	Mixed Integer Non-Linear Programming
NF_3	Nitrogen trifluoride
N_2O	Nitrous oxide
OTDLT	Order-to-delivery lead time
R&D	Research and Development
SF_6	Sulfur hexafluoride
UNFCCC	United Nations Framework Convention on Climate Change

USA	United States of America
WBSCSD	World Business Council for Sustainable Development
WRI	World Resources Institute

Symbol Directory

Symbols in Chapter 5

Sets:

S	Set of candidate suppliers indexed by s
F	Set of candidate locations for production facilities indexed by f
W	Set of candidate locations for warehouses indexed by w
C	Set of customers index by c
T	Set of same length time periods in the planning horizon indexed by t
M	Set of raw materials indexed by m
P	Set of products indexed by p
L	Set of logistic modes index by l
O	Set of capacity options for production facilities and warehouses index by o

Parameter:

SC_s	Fixed costs for contracting supplier s
FC_{fo}	Fixed setup costs of production facility f with capacity option o
WC_{wo}	Fixed setup costs of warehouse w with capacity option o
PC_{smt}	Unit purchasing costs for raw material m at supplier s in period t
MC_{fpt}	Unit manufacturing costs for product p at facility f in period t
HC_{wpt}	Unit handling costs for product p at warehouse w in period t
SC_{wpt}	Unit stocking costs for product p at warehouse w in period t
TC_{sfmlt}	Unit transportation costs for raw material m shipped by logistic mode l from supplier s to production facility f in period t
TC_{fwplt}	Unit transportation costs for product p shipped by logistic mode l from production facility f to warehouse w in period t
TC_{wcplt}	Unit transportation costs for product p shipped by logistics mode l from warehouse w to customer c in period t
LT_{smt}^{Su}	Unit purchasing lead time for raw material m at supplier s in period t
LT_{fpt}^{Fa}	Unit manufacturing lead time for product p at production facility f in period t
LT_{wpt}^{Wa}	Unit handling lead time for product p at warehouse w in period t
LT_{sfmlt}	Unit transportation lead time for raw material m shipped by logistic mode l from supplier s to production facility f in period t
LT_{fwplt}	Unit transportation lead time for product p shipped by logistic mode l form production facility f to warehouse w in period t
LT_{wcplt}	Unit transportation lead time for product p shipped by logistic mode l from warehouse w to customer c in period t
FE_{fot}	Fixed emissions for operating production facility f with capacity option o in period t

WE_{wot}	Fixed emissions for operating warehouse w with capacity option o in period t
PE_{smt}	Unit purchasing emissions for raw material m at supplier s in period t
ME_{fpt}	Unit manufacturing emissions for product p at production facility f in period t
HE_{wpt}	Unit handling emissions for product p at warehouse w in period t
SE_{wpt}	Unit stocking emissions for product p at warehouse w in period t
TE_{sfmlt}	Unit transportation emissions for raw material m shipped by logistic mode l from supplier s to production facility f in period t
TE_{fwplt}	Unit transportation emissions for product p shipped by logistic mode l from production facility f to warehouse w in period t
TE_{wcplt}	Unit transportation emissions for product p shipped by logistics mode l from warehouse w to customer c in period t
Cap_{sm}^{Su}	Capacity for raw material m at supplier s
Cap_{fo}^{Fa}	Capacity at production facility f with capacity option o
Cap_{wo}^{Wa}	Capacity at warehouse w with capacity option o
BOM_{mp}	Bill of Materials relating materials m to products p
D_{cpt}	Demand of customer c for product p in period t
$ECap$	Emission cap for each time period
Ω^{CAT}	Price of one emission credit under cap and trade scheme
Ω^{Off}	Price of one emission allowance under emission offset scheme
Ω^{Tax}	Emission tax rate

Variables:

y_s^{Su}	1 if supplier s is selected, 0 otherwise
y_{fo}^{Fa}	1 if a production facility with capacity option o is located at candidate location f, 0 otherwise
y_{wo}^{Wa}	1 if a warehouse with capacity option o is located at candidate location w, 0 otherwise
x_{sfmplt}	Amount of raw material m needed for product p shipped from supplier s to production facility f in period t with logistic mode l
x_{fwplt}	Amount of product p shipped from production facility f to warehouse w in period t with logistic mode l
x_{wcplt}	Amount of product p shipped from warehouse w to customer c in period t with logistic mode l
h_{wptc}	Amount of product p kept in stock at warehouse w in period t for customer c
$\delta_{sfmpltc}^{SF}$	Amount of raw material m from supplier s transported with logistic mode l, that is needed at facility f to produce consumer c's order of product p in period t
δ_{fwpltc}^{FW}	Amount of product p, shipped by logistic mode l form production facility f to warehouse w to fulfill the order of customer c in period t

OTD_{cpt}	Order-to-delivery lead time for product p to customer c in period t
$MaxLT$	Maximum order-to-delivery lead time
E_t	Total emissions in period t
α_t^+	Amount of carbon emission for sale in period t
α_t^-	Amount of additional emission credits needed in period t
β_t	Amount of additional emission allowances needed in period t

Symbols in Chapter 6

Sets:

S	Set of candidate suppliers indexed by s
F	Set of candidate locations for production facilities indexed by f
W	Set of candidate locations for warehouses indexed by w
C	Set of customers index by c
T	Set of same length time periods in the planning horizon indexed by t
M	Set of raw materials indexed by m
P	Set of products indexed by p
L	Set of logistic modes index by l
O	Set of capacity options for production facilities and warehouses index by o

Parameters:

SC_s	Fixed costs for contracting supplier s
FC_{fo}	Fixed setup costs of production facility f with capacity option o
WC_{wo}	Fixed setup costs of warehouse w with capacity option o
PC_{smt}	Unit purchasing costs for raw material m at supplier s in period t
MC_{fpt}	Unit manufacturing costs for product p at facility f in period t
HC_{wpt}	Unit handling costs for product p at warehouse w in period t
SC_{wpt}	Unit stocking costs for product p at warehouse w in period t
TC_{sfmlt}	Unit transportation costs for raw material m shipped by logistic mode l from supplier s to production facility f in period t
TC_{fwplt}	Unit transportation costs for product p shipped by logistic mode l from production facility f to warehouse w in period t
TC_{wcplt}	Unit transportation costs for product p shipped by logistics mode l from warehouse w to customer c in period t
LT_{smt}^{Su}	Unit purchasing lead time for raw material m at supplier s in period t
LT_{fpt}^{Fa}	Unit manufacturing lead time for product p at production facility f in period t

LT_{wpt}^{Wa}	Unit handling lead time for product p at warehouse w in period t
LT_{sfmlt}	Unit transportation lead time for raw material m shipped by logistic mode l from supplier s to production facility f in period t
LT_{fwplt}	Unit transportation lead time for product p shipped by logistic mode l form production facility f to warehouse w in period t
LT_{wcplt}	Unit transportation lead time for product p shipped by logistic mode l from warehouse w to customer c in period t
FE_{fot}	Fixed emissions for operating production facility f with capacity option o in period t
WE_{wot}	Fixed emissions for operating warehouse w with capacity option o in period t
PE_{smt}	Unit purchasing emissions for raw material m at supplier s in period t
ME_{fpt}	Unit manufacturing emissions for product p at production facility f in period t
HE_{wpt}	Unit handling emissions for product p at warehouse w in period t
SE_{wpt}	Unit stocking emissions for product p at warehouse w in period t
TE_{sfmlt}	Unit transportation emissions for raw material m shipped by logistic mode l from supplier s to production facility f in period t
TE_{fwplt}	Unit transportation emissions for product p shipped by logistic mode l from production facility f to warehouse w in period t
TE_{wcplt}	Unit transportation emissions for product p shipped by logistics mode l from warehouse w to customer c in period t
Cap_{sm}^{Su}	Capacity for raw material m at supplier s
Cap_{fo}^{Fa}	Capacity at production facility f with capacity option o
Cap_{wo}^{Wa}	Capacity at warehouse w with capacity option o
BOM_{mp}	Bill of Materials relating materials m to products p
D_{cpt}	Demand of customer c for product p in period t
$ECap$	Emission cap in one time period
Ω^{CAT}	Price of one emission credit under cap and trade scheme
Ω^{Off}	Price of one emission allowance under emission offset scheme
Ω^{Tax}	Emission tax rate
π_p	Price of Product p
LT_{cpt}^{Max}	Maximum acceptable lead time of customer c for product p in period t
LT_{cpt}^{Min}	Minimum acceptable lead time of customer c for product p in period t
D_{cpt}^{Max}	Maximum demand of customer c for product p in period t
D_{cpt}^{Min}	Minimum demand of customer c for product p in period t

Variables:

y_s^{Su}	1 if supplier s is selected, 0 otherwise

y_{fo}^{Fa}	1 if a production facility with capacity option o is located at candidate location f, 0 otherwise
y_{wo}^{Wa}	1 if a warehouse with capacity option o is located at candidate location w, 0 otherwise
x_{sfmplt}	Amount of raw material m needed for product p shipped from supplier s to production facility f in period t with logistic mode l
x_{fwplt}	Amount of product p shipped from production facility f to warehouse w in period t with logistic mode l
x_{wcplt}	Amount of product p shipped from warehouse w to customer c in period t with logistic mode l
h_{wptc}	Amount of product p kept in stock at warehouse w in period t for customer c
$\delta_{sfmpltc}^{SF}$	Amount of raw material m from supplier s transported with logistic mode l, that is needed at facility f to produce consumer c's order of product p in period t
δ_{fwpltc}^{FW}	Amount of product p, shipped by logistic mode l form production facility f to warehouse w to fulfill the order of customer c in period t
OTD_{cpt}	Order-to-delivery lead time for product p to customer c in period t
E_t	Total emissions in period t
α_t^+	Amount of carbon emission for sale in period t
α_t^-	Amount of additional emission credits needed in period t
β_t	Amount of additional emission allowances needed in period t
Π_t	Revenue in Period t
a_{cpt}	1 if $OTD_{cpt} \leq LT_{cpt}^{Min}$, 0 otherwise
b_{cpt}	1 if $LT_{cpt}^{Min} \leq OTD_{cpt} \leq LT_{cpt}^{Max}$, 0 otherwise
c_{cpt}	1 if $OTD_{cpt} \geq LT_{cpt}^{Max}$, 0 otherwise
lt_{cpt}	Actual lead time if $LT_{cpt}^{Min} \leq OTD_{cpt} \leq LT_{cpt}^{Max}$, 0 otherwise

Symbols in Chapter 7

Sets:

S	Set of candidate suppliers indexed by s
F	Set of candidate locations for production facilities indexed by f
W	Set of candidate locations for warehouses indexed by w
C	Set of customers index by c
T	Set of same length time periods in the planning horizon indexed by t
M	Set of raw materials indexed by m
P	Set of products indexed by p
L	Set of logistic modes index by l
O	Set of capacity options for production facilities and warehouses index by o
Τ	Set of scenarios indexed by τ

Parameters:

SC_s	Fixed costs for contracting supplier s
FC_{fo}	Fixed setup costs of production facility f with capacity option o
WC_{wo}	Fixed setup costs of warehouse w with capacity option o
PC_{smt}	Unit purchasing costs for raw material m at supplier s in period t
MC_{fpt}	Unit manufacturing costs for product p at facility f in period t
HC_{wpt}	Unit handling costs for product p at warehouse w in period t
SC_{wpt}	Unit stocking costs for product p at warehouse w in period t
TC_{sfmlt}	Unit transportation costs for raw material m shipped by logistic mode l from supplier s to production facility f in period t
TC_{fwplt}	Unit transportation costs for product p shipped by logistic mode l from production facility f to warehouse w in period t
TC_{wcplt}	Unit transportation costs for product p shipped by logistics mode l from warehouse w to customer c in period t
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LT_{fpt}^{Fa}	Unit manufacturing lead time for product p at production facility f in period t
LT_{wpt}^{Wa}	Unit handling lead time for product p at warehouse w in period t
LT_{sfmlt}	Unit transportation lead time for raw material m shipped by logistic mode l from supplier s to production facility f in period t
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LT_{wcplt}	Unit transportation lead time for product p shipped by logistic mode l from warehouse w to customer c in period t
FE_{fot}	Fixed emissions for operating production facility f with capacity option o in period t
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PE_{smt}	Unit purchasing emissions for raw material m at supplier s in period t
ME_{fpt}	Unit manufacturing emissions for product p at production facility f in period t
HE_{wpt}	Unit handling emissions for product p at warehouse w in period t
SE_{wpt}	Unit stocking emissions for product p at warehouse w in period t
TE_{sfmlt}	Unit transportation emissions for raw material m shipped by logistic mode l from supplier s to production facility f in period t
TE_{fwplt}	Unit transportation emissions for product p shipped by logistic mode l from production facility f to warehouse w in period t

TE_{wcplt}	Unit transportation emissions for product p shipped by logistics mode l from warehouse w to customer c in period t
Cap_{sm}^{Su}	Capacity for raw material m at supplier s
Cap_{fo}^{Fa}	Capacity at production facility f with capacity option o
Cap_{wo}^{Wa}	Capacity at warehouse w with capacity option o
BOM_{mp}	Bill of Materials relating materials m to products p
D_{cptv}	Demand of customer c for product p in period t under scenario v
$MaxLT$	Maximum order-to-delivery lead time
$ECap_{tv}$	Emission cap in period t under scenario v
$\Omega_{t\tau}^{CAT}$	Price of one emission credit under cap and trade scheme in period t under scenario τ
$\Omega_{t\tau}^{Off}$	Price of one emission allowance under emission offset scheme in period t under scenario τ
$\Omega_{t\tau}^{Tax}$	Emission tax rate in period t under scenario τ

Variables:

y_s^{Su}	1 if supplier s is selected, 0 otherwise
y_{fo}^{Fa}	1 if a production facility with capacity option o is located at candidate location f, 0 otherwise
y_{wo}^{Wa}	1 if a warehouse with capacity option o is located at candidate location w, 0 otherwise
$x_{sfmplt\tau}$	Amount of raw material m needed for product p shipped from supplier s to production facility f in period t with logistic mode l under scenario τ
$x_{fwplt\tau}$	Amount of product p shipped from production facility f to warehouse w in period t with logistic mode l under scenario τ
$x_{wcplt\tau}$	Amount of product p shipped from warehouse w to customer c in period t with logistic mode l under scenario τ
$h_{wptc\tau}$	Amount of product p kept in stock at warehouse w in period t for customer c under scenario τ
$\delta_{sfmpltc\tau}^{SF}$	Amount of raw material m from supplier s transported with logistic mode l, that is needed at facility f to produce consumer c's order of product p in period t under scenario τ
$\delta_{fwpltc\tau}^{FW}$	Amount of product p, shipped by logistic mode l form production facility f to warehouse w to fulfill the order of customer c in period t under scenario τ
$OTD_{cpt\tau}$	Order-to-delivery lead time for product p to customer c in period t under scenario τ
$E_{t\tau}$	Total emissions in period t under scenario τ
$\alpha_{t\tau}^{+}$	Amount of carbon emission for sale in period t under scenario τ
$\alpha_{t\tau}^{-}$	Amount of additional emission credits needed in period t under scenario τ
$\beta_{t\tau}$	Amount of additional emission allowances needed in period t under scenario τ

Symbols in Chapter 8

Sets:

A	Set of countries indexed by a
S	Set of candidate suppliers indexed by s
S_a	Set of candidate suppliers in country a; $S_a \in S$
F	Set of candidate locations for production facilities indexed by f
F_a	Set of candidate locations for production facilities in country a; $F_a \in F$
W	Set of candidate locations for warehouses indexed by w
W_a	Set of candidate locations for warehouses in country a; $W_a \in W$
C	Set of customers index by c
T	Set of same length time periods in the planning horizon indexed by t
M	Set of raw materials indexed by m
P	Set of products indexed by p
L	Set of logistic modes index by l
O	Set of capacity options for production facilities and warehouses index by o

Parameters:

SC_s	Fixed costs for contracting supplier s
FC_{fo}	Fixed setup costs of production facility f with capacity option o
WC_{wo}	Fixed setup costs of warehouse w with capacity option o
PC_{smt}	Unit purchasing costs for raw material m at supplier s in period t
MC_{fpt}	Unit manufacturing costs for product p at facility f in period t
HC_{wpt}	Unit handling costs for product p at warehouse w in period t
SC_{wpt}	Unit stocking costs for product p at warehouse w in period t
TC_{sfmlt}	Unit transportation costs for raw material m shipped by logistic mode l from supplier s to production facility f in period t
TC_{fwplt}	Unit transportation costs for product p shipped by logistic mode l from production facility f to warehouse w in period t
TC_{wcplt}	Unit transportation costs for product p shipped by logistics mode l from warehouse w to customer c in period t
LT^{Su}_{smt}	Unit purchasing lead time for raw material m at supplier s in period t
LT^{Fa}_{fpt}	Unit manufacturing lead time for product p at production facility f in period t
LT^{Wa}_{wpt}	Unit handling lead time for product p at warehouse w in period t

LT_{sfmlt}	Unit transportation lead time for raw material m shipped by logistic mode l from supplier s to production facility f in period t
LT_{fwplt}	Unit transportation lead time for product p shipped by logistic mode l form production facility f to warehouse w in period t
LT_{wcplt}	Unit transportation lead time for product p shipped by logistic mode l from warehouse w to customer c in period t
FE_{fot}	Fixed emissions for operating production facility f with capacity option o in period t
WE_{wot}	Fixed emissions for operating warehouse w with capacity option o in period t
PE_{smt}	Unit purchasing emissions for raw material m at supplier s in period t
ME_{fpt}	Unit manufacturing emissions for product p at production facility f in period t
HE_{wpt}	Unit handling emissions for product p at warehouse w in period t
SE_{wpt}	Unit stocking emissions for product p at warehouse w in period t
TE_{sfmlt}	Unit transportation emissions for raw material m shipped by logistic mode l from supplier s to production facility f in period t
TE_{fwplt}	Unit transportation emissions for product p shipped by logistic mode l from production facility f to warehouse w in period t
TE_{wcplt}	Unit transportation emissions for product p shipped by logistics mode l from warehouse w to customer c in period t
Cap_{sm}^{Su}	Capacity for raw material m at supplier s
Cap_{fo}^{Fa}	Capacity at production facility f with capacity option o
Cap_{wo}^{Wa}	Capacity at warehouse w with capacity option o
BOM_{mp}	Bill of Materials relating materials m to products p
D_{cpt}	Demand of customer c for product p in period t
$MaxLT$	Maximum order-to-delivery lead time
$ECap_{a}$	Emission cap in country a
Ω^{CAT}	Price of one emission credit under cap and trade scheme
Ω^{Off}	Price of one emission allowance under emission offset scheme
Ω^{Tax}	Emission tax rate

Variables:

y_{s}^{Su}	1 if supplier s is selected, 0 otherwise
y_{fo}^{Fa}	1 if a production facility with capacity option o is located at candidate location f, 0 otherwise
y_{wo}^{Wa}	1 if a warehouse with capacity option o is located at candidate location w, 0 otherwise

x_{sfmplt}	Amount of raw material m needed for product p shipped from supplier s to production facility f in period t with logistic mode l
x_{fwplt}	Amount of product p shipped from production facility f to warehouse w in period t with logistic mode l
x_{wcplt}	Amount of product p shipped from warehouse w to customer c in period t with logistic mode l
h_{wpct}	Amount of product p kept in stock at warehouse w in period t for customer c
$\delta^{SF}_{sfmpltc}$	Amount of raw material m from supplier s transported with logistic mode l, that is needed at facility f to produce consumer c's order of product p in period t
δ^{FW}_{fwpltc}	Amount of product p, shipped by logistic mode l form production facility f to warehouse w to fulfill the order of customer c in period t
OTD_{cpt}	Order-to-delivery lead time for product p to customer c in period t
E_{ta}	Total emissions in period t in country a
α^{+}_{ta}	Amount of carbon emission for sale in period t in country a
α^{-}_{ta}	Amount of additional emission credits needed in period t in country a
β_{ta}	Amount of additional emission allowances needed in period t in country a

1 Introduction and organization of the research

1.1 Relevance of Lead Times and Emission Policies in Supply Chain Design

The design of supply chain networks includes making decisions about matters such as the location of production facilities and warehouses. The capacity allocation and the assignment of markets to each facility also need to be considered. Such design decisions have a significant impact on the performance of a supply chain. Most of these decisions are interdependent, which must be considered when deciding on the shape of a supply chain.[1]

Given the long-term horizon and the importance of such decisions, supply chain design problems have received considerable attention from academics and practitioners in recent decades. One of the earliest works was published by GEOFFRION AND GRAVES[2]. Since then, various scientific contributions have been made to improve the knowledge of this topic. The field of supply chain management undergoes constant change. Companies are expected to act as international players and use their capabilities to offer customized products and services quickly and efficiently. This competitive environment leads to complexity and increases the diversity of management decisions.[3] Many early contributions in supply chain design focused on minimizing the total cost.[4] However, due to the increasing complexity and customer expectations, authors have more recently noted the need to incorporate additional performance measures into models. These measures may be implemented as objectives or constraints.[5]

Today, customers expect their demands to be fulfilled within a short order-to-delivery lead time (OTDLT) and at an affordable price. As a recent study by MCKINSEY indicates, the role of OTDLT has become more important to customers, and online shops, in particular, have substantially decreased the shipping time in recent years.[6] STALK mentioned as early as 1988 that lead time reduction can be a source of competitive advantage.[7] Moreover, the efficient use of time can create benefits for customer service and decrease costs.[8]

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[1] Cf. CHOPRA, S.; MEINDL, P., 2016, p. 130f.
[2] See GEOFFRION, A. M.; GRAVES, G. W., 1974.
[3] Cf. HALLDORSSON, A. ET AL., 2007, p. 283.
[4] Cf. MELO, M. T.; NICKEL, S.; SALDANHA-DA-GAMA, F., 2009, p. 410.
[5] Cf. ERENGÜÇ, Ş. S.; SIMPSON, N. C.; VAKHARIA, A. J., 1999, p. 232; VIDAL, C. J.; GOETSCHALCKX, M., 1997, p. 14f.; MEIXELL, M. J.; GARGEYA, V. B., 2005, p. 547.
[6] Cf. ARYAPADI, M.; ECKER, T.; SPIELVOGEL, J., 2020, p. 2.
[7] Cf. STALK, G. J., 1988, p. 42.
[8] Cf. CHRISTOPHER, M.; BRAITHWAITE, A., 1989, p. 192.

In general, time-related characteristics of products and services can be a source of differentiation.[9] Because the ability to reduce lead time is considered a crucial competitive factor, many companies have approached it as a competitive strategy.[10] Hence, in addition to the quality of a product, lead time is generally seen as a market qualifier.[11] Customized and specialized products, which can be produced in small lot sizes and delivered quickly, are necessary to compete in modern markets.[12] Furthermore, HAMMAMI AND FREIN state that lead time strongly influences decisions about strategic facility location.[13] Therefore, to achieve a competitive supply chain, decision makers should consider lead time during the design phase for a supply chain.

In addition to the increasing pressure of competitive markets, climate change is one of the major problems of the modern world. In the Paris Agreement of 2015, governments worldwide agreed to limit global warming to less than 2°C.[14] However, many countries have indicated that they probably cannot meet this target.[15] Various groups, such as Fridays for Future, have strongly pressured governments to increase their efforts to meet the targets. By March 2019, more than 28,000 scientists had signed a statement supporting the climate protestors' concerns.[16] Such publicity has increased the pressure on governments worldwide to reduce greenhouse gas (GHG) emissions globally.

Customers have also become familiar with the concept of carbon footprint, and they demand more sustainable products than before.[17] As a result, increasing weight is placed on the issue of sustainability among voters. Companies face pressure from various stakeholders that require higher levels of sustainability than before in their operations.[18] Governments can implement various emission policies to force companies and customers to reduce their GHG emissions. Emission tax, emission cap and trade policies have already been implemented in several countries.[19] While there are also voluntary approaches to offset emissions, in many cases, companies face legal regulations such as the European

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[9] Cf. DE TONI, A.; MENEGHETTI, A., 2000, p. 255.
[10] Cf. HSU, S.-L.; LEE, C. C., 2009, p. 398.
[11] Cf. MASON-JONES, R.; NAYLOR, B.; TOWILL, D. R., 2000, p. 4064.
[12] Cf. BIANCHINI, A. ET AL., 2019, p. 1194.
[13] Cf. HAMMAMI, R.; FREIN, Y., 2013, p. 2772.
[14] Cf. UNFCCC, 2015, p. 3.
[15] Cf. THE LANCET PLANETARY HEALTH, 2018, p. e140.
[16] Cf. SCIENTISTS FOR FUTURE, n. y.
[17] Cf. GROENING, C.; INMAN, J. J.; ROSS JR., W. T., 2015, p. 263.
[18] Cf. MEIXELL, M. J.; LUOMA, P., 2015, p. 69.
[19] Cf. WORLD BANK GROUP, 2020.

Union Emission Trading Scheme (EU-ETS). These laws force people to deal with the problem of generated GHG emissions.

Because there are no global regulations on GHG emissions, decision-makers often face the problem of country-specific regulations.[20] The planning of a supply chain's structure can strongly influence the environmental performance of that supply chain.[21] Therefore, environmental regulations should be considered even in the design phase of a supply chain.

1.2 Research Questions and Outline of the Thesis

The above section discussed how supply chain design impacts a supply chain's environmental and economic performance. This thesis investigates the influence of OTDLT and various emission policies on the design of a supply chain. Mathematical models are developed to represent and evaluate these influences. Such optimization models are widely used in the scientific literature and provide insight into the design of supply chains under changing circumstances. In the context of this thesis, the following research questions (RQs) are addressed:

RQ1 *How does the trade-off between OTDLT and total cost influence the design of the supply chain, and how do different emission policies influence this trade-off?*

RQ2 *How do OTDLT-sensitive customers influence the design of a supply chain, and what influence do different emission policies have?*

RQ3 *How does OTDLT influence the supply chain design regarding uncertainties in demand and the design of emission policies?*

RQ4 *How does OTDLT influence the design of a supply chain, and what is the impact of country-specific emission policies on supply chain design?*

The study is organized as follows:

Chapter 2 gives a brief but detailed overview of the fundamentals of supply chain management and design. It also discusses the importance of lead time in the supply chain context. Chapter 3 briefly examines the role of GHG emissions and the greenhouse gas effect and describes the impact of supply chains on the generation of such emissions. The

[20] Cf. CHRISTMANN, P.; TAYLOR, G., 2001, p. 441.
[21] Cf. ARONSSON, H.; HUGE BRODIN, M., 2006, p. 397; HARRIS, I. ET AL., 2011a, p. 313.

chapter concludes with an overview of current emission policies. In Chapter 4, a literature review is presented. First, the literature dealing with the integration of lead time into supply chain design models is described, and supply chain design models that reflect various emission policies are discussed. Finally, the results of the review are summarized, and research gaps are outlined. In Chapter 5, a model is developed that represents OTDLT and total costs, and various emission policies are implemented. A model reflecting the influence of OTDLT-sensitive consumers is presented in Chapter 6, and various emission policies are again implemented to investigate their effects. Lead time, demand uncertainty, and uncertainties in the design of different emission policies are investigated in Chapter 7 by developing a suitable mathematical optimization model. The effects of differently designed emission policies in several countries are examined in Chapter 8. For this purpose, a suitable model is developed to represent country-specific emission policies and lead times. Chapter 9 summarizes the thesis results concerning the research questions; it also identifies the study’s limitations and suggests directions for possible future research.

2 Supply Chain Management

2.1 Definition of Supply Chain

One of the first scholars to introduce the concept of supply chains is PORTER, who envisaged value chains as a concept of vertical cooperation between companies.[22] Since then, many researchers have provided definitions for the term "supply chain." LA LONDE AND MASTERS define the supply chain simply as a number of companies that provide materials for each other.[23] A broader definition s given by BEAMON, who states that a supply chain is an integrated process in which numerous business entities cooperate to obtain raw materials, produce specific final products, and supply these products to retailers. Furthermore, a supply chain is characterized by a forward flow of materials and a backflow of information.[24]

Many different business entities can be involved to produce a final product, and other value-creating participants are also part of the supply chain. Hence, the term "supply network" is often used as a synonym.[25] MENTZER ET AL. define a supply chain as a set of at least three entities that are directly involved in the forward and backward flows of products, finances, services, and information. In contrast to BEAMON, they state that the supply chain covers all activities from source to the final customer.[26] AITKEN defines the supply chain as "a network of connected and interdependent organizations mutually and co-operatively working together to control, manage and improve the flow of materials and information from suppliers to end-users."[27] The importance of the final customer is emphasized by STEVENSON, who states that "a supply chain is the sequence of organizations – their facilities, functions, and activities – that are involved in producing and delivering a product or service. The sequence begins with basic suppliers of raw materials and extends all the way to the final customer. Facilities include warehouses, factories, processing centers, distribution centers, retail outlets, and offices. Functions and activities include forecasting, purchasing, inventory management, information management, quality assurance, scheduling, production, distribution, delivery, and customer service."[28]

[22] Cf. PORTER, M. E., 1985, p. 33.
[23] Cf. LA LONDE, B. J.; MASTERS, J. M., 1994, p. 38.
[24] Cf. BEAMON, B. M., 1998, p. 281.
[25] Cf. CHRISTOPHER, M., 2016, p. 3.
[26] Cf. MENTZER, J. T. ET AL., 2001, p. 4.
[27] AITKEN, J. M., 1998, p. 67.
[28] STEVENSON, W. J., 2012, p. 663f.

The two definitions in the previous paragraph highlight the importance of the end customer, who is the source of demand. Therefore, supply chains can also be seen as demand chains because they are driven by market requirements rather than by suppliers.[29] Furthermore, the above definitions indicate that value creation links the entities in a supply chain. The definition provided by IVANOV[30] takes account of these influences. The supply chain is described as a networked organization that has various companies, such as suppliers, manufacturers, distributors, and retailers; these companies cooperate to gain raw materials, turn them into final products, and deliver them to customers. Moreover, the network uses appropriate technologies "to make supply chains agile, responsive, flexible, robust, sustainable, cost-effective, and competitive in order to increase customer satisfaction and decrease costs, resulting in increasing supply chain profitability and stability."[31] CHOPRA AND MEINDL state that a supply chain consists of directly and indirectly involved parties that have the objective of fulfilling customer requests. In addition to manufacturers and suppliers, other actors – such as transporters, warehouses, retailers, and customers – are part of the supply chain. Furthermore, the supply chain includes each organization's function to receive and fulfill customer needs.[32]

Fig. 2.1 illustrates the key points in findings of the definitions.

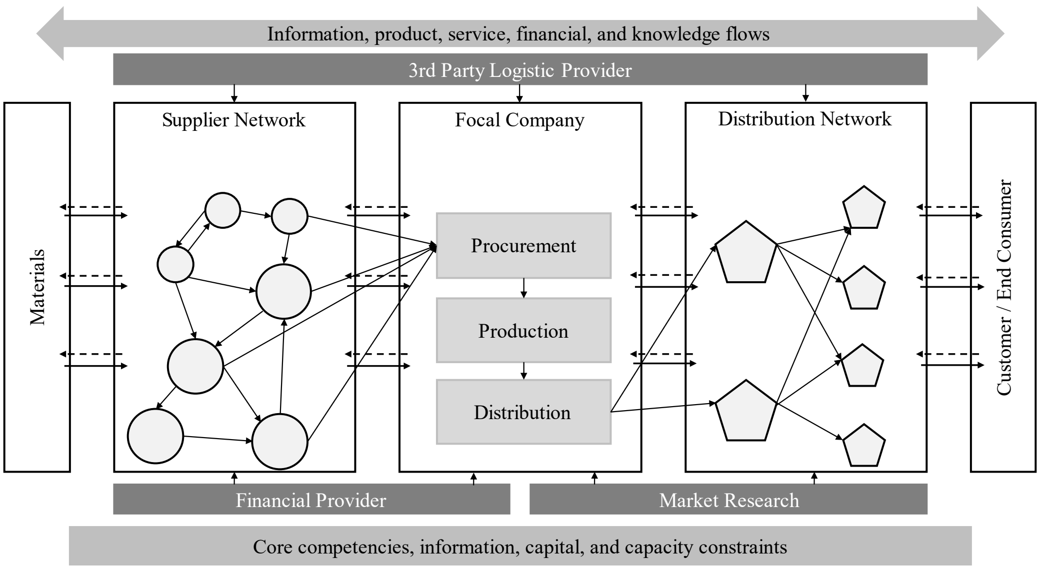

Figure 2.1: Illustration of an exemplary supply chain[33]

[29] Cf. CHRISTOPHER, M., 2016, p. 3.
[30] Cf. IVANOV, D., 2010, p. 4000.
[31] IVANOV, D., 2010, p. 4000.
[32] Cf. CHOPRA, S.; MEINDL, P., 2016, p. 22.
[33] The figure is based on: BOWERSOX, D. J.; CLOSS, D. J.; COOPER, M. B., 2002, p. 6; LAMBERT, D. M.; COOPER, M. C.; PAGH, J. D., 1998, p. 3; MENTZER, J. T. ET AL., 2001, p. 5; ALTMANN, M., 2014, p. 5.

In this work, the following definition of "supply chain" is used:

A supply chain is a network of business entities and their various functions, activities, and facilities. These entities cooperate and are coordinated along the value chain. Their aims are to obtain raw materials, process those materials into final products, and provide the products to customers, thereby fulfilling customer needs and increasing customer satisfaction.

This definition offers critical foundations for the following chapters. For example, it is necessary to view facilities as an essential factor in the design of a supply chain. Furthermore, activities aimed at satisfying customer needs must be considered because of their associated costs, lead times, and emissions. Finally, it is vital to consider focal company functions and the functions of other supply chain partners.

2.2 Definition of Supply Chain Management

The term "supply chain management" was introduced by consultants in 1982[34] and thereafter gained much attention from practitioners and researchers.[35] However, there is no commonly accepted definition of the term. The concept covers all relevant aspects of the topic as presented in the literature.[36] Definitions from various authors are introduced and briefly discussed to provide the theoretical fundamentals for this work.

Early definitions of the term supply chain management focus on the overall flow from supplier to final customers.[37] Furthermore, they highlighted the importance of collaboration between companies and the need to coordinate and manage various activities along the chain. CHRISTOPHER extends these definitions by stating that supply chain management is "the management of upstream and downstream relationships with suppliers and customers in order to deliver superior customer value at less cost to the supply chains as a whole."[38] Strategic objectives, such as delivering customer value at less cost to the supply chain, are explicitly considered in this definition, and upstream and downstream relationships are revealed. These components lead to complexity in decision making and illustrate the holistic nature of the concept. MENTZER ET AL. see supply chain management "as the systemic, strategic coordination of the traditional business functions and the

[34] Cf. OLIVER, R. K.; WEBBER, M. D., 2012, p. 183f.
[35] Cf. STOCK, J. R.; BOYER, S. L., 2009, p 691.
[36] Cf. MENTZER, J. T. ET AL., 2001, p. 5; CHICKSAND, D. ET AL., 2012, p. 456; LEMAY, S. ET AL., 2017, p. 2.
[37] Cf. JONES, T. C.; RILEY, D. W., 1985, p. 19; ELLRAM, L. M.; COOPER, M. C., 1990, p. 2.
[38] CHRISTOPHER, M., 2016, p. 3.

tactics across these business functions within a particular company and across businesses within the supply chain, for the purposes of improving the long-term performance of the individual companies and the supply chain as a whole."[39] The strategic and tactical functions of supply chain management are highlighted in this definition; in addition, the coordination between the involved companies and business units is emphasized. STOCK AND BOYER define supply chain management as "the management of a network of relationships within a firm and between interdependent organizations and business units consisting of material suppliers, purchasing, production facilities, logistics, marketing, and related systems that facilitate the forward and reverse flow of materials, services, finances, and information from the original producer to the final customer with the benefits of adding value, maximizing profitability through efficiencies, and achieving customer satisfaction."[40] They highlight the network character of a supply chain, explicitly including reverse flows in the definition – as well as management objectives and goals. According to SIMCHI-LEVI, KAMINSKY, AND SIMCHI-LEVI, "supply chain management is a set of approaches utilized to efficiently integrate suppliers, manufacturers, warehouses, and stores so that merchandise is produced and distributed at the right quantities, to the right locations, and at the right time, in order to minimize system-wide costs while satisfying service level requirements."[41] In this explanation, the importance of the efficient management of supply chains is mentioned, and the aspects of quantities, locations, and time are emphasized.

The above definitions reveal the strategic character of supply chain management. Managerial objectives are essential, as is the coordination between supply chain partners. Most definitions include the strategic objective of customer satisfaction; hence, after cost, customers play a crucial role in supply chain management. Coordinating the involved companies and business units is also crucial in supply chain management, as STADTLER highlights.[42]

There are many different tasks in supply chain management. Frameworks have been developed to characterize particular supply chain management topics. Often the time frame – or distinguishing between long- and short-term decisions – is used to differentiate between supply chain management tasks. RHODE ET AL. use the different business units

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[39] MENTZER, J. T. ET AL., 2001, p. 18.
[40] STOCK, J. R.; BOYER, S. L., 2009, 706.
[41] SIMCHI-LEVI, D.; SIMCHI-LEVI, E.; KAMINSKY, P., 1999, p. 1.
[42] Cf. STADTLER, H., 2015, p. 9.

involved in the supply chain management tasks of a company as a second criterion to classify different topics.[43] Their planning matrix is shown in Fig. 2.2.

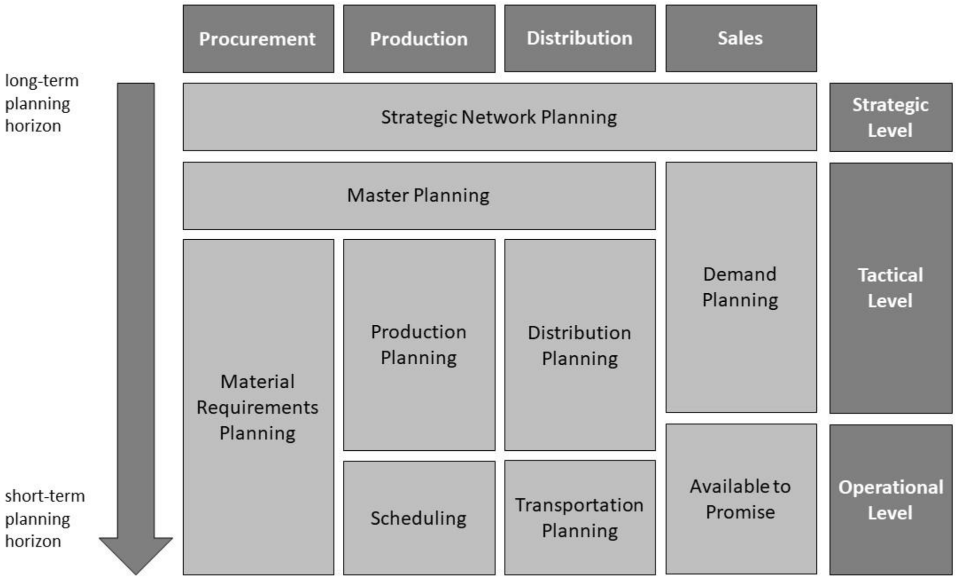

Figure 2.2: Supply Chain Planning Matrix[44]

Strategic network design is classified in this framework as a strategic task with a long-term planning horizon that involves procurement, production, distribution, and sales tasks. Underlying tasks – such as master planning, production planning, distribution planning, demand planning, and material requirements planning – are, according to this framework, tactical decisions with a medium-term planning horizon. In contrast, tasks such as scheduling, transportation planning, and available to promise are viewed as topics related to the operational level, with a short-term planning horizon.

IVANOV proposes a framework that considers the interrelationships between the various topics of supply chain management.[45] The interrelation between tasks is examined, starting with defining the supply chain goals and ending with supply chain adaption. Other frameworks hierarchically arrange the supply chain management topics, whereas IVANOV highlights the dependencies and interrelations between the tasks. These relationships are shown in Fig. 2.3. In short, it is crucial to consider influences from all planning topics at each hierarchical planning level. In the case of supply chain design (an essential topic in

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[43] Cf. ROHDE, J.; MEYR, H.; WAGNER, M., 2000, p. 10.
[44] The figure is based on ROHDE, J.; MEYR, H.; WAGNER, M., 2000, p. 10.
[45] Cf. IVANOV, D., 2010, p. 4005.

this thesis), it is also beneficial to consider the supply chain goals and influences from the tactical or operational planning phase.

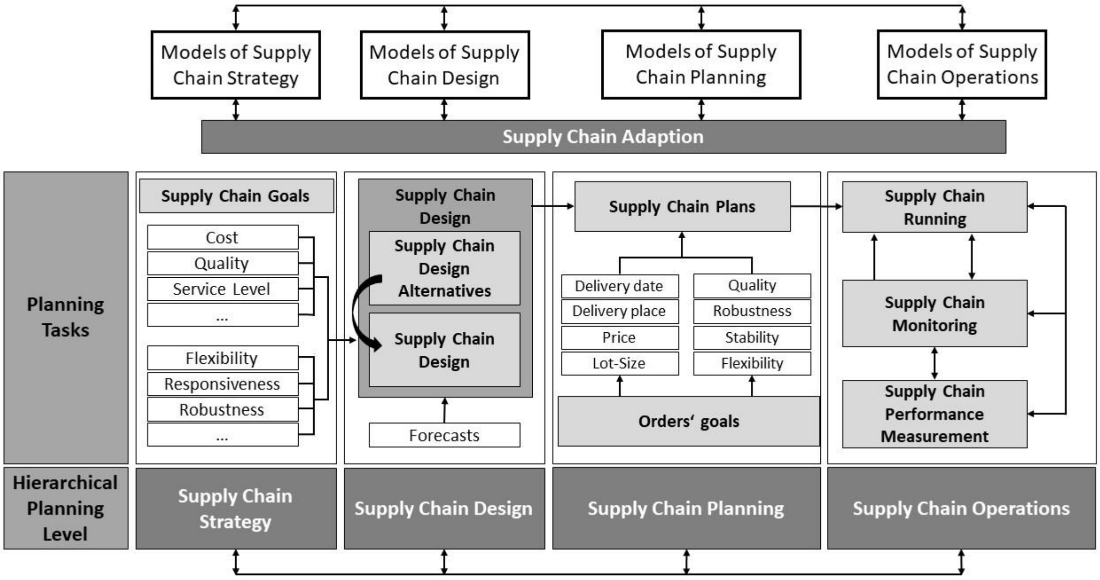

Figure 2.3: Linkages between supply chain strategy, design, planning, and operations[46]

2.3 Supply Chain Design

In general, supply chain design deals with the strategic issues related to supply chain planning. Therefore, strategic decisions about distribution networks and the integration of suppliers and customers are critical elements of supply chain design.[47] HARRISON defines supply chain design as “the process of determining the supply chain infrastructure – the plants, distribution centers, transportation modes and lanes, production processes, etc. that will be used to satisfy customer demands.”[48] According to this definition, infrastructure planning and customer demand satisfaction are core functions of the supply chain design. CHOPRA AND MEINDL explain that a company decides on the supply chain structure for the next years during the supply chain design phase.[49] Furthermore, the company decides "what the chain's configuration will be, how resources will be allocated, and what processes each stage will perform. Strategic decisions made by companies include whether to outsource or perform a supply chain function in-house, the location and capacities of production and warehousing facilities, the products to be manufactured or stored at various locations, the modes of transportation to be made available along

[46] The figure is based on IVANOV, D., 2010, p 4005.
[47] Cf. COHEN, M. A.; LEE, H. L., 1988, p. 216; BEAMON, B. M., 1998, p. 282.
[48] HARRISON, T. P., 2001, p. 413.
[49] Cf. CHOPRA, S.; MEINDL, P., 2016, p 18.

different shipping legs, and the type of information system to be used."[50] The importance of location and capacity planning in the context of supply chain design is similarly highlighted by SANTOSO ET AL.[51] According to TRUONG AND AZADIVAR, relevant decisions during the supply chain design relate to facility location decisions, distribution center to customer assignments, make-or-buy decisions, supplier selection, transportation mode selection, and selecting a production planning policy.[52] They state that all relevant company functions are involved in supply chain design topics. In addition, all these decisions involve capital resources over a long time, which indicates the significance of supply chain design problems. Moreover, such decisions are not flexible – or would incur high costs to alter. Hence, in supply chain design, uncertainties must be taken into account.[53]

SABRI AND BEAMON present a definition, which highlights the optimization character of supply chain design. They state that “the primary objective of strategic optimization models is to determine the most cost-effective location of facilities (plants and distribution centers), flow of goods throughout the supply chain (SC), and assignment of customers to distribution centers (DCs). These types of models do not seek to determine required inventory levels and customer service levels.”[54] Hence, the complexity of decisions in supply chain design means that optimization approaches are emphasized. Generally, optimization approaches concentrate on financial or cost objectives, as mentioned in the definition of SABRI AND BEAMON. Nevertheless, there are many other performance measures in the literature; examples include customer service level, lead times, and supply chain flexibility.[55] Therefore, it would be beneficial to incorporate additional objectives – such as lead time – to improve the optimization approaches.[56]

2.4 Lead Time in Supply Chain Design Context

Lead time is a standard performance indicator, and lead time reduction is an essential goal in supply chain design. The term “lead time” depicts the end-to-end delay in a business process.[57] However, the literature provides no standard definition of lead time specifically for the supply chain context. Given the relevance of the concept for this work,

[50] CHOPRA, S.; MEINDL, P., 2016, p. 18.
[51] Cf. SANTOSO, T. ET AL., 2005, p. 96.
[52] Cf. TRUONG, T. H.; AZADIVAR, F., 2005, p. 2220.
[53] CHOPRA, S.; MEINDL, P., 2016, p. 19; SANTOSO, T. ET AL., 2005, p. 96.
[54] SABRI, E. H.; BEAMON, B. M., 2000, p. 581.
[55] Cf. BEAMON, B. M., 1999, p.281ff. ; KLEIJNEN, J. P. C.; SMITS, M. T., 2003, p. 508f.; SHEPHERD, C.; GÜNTER, H., 2010, p. 111 ff.
[56] Cf. MEIXELL, M. J.; GARGEYA, V. B., 2005, p. 547; VIDAL, C. J.; GOETSCHALCKX, M., 2000, p. 15.
[57] Cf. BISWAS, S.; NARAHARI, Y., 2004, 706.

components of lead time in the supply chain context are defined in the following paragraphs. In addition, the influences on supply chain design are briefly discussed.

Supply chain lead time is widely viewed as the time needed to process raw materials into final products and distribute these products to the final customer.[58] In general, supply chain lead time consists of supplier lead time, manufacturing lead time, distribution lead time, and the logistics lead time (required to ship raw materials and semi-finished or finished goods).[59] Supplier lead time is generally defined as the time between the placement of an order at a supplier and the moment it is shipped.[60] It consists of components such as inhouse moving time, waiting time, setup time, queuing time, and processing time.[61] The sum of time needed to process raw material into finished goods, including the waiting times, is called the manufacturing lead time.[62] Typically, it consists of the same components as supplier lead time. Logistics or transportation lead time covers the waiting time for goods before they are loaded on vehicles as well as the loading and unloading time and the actual moving time. Distribution lead time usually comprises the time required for transport operations in warehouses as well as movement to the customer or retailer.[63]

Generally, customers are willing to wait a certain amount of time for their orders to be fulfilled. Therefore, another essential type of lead time is the order-to-delivery lead time (OTDLT). It is typically defined as the elapsed time between order placement by a customer and the delivery of that order to the customer; it reflects the period that customers are willing to wait for their ordered goods.[64]

When supply chain lead time exceeds OTDLT, this difference is described as a “lead time gap.” To close this gap, it is necessary either to reduce the supply chain lead time or to extend the OTDLT.[65] Figure 2.4 illustrates this gap. Given the lead time gap, inventories are an important factor in meeting customers’ preferred OTDLT.[66] If the lead time gap is wide (as measured in units of time), it is necessary to keep many products in stock to meet

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[58] Cf. BISWAS, S.; NARAHARI, Y., 2004, p. 706.
[59] Cf. BERTOLINI, M. ET AL., 2007, p. 199; SINGH, R. K., 2015, p. 873; VISWANADHAM, N., 2000, p. 242.
[60] Cf. LIAO, C.; SHYU, C., 1991, p. 72.
[61] Cf. VISWANADHAM, N., 2000, p. 242.
[62] Cf. KIM, I.; TANG, C. S., 1997, p. 474.
[63] Cf. VISWANADHAM, N., 2000, p. 243; VAN DER VORST, J. G. A. J. ET AL., 1998, p. 489.
[64] Cf. BISWAS, S.; NARAHARI, Y., 2004, p. 706; VISWANADHAM, N., 2000, p. 242; DING, H.; BENYOUCEF, L.; XIE, X., 2005, p. 217; HOLWEG, M., 2005, p. 605; CHRISTOPHER, M., 2016, p. 96.
[65] Cf. CHRISTOPHER, M., 2016, p. 96; VISWANADHAM, N., 2000, p. 243f.
[66] Cf. CHRISTOPHER, M., 2016, p. 96; RUSHTON, A.; CROUCHER, P., 2014, p. 220.

customers' requirements according to OTDLT. With a smaller lead time gap, the number of goods in stock can be reduced.[67]

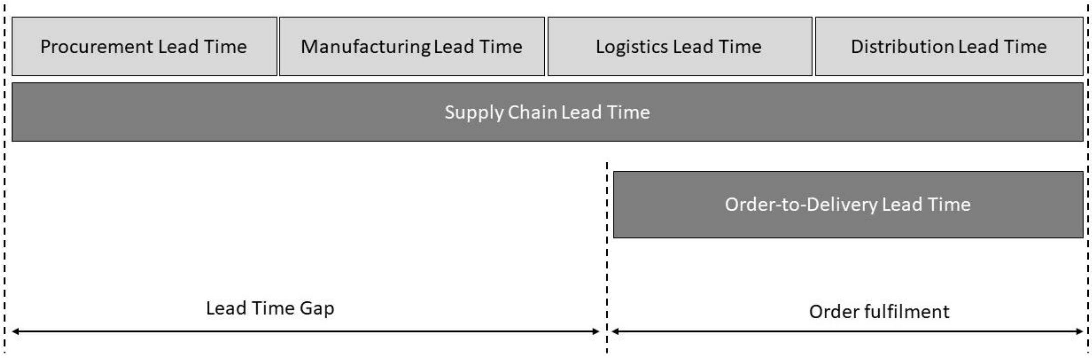

Figure 2.4: Lead Time Gap[68]

Time – like labor and capital – is a critical resource in business environments.[69] Therefore, a short quoted OTDLT can be a source of competitive advantage because of the fast delivery of goods to customers. This speed can affect consumers' perceptions of services and products. Therefore, time-related characteristics can become a source of differentiation.[70] Reduced lead times enable rapid customer response, quick movement of goods through the supply chain, and fast development of services and products.[71] Hence, lead time is a market qualifier for fashionable goods and commodities. Supply chains must be highly competitive in their market qualifier metrics to succeed in competitive business environments.[72] In addition, lead time is an essential enabler for lean, agile, and leagile supply chains.[73]

When goods are transferred between geographically dispersed production and distribution centers, lead times for transportation play an important role in the success of a global manufacturing strategy.[74] MEIXELL AND GARGEYA state that in the global context, lead times are crucial because of the need to balance costs and lead time.[75] Because inventories are a probate method to reduce OTDLT, this trade-off is especially important.

[67] Cf. RUSHTON, A.; CROUCHER, P., 2014, p. 220.
[68] The figure is based on CHRISTOPHER, M., 2016, p. 97.; RUSHTON, A.; CROUCHER, P., 2014, p. 220.
[69] Cf. TERSINE, R., 1994, p. 8.
[70] Cf. STALK, G. J., 1988, p. 46; TERSINE, R. J.; HUMMINGBIRD, E. A., 1995, p. 10; TOWILL, D. R., 1996, p. 26; WILDING, R. D.; NEWTON, J. M., 1996, p. 37; DE TONI, A.; MENEGHETTI, A., 2000, p. 255.
[71] Cf. STALK, G.; HOUT, T. M., 1990, p. 133 f.
[72] Cf. MASON-JONES, R.; NAYLOR, B.; TOWILL, D. R., 2000, p 4064.
[73] Cf. AGARWAL, A.; SHANKAR, R.; TIWARI, M. K., 2006, p. 2006; 2007, p. 446; MASON-JONES, R.; TOWILL, D. R., 1999, p. 67; BEN NAYLOR, J.; NAIM, M. M.; BERRY, D., 1999, p. 110.
[74] Cf. FAWCETT, S., 1992, p. 1082.
[75] Cf. MEIXELL, M. J.; GARGEYA, V. B., 2005, p. 533.

Furthermore, in a complex supply chain in which products are manufactured in facilities across the world, inventory costs are a significant part of the total network costs.[76]

Nevertheless, costs are not the only key to success for a company; responsiveness has also become essential,[77] and lead time determines the responsiveness of a supply chain.[78] In addition, the broadening of product ranges and the unpredictability of supply chains have made time-to-market a critical issue in avoiding excessive inventories.[79] Furthermore, long lead times have a negative impact on demand forecasts[80] and are related to the bullwhip effect.[81] Shorter lead times can reduce safety stocks, lower the losses due to stock-outs, influence customer service positively, and improve competitiveness.[82]

Another challenge in the design of supply chains is uncertainty. According to ACAR ET AL., after sources of uncertainty such as fluctuations in demand, supply, and exchange rate, the transportation lead time is another significant source of uncertainty.[83] In a recent study, HABERMANN ET AL. report that supplier lead times are significantly correlating with disruption risks in a supply chain.[84] Therefore, lead time variability is an essential factor. BAGCHI ET AL. highlight the importance of lead time variability for inventory planning due to the risk of shortages.[85] With the trend of global sourcing, lead times are becoming longer, and their variability is probably increasing.[86]

CHRISTOPHER ET AL. state that lead time must be part of every useful taxonomy. The reason is the critical impact of replenishment lead time on responsiveness to demand – as well as the longer lead times due to globalization.[87] Supply chain lead time is influenced by strategical, tactical, and operational decisions.[88] According to Ivanov,[89] such decisions are strongly interconnected, and companies must incorporate those relationships into their

[76] Cf. KAMINSKY, P.; KAYA, O., 2008, p. 276.
[77] Cf. FISHER, M., 1997, p. 110; CHRISTOPHER, M., 2000, p. 39.
[78] Cf. HOLWEG, M., 2005, p. 39; ROH, J.; HONG, P.; MIN, H., 2014, p. 200.
[79] Cf. VAN HOEK, R.; CHAPMAN, P., 2006, p. 385.
[80] Cf. CHOPRA, S.; SODHI, M. S., 2004, p. 54.
[81] Cf. CIECHANOVER, A., 2005, p. 1877.
[82] Cf. OUYANG, L. Y.; WU, K. S., 1997, p. 875; YANG, B.; GEUNES, J., 2007, p. 439.
[83] Cf. ACAR, Y.; KADIPASAOGLU, S.; SCHIPPERIJN, P., 2010, p. 3245.
[84] Cf. HABERMANN, M.; BLACKHURST, J.; METCALF, A. Y., 2015, p. 517.
[85] Cf. BAGCHI, U.; HAYYA, J. C.; CHU, C.-H., 1986, p. 174.
[86] Cf. FANG, X. ET AL., 2013, p. 390.
[87] Cf. CHRISTOPHER, M.; PECK, H.; TOWILL, D., 2006, p. 286.
[88] Cf. BISWAS, S.; NARAHARI, Y., 2004, p. 715.
[89] Cf. IVANOV, D., 2010, p. 4005.

strategy. Therefore, supply chain design models should incorporate objectives other than total costs.[90]

3 Emission Policies

3.1 Greenhouse Gas Emissions and Greenhouse Effect

About 30% of the energy from sunlight that reaches the earth’s atmosphere is reflected back into space because of clouds and aerosols. The energy not reflected must be balanced by earth itself. The earth emits longwave radiation that, on average, is an equivalent amount to balance the incoming energy. To emit the incoming amount of energy, the estimated temperature of a surface would need to be about -18°C to -19°C. However, the earth's surface has an average temperature of about 14°C to 15°C due to greenhouse gases in the atmosphere.[91] The INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE (IPCC) defines GHG as "gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of thermal infrared radiation emitted by the Earth's surface, the atmosphere itself, and by clouds."[92] These gases absorb part of the radiation from the earth and redirect some of it to outer space. However, the temperature of the troposphere is low, around -30°C to -50°C, and this cold layer limits the amount of radiation emitted into space. Therefore, greenhouse gases work as a blanket and keep the temperature on the earth’s surface relatively warm. In general, this effect is known as the natural greenhouse effect.[93]

The most important greenhouse gases are carbon dioxide (CO_2) and water vapor. The water vapor in the atmosphere originates from evaporation from ocean surfaces. Therefore, the quantity of water vapor depends mainly on the temperature of the surface of the oceans, which is not directly affected by human activities. In contrast, the amount of CO_2 in the atmosphere has changed fundamentally due to human activities (see Fig. 3.1). Industry, combustion of fossil fuels, and deforestation vastly increase the CO2 in the atmosphere, leading to the so-called enhanced greenhouse effect.[94] This effect reinforces

[90] VIDAL, C. J.; GOETSCHALCKX, M., 1997, p. 13 ff; ERENGÜÇ, Ş. S.; SIMPSON, N. C.; VAKHARIA, A. J., 1999, p. 232; MEIXELL, M. J.; GARGEYA, V. B., 2005, p. 547.
[91] HOUGHTON, J. T., 2009, p. 20; BRYANT, E., 1997, p. 118; LE TREUT, H. ET AL., 2007, p. 97.
[92] IPCC, 2007, p. 82.
[93] Cf. PLANTON, S. ET AL., 2013, p.1455; IPCC, 2007, p. 81f; HOUGHTON, J. T., 2009, p. 20ff; LE TREUT, H. ET AL., 2007, p. 96f.; BRYANT, E., 1997, p.118.
[94] Cf. HOUGHTON, J. T., 2009, p. 31ff; PLANTON, S. ET AL., 2013, p. 1455.; BRYANT, E., 1997, p. 118.

the impact of the natural greenhouse effect and leads to climate change and global warming.[95]

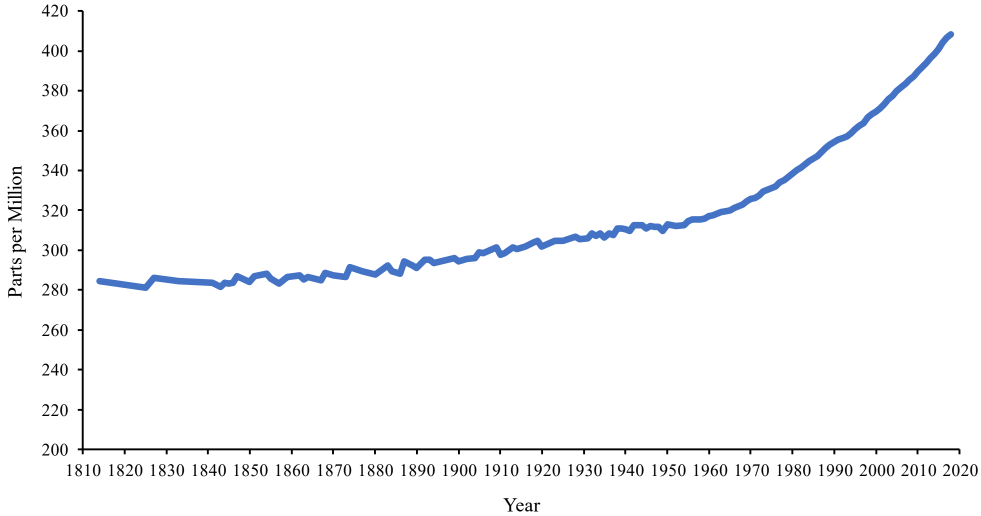

Figure 3.1: CO_2 concentration in the atmosphere between 1810 and 2020[96]

The UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE (UNFCCC) in its KYOTO PROTOCOL covers six greenhouse gases: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFC), and sulfur hexafluoride (SF_6).[97] In the DOHA AMENDMENT, nitrogen trifluoride (NF_3) was added to the list.[98] The radiative forcing generated by each greenhouse gas can be compared using their global warming potentials (GWPs). The GWP index allows a relative comparison of the global warming effects of the various greenhouse gases. It compares the effects of the instantaneous release of 1 kg of a greenhouse gas to the effect of the release of 1 kg of CO_2. Because CO_2 is the reference gas, its GWP value is always 1.

A time horizon must be specified for the time over which the radiative forcing is performed.[99] Table 3.1 presents the GWP values of the greenhouse gases covered by the KYOTO PROTOCOL. Using the GWP values, researchers can represent other GHGs as an amount of CO_2 equivalent (CO_2e). An additional significant value is the atmospheric residence time or half-life time of a GHG. A GHG with a long half-life time is quasi-

[95] Cf. WIGLEY, T. M. L.; PEARMAN, G. I.; KELLY, P. M., 1992, p. 95.
[96] The figure is based on data from RITCHIE, H.; ROSER, M., 2020; KEELING, C. D. ET AL., 2005; BEREITER, B. ET AL., 2015; TANS, P.; KEELING, R., 2020.
[97] Cf. UNFCCC, 1998, p. 19.
[98] Cf. UNFCCC, 2012, p. 4.
[99] HOUGHTON, J. T., 2009, p. 63; DILMORE, R.; ZHANG, L., 2018, p. 18.

irreversible and causes radiative forcing over a very long time horizon before natural processes can remove the emitted quantities.[100]

Greenhouse Gas	**Half-life time (years)**	**GWP time horizon**	
		20 years	100 years
Carbon dioxide (CO_2)		1	1
Methane *(CH_4)*	12.4	84	265
Nitrous oxide *(N_2O)*	121	264	12,400
Hydrofluorocarbons (HFC-23)[101]	222	10,800	1300
Perfluorocarbons (CF4)[102]	50,000	4880	6630
Sulfur hexafluoride (SF_6)	3200	17,700	23,500
Nitrogen trifluoride (NF_3)	500	12,800	16,100

Table 3.1: Summary of GWP values of selected greenhouse gases[103]

To delineate between direct and indirect sources of emissions, the WORLD BUSINESS COUNCIL FOR SUSTAINABLE DEVELOPMENT (WBCSD) and the WORLD RESOURCES INSTITUTE (WRI) defined three scopes for the purposes of GHG accounting and reporting. These scopes improve the transparency of reporting. Scope 1 covers direct GHG emissions, which are caused by sources owned or controlled by a company. Scope 2 includes indirect GHG emissions originating from purchased electricity; these emissions occur at the producing facility. Scope 3 covers all other indirect GHG emissions, such as the production of purchased materials, the ways in which the company's products or services are used, and the transportation of purchased fuels.[104]

3.2 Greenhouse Gas Emissions in the Supply Chain

To document and analyze emission sources, the IPCC proposes using sector categories.[105] Fig. 3.2 shows the worldwide emissions by sector during 2016. Data is gathered from the WRI's CAIT tool.[106][107] The GHG emissions are divided into sectors based on the IPCC

[100] IPCC, 2001, p. 38.
[101] For Hydrofluorocarbons, HFC-23 is used as an example, the GWP of all HFCs can be found in SHINDELL, D. ET AL., 2013, p. 731 ff.
[102] For Perfluorocarbons, CF4 is used as an example, the GWP of all PFCs can be found in SHINDELL, D. ET AL., 2013, p. 733 f.
[103] The table is based on SHINDELL, D. ET AL., 2013, p. 731 ff.; DILMORE, R.; ZHANG, L., 2018, p. 18.
[104] Cf. WORLD BUSINESS COUNCIL FOR SUSTAINABLE DEVELOPMENT (WBCSD); WORLD RESOURCES INSTITUTE (WRI), 2004, p. 25.
[105] Cf. IPCC, 1997, p. 1.2.
[106] Cf. WORLD RESOURCES INSTITUTE (WRI), 2015.
[107] For further information about the methodology, sector definition ,and covered GHG see WORLD RESOURCES INSTITUTE (WRI), 2015.

proposal. Sectors linked to supply chain operations – such as industrial processes, manufacturing and construction, and transportation – account for a high proportion of global GHG emissions. According to the INTERNATIONAL ENERGY AGENCY (IEA), the industrial sector consumed 37% of all produced energy in 2017. The second largest consumer sector was transport, at 29%. It is evident that emissions from the subcategory of energy/heat play a significant role in GHG emissions originating from supply chains.[108]

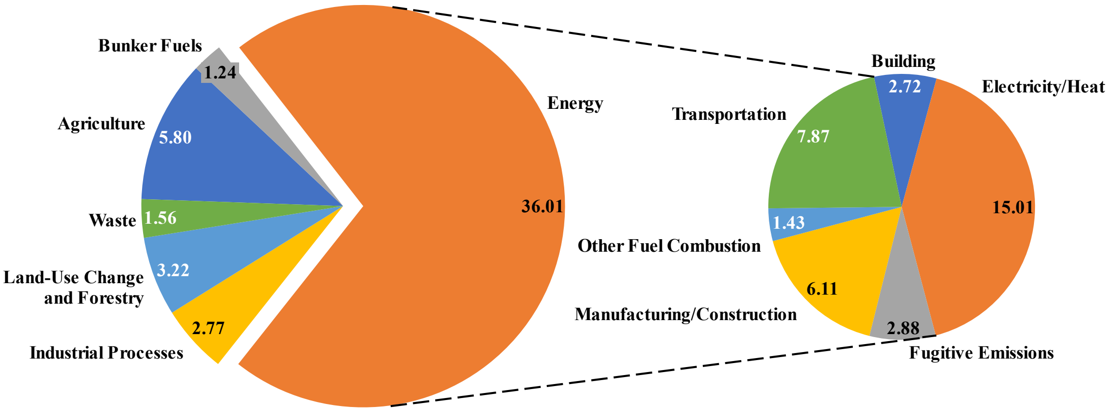

Figure 3.2: Total value of global GHG emissions in 2016 by sector (gigatons)[109]

Despite the decreasing share of industry in global gross domestic product, GHG emissions from this sector are continuously increasing. In addition, industry-related emissions are higher than GHG emissions of all other end-use sectors.[110] Fig. 3.3 shows the GHG emissions from sectors related to industrial production and supply chain operations between 1970 and 2015. These sectors are identified by the EMISSION DATABASE FOR GLOBAL ATMOSPHERIC RESEARCH (EDGAR) as follows: Power industry (power and heat generation plants), transport (mobile combustion), other industrial combustion (combustion for fuel production and industrial manufacturing), and other sectors (industrial process emissions, agriculture, and waste).[111]

All these GHG emissions increased over the examined horizon. Therefore, supply chain operations and logistics are identified as significant contributors to global GHG emissions, with about 13% of such emissions attributed to the logistics industry.[112] In the

[108] Cf. IEA, 2019, p. 8.
[109] The figure is based on data provided by WORLD RESOURCES INSTITUTE, 2018, based on data by U.S. ENVIRONMENTAL PROTECTION AGENCY (EPA), 2012; INTERNATIONAL ENERGY AGENCY, 2019; FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS (FAO), n. y.; U.S. ENERGY INFORMATION ADMINISTRATION (EIA), n. y.; BODEN, T. A.; ANDRES, R. J.; MARLAND, G., 2015.
[110] Cf. FISCHEDICK, M. ET AL., 2014, p. 743.
[111] Cf. CRIPPA, M. ET AL., 2019.
[112] Cf. WORLD ECONOMIC FORUM, 2016, p. 5.

United States, transportation emissions comprise around 28% of total emissions.[113] Similarly, in Germany, transportation emissions accounted for around 20% of total emissions in 2019.[114] The supply chain is responsible for 50% to 70 % of most manufacturing companies' total costs and GHG emissions.[115]

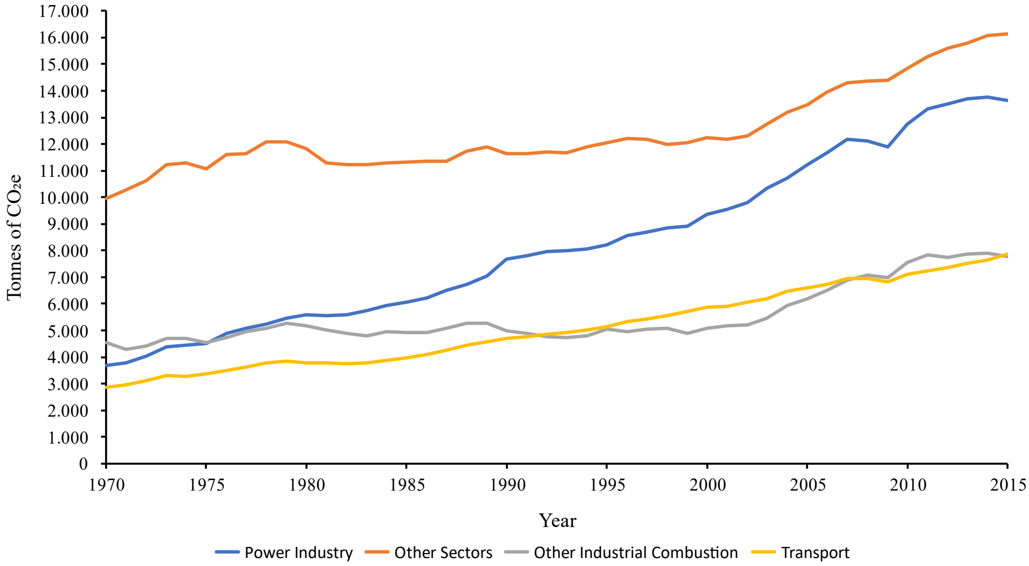

Figure 3.3: Global GHG emissions from different sectors between 1970 and 2015[116]

3.3 Environmental Emission Policy Instruments

With the CLUB OF ROME's publication "The Limits of Growth"[117] and the Report "Our Common Future"[118] by the WORLD COMMISSION ON ENVIRONMENT AND DEVELOPMENT, environmental issues, resource scarcity, and global warming were presented to the public at large. Participating countries set up targets, which were listed in the Kyoto Protocol and further agreements to tackle the problem of global warming and rising GHG emissions. In the Kyoto protocol, the target was to reduce GHG emissions by 5% before 2012, to achieve the levels of 1990.[119] In the Doha Amendment, governments agreed to reduce emissions at last by 18% to achieve the 1990 level.[120] In the Paris Agreement, it was decided to hold the increase of global average temperature below 2°C and to pursue efforts to limit the temperature increase to 1.5°C above the pre-industrial level.[121]

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[113] UNITED STATES ENVERIONMENTAL PROTECTION AGENCY, 2020.
[114] UMWELTBUNDESAMT, 2020.
[115] Cf. HANIFAN, G. L.; SHARMA, A. E.; MEHTA, P., 2012, p. 2.
[116] The figure is based on data provided by EDGAR V5.0, 2019 and CRIPPA, M. ET AL., 2019, p. 37ff.
[117] MEADOWS, DONELLA, H.; MOADOWS, D. L.; RANDERS, J., 1972.
[118] WORLD COMMISSION ON ENVIRONMENT AND DEVELOPMENT, 1987.
[119] Cf. UNFCCC, 1998, p. 3.
[120] Cf. UNFCCC, 2012, p. 4.
[121] Cf. UNFCCC, 2015, p. 3.

Given the risk of climate change and global warming as well as the above targets, governments are under pressure to implement environmental policies on GHG emission reduction. Those policies are concerned with managing the relationship between humans and the natural environment in a beneficial manner.[122] ROBERTS defines environmental policies as “a set of principles and intentions used to guide decision making about human management of environmental capital and environmental services.” In the late 1960s, environmental policies started to evolve.[123] Environmental policies can employ different instruments to provide the necessary guidance for decision making. According to MICKWITZ, environmental policy instruments are a “set of techniques by which governmental authorities wield their power in attempting to affect society – in terms of values and beliefs, action and organization – in such a way as to improve, or to prevent the deterioration of, the quality of the natural environment."[124]

There is a wide variety of environmental policy instruments, and they can be classified in different ways.[125] A basic classification scheme is the threefold typology of public policy instruments proposed by VEDUNG,[126] among others. This scheme divides environmental policies into direct regulations, market-based approaches, and information approaches. All types of environmental policy instruments can be placed in one of these categories. Furthermore, the number of categories cannot be reduced without loss of insight.[127] Fig. 3.4 illustrates this classification scheme.

Direct regulations include measures initiated by a government administration to regulate people's habits through directives and rules. These directives force receivers to act in a manner that complies with what is commanded.[128] Direct regulations are also called command and control regulations.[129] Direct regulation approaches can be based on three standards: ambient, performance-based, or technology-based. Ambient standards specify the desired level of an environmental element, such as air or water quality. In general, they are expressed as the maximum allowed concentration of a specific pollutant in the

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[122] Cf. BENSON, D.; JORDAN, A., 2015, p. 778.
[123] Cf. DOLZER, R., 2001, p. 4638; COCKLIN, C., 2009, p. 541.
[124] MICKWITZ, P., 2003, p. 419.
[125] Classification schemes of environmental policy instruments can e.g. be found at: DE SERRES, A.; MURTIN, F.; NICOLETTI, G., 2010; DUVAL, R., 2008; GOULDER, L. H.; PARRY, I. W. H., 2008; HATCH, M. T., 2005; SORRELL, S., 2003; GÖRLACH, B., 2013; VEDUNG, E., 2010; OATES, W. E.; BAUMOL, W. J., 1975.
[126] Cf. VEDUNG, E., 2010, p. 30.
[127] Cf. VEDUNG, E., 2010, p. 30.
[128] Cf. VEDUNG, E., 2010, p. 31; WIESMETH, H., 2012, p. 135; STAVINS, R., 1997, p. 297.
[129] Cf. COMMON, M. S.; STAGL, S., 2012, p. 411.

environment.[130] Technology-based standards specify the equipment or method to be used to achieve a specific pollution reduction.[131] Performance-based standards designate a specific limit of emissions to be achieved by every regulated polluter, but without specifying the technology.[132]

The prohibition or mandating of certain products and practices are an extreme form of these standards and are thus direct regulations.[133] A practical example would be the ban of chlorofluorocarbons (CFCs) in the MONTREAL PROTOCOL.[134] Command and control regulations set codes and standards to designate environmental targets in the construction of buildings and land use planning or zoning. These set the standard for how to use the land without restrictions on the technology used in the planned space.[135]

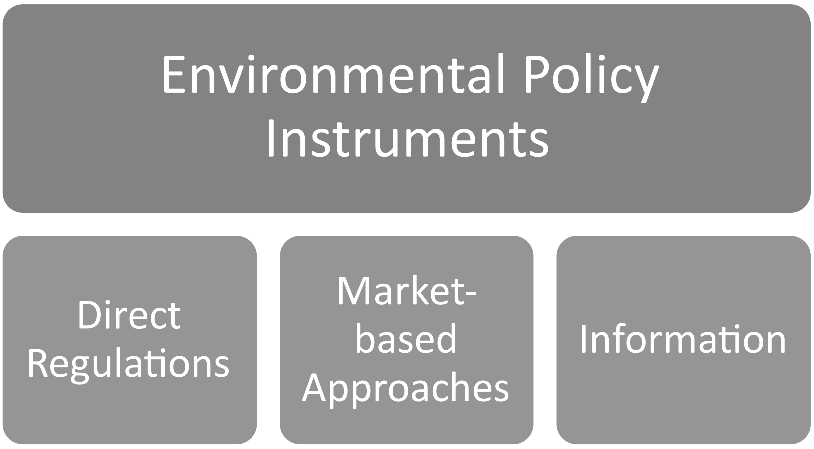

Figure 3.4: Classification of environmental policy instruments[136]

Market-based approaches include policies that give out or take away material resources. These resources can be monetary or any other resource. Market-based approaches render specific actions more or less expensive regarding time, effort, or money.[137] These approaches encourage certain behavior by price signals instead of orders or directives.[138] Market-based environmental policy instruments can generally be classified into four

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[130] Cf. CALLAN, S. J.; THOMAS, J. M., 2013, p. 81; HAMILTON, S. F.; REQUATE, T., 2012, p. 377.
[131] Cf. GOULDER, L. H.; PARRY, I. W. H., 2008, p. 157; JAFFE, A. B.; STAVINS, R. N., 1995, p. 45; GÖRLACH, B., 2013, p. 34; ROSEN, H. S.; GAYER, T., 2008, p. 94f.
[132] Cf. GÖRLACH, B., 2013, p. 34; CALLAN, S. J.; THOMAS, J. M., 2013, p. 81; GOULDER, L. H.; PARRY, I. W. H., 2008, p. 157f.; BUCHHOLZ, W.; RÜBBELKE, D., 2019, p. 70; ROSEN, H. S.; GAYER, T., 2008, p. 95.
[133] Cf. DE SERRES, A.; MURTIN, F.; NICOLETTI, G., 2010, p. 24.
[134] Cf. UNITED NATIONS, 1987.
[135] Cf. GÖRLACH, B., 2013, p. 34f.
[136] The figure is based on VEDUNG, E., 2010, p. 30.
[137] VEDUNG, E., 2010, p. 32.
[138] STAVINS, R. N., 2000, p. 31.

groups: pollution charges, tradable pollution permits, governmental subsidy reductions, and market barrier reductions.[139] In a pollution charge system, a fee or a tax is assessed on the amount of pollution a source emits. Tradable pollution permits employ a similar approach: There is a maximum number of allowed pollution, and permits for polluting are sold or given to sources. If sources perform well environmentally, they can sell their surplus of permits. Sources also have the opportunity to buy additional permits on the market. By removing market barriers, essential gains can be made in environmental protection by boosting environmentally friendly market entrants. Government subsidies can be used to promote environmentally beneficial behavior. However, in many cases, the subsidies are economically inefficient and promote environmentally harmful activities. Hence, the reduction of government subsidies can also be an environmental policy instrument.[140]

Information is often referred to as “moral suasion.” These approaches affect people through knowledge transfer, persuasion, and general communication of arguments. In this case, an authority aims to pressure individuals to behave in a specific manner but without using force.[141] These instruments aim to improve customer decision-making by providing better information.[142] Education and training instruments also account for such approaches. Moral suasion tries to build capacities to respond to consumer values and to modify those values.[143] Product certification and labeling can be used to support such actions. Examples of product labeling are the Environmentally Friendly Label in Hungary and the Blue Angel label in Germany.[144]

Environmental emission policies, especially command and control approaches, do not necessarily consider total emission amounts alone. Furthermore, according to TA LUFT in Germany, restrictions can be based on the mass concentration of emissions or the emission mass flow. Emission mass concentration reflects the emission per unit of a carrier medium (e.g., wastewater or exhaust gas). On the other hand, emission mass flow reflects the emission per unit of time (e.g., emission output of a machine per hour).[145] Due to the strategic nature of this work, the focus is on total emission over a certain planning period.

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[139] Cf. STAVINS, R. N., 2000, p. 33f.
[140] Cf. STAVINS, R. N., 2000, p. 34f; CALLAN, S. J.; THOMAS, J. M., 2013, p. 99.
[141] Cf. VEDUNG, E., 2010, p. 33; COMMON, M. S.; STAGL, S., 2012, p. 406; ROBERTS, J., 2010, p. 167f.
[142] Cf. DE SERRES, A.; MURTIN, F.; NICOLETTI, G., 2010, p. 24; GÖRLACH, B., 2013, p. 35.
[143] Cf. SORRELL, S., 2003, p. 19; GÖRLACH, B., 2013, p. 36.
[144] Cf. GÖRLACH, B., 2013, p. 36.
[145] See BUNDESMINISTERIUM FÜR UMWELT NATURSCHUTZ UND REAKTORSICHERHEIT, 2002; LANGE, C., 1978, p. 131f.

The determination of total emission is loosely based on the various scopes proposed by the WRI.[146]

For simplicity, in the following, the term "emission" is used as a synonym for GHG emissions. Further, this work concentrates on the approaches often used in supply chain design models. These are the emission cap, as a performance standard and direct regulation; emission tax and emission cap and trade, as market-based approaches; and emission offset, as a voluntary market-based approach.

3.3.1 Emission Cap

Carbon or emission caps are a legislated or negotiated limit of emissions that a company or country may emit during a time interval.[147] Political processes set such emission targets or performance standards. The targets are based on scientific findings about the safe emission levels, and in most cases depend on what policymakers and stakeholders see as technically and economically feasible. Regulation authorities can create licenses, quotas, or permits that limit the volume of allowed emissions to create an emission limit for a distinct polluter, such as a company. These licenses cannot be traded or transferred.[148] The number of licenses specifies the number of GHG (for example) that a polluter may emit; hence, this method can be seen as a strict cap. In many cases, the level of allowed pollution is the same for all corporations.[149] It is necessary to monitor the emission levels of polluters regularly to guarantee the functionality of such systems. Penalties are needed for non-compliance, and they must be enforced.[150]

When well drafted, such legislation has many advantages, and this instrument is widely used. Because of the direct restriction of environmental pollution, these instruments show high environmental effectiveness.[151] Another benefit – unlike technology standards – is that firms have the flexibility to choose a method to abate their emissions to meet the cap. There is the option for companies to choose between abatement level and output

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[146] See WORLD BUSINESS COUNCIL FOR SUSTAINABLE DEVELOPMENT (WBCSD); WORLD RESOURCES INSTITUTE (WRI), 2004, p. 25.
[147] Cf. MEGANCK, R. A.; SAUNIER, R. E., 2009, p. 121.
[148] Cf. COMMON, M. S.; STAGL, S., 2012, p. 411.
[149] Cf. CALLAN, S. J.; THOMAS, J. M., 2013, p. 92; STURM, B.; VOGT, C., 2018, p. 114.
[150] Cf. COMMON, M. S.; STAGL, S., 2012, p. 411.
[151] Cf. COMMON, M. S.; STAGL, S., 2012, p. 411; BUCHHOLZ, W.; RÜBBELKE, D., 2019, p. 71; ROBERTS, J., 2010, p. 163.

reduction, which means the company can choose between abatement investments or reducing the output.[152]

A performance standard can be beneficial in situations with imperfect information about environmental risks or the irreversibility of environmental harm. Standards are suitable for these situations because they can set strict boundaries for the use of environmental resources. In such cases, market-based or information approaches can lead to the exploitation of environmental resources.[153] Furthermore, if the marginal damage curve is assumed to be steep and the marginal costs of the abatement curve are not, choosing a command and control approach seems beneficial.[154]

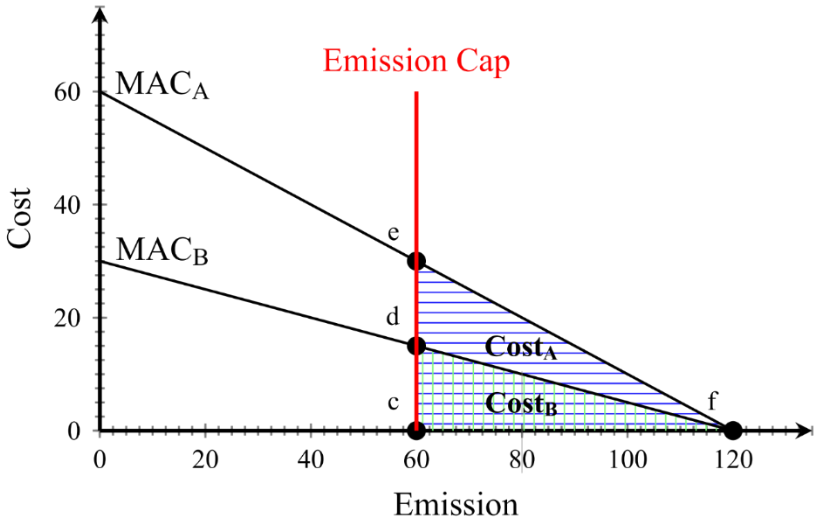

Figure 3.5: Mechanism of a performance standard via an emission cap[155]

Nevertheless, since regulatory approaches require rules that apply to all emitters of a specific pollutant, performance standards cannot accommodate distinct differences between branches and companies.[156] If cost structures for emission abatement differ between branches or companies, the performance standards may be more costly to society than necessary.[157] As shown in Fig. 3.5, two polluters have different marginal costs for abating pollution. Polluter A has marginal costs for abating the emission of MAC_A, whereas Polluter B has marginal costs for abatement of MAC_B. The strict carbon cap forces both polluters to reduce their carbon emissions to 60 emission units. This leads to abating

[152] Cf. STERNER, T.; CORIA, J., 2012, p. 70.
[153] Cf. HAMILTON, C. ET AL., 2019, p. 3; SIEBERT, H., 2008, p. 133.
[154] BOJÖ, J.; MÄLER, K.-G.; UNEMO, L., 1992, p. 98.
[155] The figure is based on COMMON, M. S.; STAGL, S., 2012, p. 411f; CALLAN, S. J.; THOMAS, J. M., 2013, p. 94; STERNER, T.; CORIA, J., 2012, p. 62f.
[156] Cf. SIEBERT, H., 2008, p. 133.
[157] Cf. COMMON, M. S.; STAGL, S., 2012, p. 411; CALLAN, S. J.; THOMAS, J. M., 2013, p. 92.

emission costs of $Cost_A$ (triangle CEF) for polluter A and $Cost_B$ (triangle CDF) for Polluter B. Because of the higher marginal costs of Polluter A, abating the same amount of emission is more expensive than for Polluter B.

Because it is not feasible to consider the particular conditions of individual emitting companies, these standards become expensive and can lead to welfare losses. Therefore, regulation is often economically inefficient.[158] Additionally, such systems can lead to high administration and compliance costs because government institutions need to monitor polluters' compliance and must litigate when violations of the limits occur. The affected companies may face legal and other costs due to implementing these regulations.[159] Furthermore, such approaches offer no incentives for further investment in emission reduction beneath the required limit. Most companies thus abate their emissions only to the ordered limit but not below it.[160]

Regulatory instruments affecting scale are generally the most commonly used instruments worldwide.[161] Typically, they control pollution and the management of common property resources.[162]

3.3.2 Emission Tax

The idea of a tax on externalities dates back to PIGOU.[163] The basic idea in this approach is to tax polluters so that their private marginal costs increase to keep up with social marginal costs at the point of optimal output volume.[164] A tax per unit of output is levied to increase the private marginal costs.[165] Due to profit maximization, polluters would otherwise produce the number of goods for which their private marginal costs equal the marginal benefits. The PIGOUVIAN TAX ensures that private marginal costs are increased to the level of social marginal costs; therefore, the polluter has to consider the costs of externalities and produce more efficiently.[166] Taxing pollution to achieve a price that reflects social marginal cost ensures that the total cost of polluters' actions is considered. In

[158] Cf. ROBERTS, J., 2010, p. 164; BUCHHOLZ, W.; RÜBBELKE, D., 2019, p. 71.
[159] Cf. HAMILTON, C. ET AL., 2019, p. 2.
[160] Cf. DALY, H. E.; FARLEY, J., 2011, p. 429; ROBERTS, J., 2010, p. 164.
[161] Cf. DALY, H. E.; FARLEY, J., 2011, p. 427.
[162] Cf. COMMON, M. S.; STAGL, S., 2012, p. 410.
[163] Cf. PIGOU, A. C., 1929, p. 174ff.
[164] Cf. FRITSCH, M., 2018, p. 112.
[165] Cf. WIESMETH, H., 2012, p. 83.
[166] Cf. ROSEN, H. S.; GAYER, T., 2008, p. 82.

this approach, firms are forced to lower their production to an efficient level,[167] which inevitably leads to allocative efficiency.[168]

The PIGOU solution has the disadvantage of needing abundant information. In reality, the detection of the ideal PIGOU TAX is based on external costs and benefits; however, capturing, evaluating, and attributing these data is technically impossible. Furthermore, the PIGOU solution is only valid for a distinct supply and demand constellation and would have to be evaluated and revised regularly.[169]

Another approach to environmental taxation is the price-standard approach. This approach is described by BAUMOL AND OATES, who proposed setting a price for emissions to reduce them to a given standard.[170] Contrary to the PIGOU solution, no optimal situations are considered, but governmental authorities issue an internalization target. The basis of the price-standard approach is to force polluters to pay a tax on every emission unit. Therefore, every polluter has the choice to abate their emissions or pay the total tax. [171] Fig. 3.6 illustrates the mechanism of the price-standard approach. Two polluters, A and B, are considered. They have different marginal costs for abating their emissions. If an environmental tax (in the form of an emission tax) is applied in the height of 20 monetary units, both polluters will reduce their emissions. However, according to their marginal abatement costs, Polluter A will reduce their emissions to 40 emission units, whereas Polluter B will reduce theirs to 80 units. Therefore, Polluter A must pay a tax amount of Tax_A (rectangle CDFE), and Polluter B will pay Tax_B (rectangle CDHG). The government's overall target of emissions no higher than 120 emission units can be achieved, but unlike in the performance standard approach, every polluter reduces their emissions according to their marginal costs of abatement.

Taxes on emissions have a positive effect on the choice of available technology. Polluters tend to use greener technology for production, logistics, and so on to reduce their taxation.[172] REQUATE states that environmental taxation has a stronger effect on technology selection than, e.g., cap and trade systems.[173] Furthermore, environmental taxes can

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[167] Cf. CALLAN, S. J.; THOMAS, J. M., 2013, p. 101.
[168] Cf. COMMON, M. S.; STAGL, S., 2012, p. 415.
[169] Cf. FRITSCH, M., 2018, p. 114f; COMMON, M. S.; STAGL, S., 2012, p. 417; STERNER, T.; CORIA, J., 2012, p. 73.
[170] Cf, BAUMOL, W. J.; OATES, W. E., 1988, p. 159ff
[171] Cf. FRITSCH, M., 2018, p. 115; CALLAN, S. J.; THOMAS, J. M., 2013, p. 101.
[172] Cf. BUCHHOLZ, W.; RÜBBELKE, D., 2019, p. 74; FRITSCH, M., 2018, p. 119.
[173] Cf. REQUATE, T., 2005, p. 193.

equalize marginal abatement costs among firms and induce a cost-efficient solution to abate emissions between different options of abating within a single firm.[174] Another advantage is that beyond allocation efficiency, the state generates tax income, which can be used to lower other taxes or to invest in the country's infrastructural competitiveness.[175]

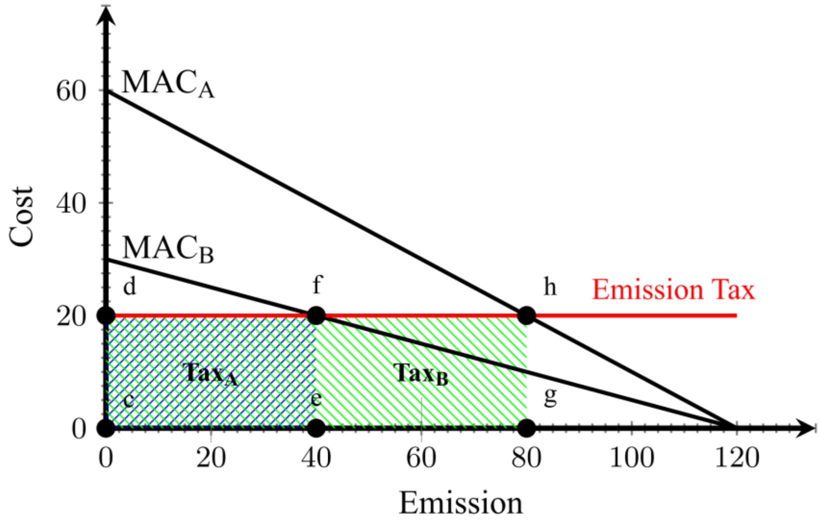

Figure 3.6: Mechanism of an emission tax

Nevertheless, taxes require regulation. The tax domain has to be defined, the formal incidence has to be set, collection must be organized, and inspection and compliance mechanisms must be developed.[176] In addition, government authorities typically do not know about companies' marginal costs of abatement, which renders the determination of an appropriate tax to achieve the abatement target almost possible.[177] A solution can be to determine taxes iteratively.[178] However, this approach is time-consuming and lowers the flexibility of polluters in future periods because of long-term investments in abatement technologies. Therefore, tax adjustment may have only a negligible influence on abatement activities in the short term. Also, this mechanism can fail to lead to the desired abatement level in the long term because polluters may already have invested in abatement activities based on the initial tax rate and are now locked in into this decision.[179]

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174 Cf. BUCHHOLZ, W.; RÜBBELKE, D., 2019, p. 77.
175 Cf. FRITSCH, M., 2018, p. 119.
176 Cf. HELM, D., 2004, p. 212.
177 Cf. BUCHHOLZ, W.; RÜBBELKE, D., 2019, p. 84.
178 Cf. BAUMOL, W. J.; OATES, W. E., 1988, p. 161.
179 Cf. BUCHHOLZ, W.; RÜBBELKE, D., 2019, p. 85.

According to WORLD BANK GROUP, 25 national and four subnational jurisdictions have implemented an emission tax. The tax fee differs sharply between countries: the lowest rates are around USD 0.5 and the highest is USD 127.[180]

3.3.3 Emission Cap and Trade

The approach that employs tradable emission permits can be seen as a combination of the COASE THEOREM and the price-standard approach.[181] The theory of COASE proposes that there are exclusive, transferable property rights to the environment. Furthermore, there are no transaction costs; every individual maximizes their utilities and is non-altruistic. Moreover, there is a bargaining solution between users of the environment, which results in a Pareto-optimal allocation of the environment.[182]

The concept of tradable emission credits depends on the declaration of a tolerable emission level in a specific region, as determined by government authorities.[183] Since authorities control the number of credits, the aggregated quantity is controllable by them.[184] Only polluters who own credits – which specify a certain amount of emissions in a certain period – are allowed to pollute, up to the limit of the number of their credits.[185] Pollution without emission credits would be a violation of the law.[186] Emission credits can be assigned (e.g., in the context of historical pollution, to specific polluters) or can be auctioned at the point of introduction.[187] The assignment of emission credits to polluters is called "grandfathering."[188] Because all credits are tradable between polluters, a so-called cap and trade system is established.[189]

An essential basis of this system is a functioning market that allows the trading of emission credits.[190] In a functioning market, the credit price is the result of demand and supply and is a measure of scarcity of an environmental medium.[191] Therefore, polluters with high marginal costs of abatement have an incentive to bid for additional permits. By

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[180] Cf. WORLD BANK, 2019, p. 14f; WORLD BANK GROUP, 2020.
[181] Cf. FRITSCH, M., 2018, p. 128.
[182] Cf. COASE, R. H., 2013, p. 837; COMMON, M. S.; STAGL, S., 2012, p. 328; WIESMETH, H., 2012, p. 98; ROSEN, H. S.; GAYER, T., 2008, p. 80; SIEBERT, H., 2008, p. 99.
[183] Cf. CALLAN, S. J.; THOMAS, J. M., 2013, p. 115; FRITSCH, M., 2018, p. 128.
[184] Cf. COMMON, M. S.; STAGL, S., 2012, p. 426.
[185] Cf. BUCHHOLZ, W.; RÜBBELKE, D., 2019, p. 111.
[186] Cf. CALLAN, S. J.; THOMAS, J. M., 2013, p. 115.
[187] Cf. FRITSCH, M., 2018, p. 128; WIESMETH, H., 2012, p. 196.
[188] Cf. MEGANCK, R. A.; SAUNIER, R. E., 2009, p. 160.
[189] Cf. BUCHHOLZ, W.; RÜBBELKE, D., 2019, p. 110.
[190] Cf. SIEBERT, H., 2008, p. 142.
[191] Cf. FRITSCH, M., 2018, p. 128.

contrast, polluters with low marginal costs of abatement can sell their surplus permits.[192] The principle of cap and trade systems is based on the mechanism that the number of emissions increased by one source must be decreased by another.[193] Fig. 3.7 illustrates the mechanism of a cap and trade system.

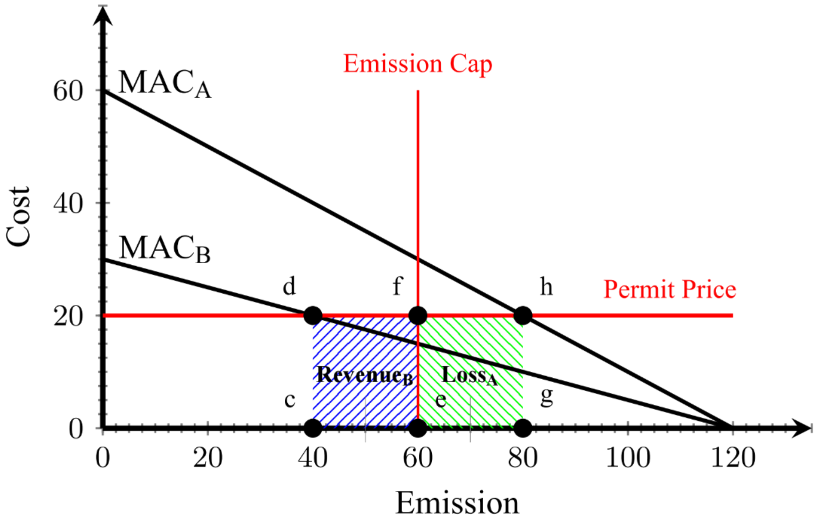

Figure 3.7: Mechanism of an emission cap and trade system[194]

As in the previous sections, two polluters with different marginal costs of abatement, MAC_A and MAC_B, are considered. Governmental authorities set an emission cap and equally give emission credits to both parties. A credit price on the market of 20 monetary units is assumed. Polluter B will try to sell credits, to enable emitting 20 emission units, because their marginal costs of abatement are lower than the emission credit price. Polluter A will try to buy credits to enable them to emit 20 additional emission units, because it is cheaper to buy additional permits than to abate. Therefore, Polluter B can achieve $Revenue_B$ (rectangle CDEF), and Polluter A has to pay for the additional credits in the form of $Loss_A$ (rectangle FEGH).

In the case of an emission tax, authorities fix the price for emitting with the help of a tax rate. By contrast, in a cap and trade system, the quantity of emission that polluters can emit is regulated by governmental authorities.[195] The effects of a cap and trade system are comparable to the effect of an environmental tax in both static and dynamic efficiency.[196] The advantages of such a system, which explicitly uses a marked approach, are

[192] Cf. CALLAN, S. J.; THOMAS, J. M., 2013, p. 115.
[193] Cf. COMMON, M. S.; STAGL, S., 2012, p. 426.
[194] Cf. ROSEN, H. S.; GAYER, T., 2008, p. 90; STURM, B.; VOGT, C., 2018, p. 95.
[195] Cf. COMMON, M. S.; STAGL, S., 2012, p. 426.
[196] Cf. FRITSCH, M., 2018, p. 130; BUCHHOLZ, W.; RÜBBELKE, D., 2019, p. 110f.

often highlighted.[197] However, according to the WEITZMAN theorem,[198] if marginal costs of abatement increase more than the marginal damage caused by emissions, a percentual fault by determining a tax results in a lower welfare loss than a percentual fault in determining the emission quantities that polluters can emit.[199] Furthermore, the fluctuation of emission credit prices can lead to problems by reducing emissions.[200]

Well-known examples of cap and trade systems that have been implemented are the EU-ETS,[201] which covers carbon emission of various industry sectors within EU states, and the US Clean Air Act Amendments of 1990,[202] which control sulfur dioxide emissions. Furthermore, 27 cap and trade systems around the world cover 37 national and 28 subnational jurisdictions.[203]

3.3.4 Emission Offset

“Emission offset” describes a unit of CO_2e that is avoided or reduced to compensate for carbon dioxide equivalents elsewhere. Offset allowances or permits are generally measured in tons. They are often described as an alternative to direct reductions for meeting the emission caps in cap and trade systems.[204] A significant difference from the cap and trade system is that unused emission allowances or permits cannot be sold. Therefore, a polluter cannot make additional profit by selling unused permits. Nevertheless, polluters can buy additional allowances if needed.[205] The government or environmental agencies set an acceptable level of emission that polluters may emit. For the difference between the actual emissions and the acceptable level (the cap), polluters must pay a charge per emission unit.[206] Fig. 3.8 shows the emission offset mechanism.

There are two polluters with different marginal costs of abatement, MCA_A for Polluter A and MAC_B for Polluter B. The emission cap generally allows 60 emission units for each polluter, and there is a price for additional permits of 20 monetary units. Polluter B, which has higher marginal costs of abatement, will buy additional permits until their marginal

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[197] Cf. CALLAN, S. J.; THOMAS, J. M., 2013, p. 119.
[198] Cf. WEITZMAN, M. L., 1974.
[199] Cf. STURM, B.; VOGT, C., 2018, p. 96.
[200] Cf. FRITSCH, M., 2018, p. 130.
[201] Cf. EUROPEAN COMMISSION, 2015.
[202] Cf. UNITED STATES ENVERIONMENTAL PROTECTION AGENCY, 2017.
[203] Cf. WORLD BANK GROUP, 2020.
[204] Cf. GOODWARD, J.; KELLY, A., 2010, p. 1.
[205] Cf. MARUFUZZAMAN, M.; EKSIOGLU, S. D.; HERNANDEZ, R., 2014; PALAK, G.; EKŞIOĞLU, S. D.; GEUNES, J., 2014; MOHAMMED, F. ET AL., 2017, p. 160.
[206] Cf. CALLAN, S. J.; THOMAS, J. M., 2013, p. 101.

costs of abatement are lower than the permit price. Therefore, polluter A will buy 20 additional permits and pay an amount of $Loss_A$ (rectangle CDEF). As the emission cap requires, polluter B will reduce their emissions to 60 emission units because their marginal costs of abatement are lower than the permit price. Since there is no opportunity to sell unused permits, polluter B will not further reduce their emissions even if their marginal costs of abatement are lower than the permit price.

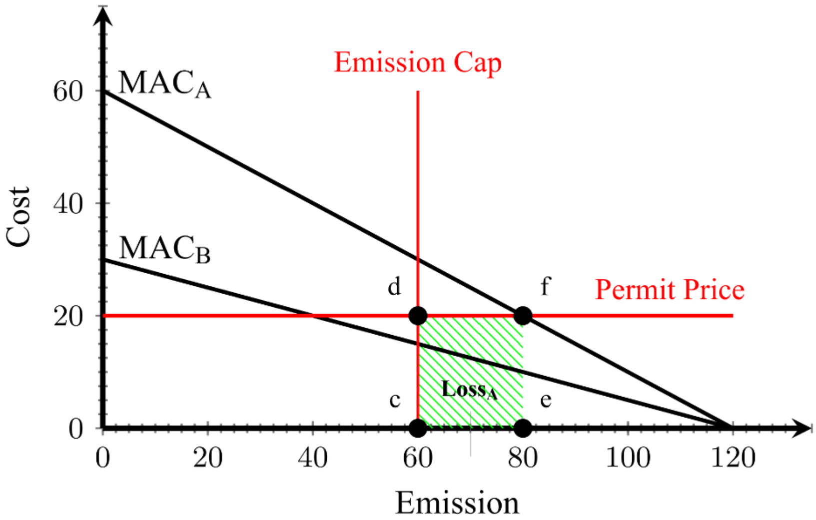

Figure 3.8: Mechanism of an emission offset system

Emission offset schemes offer a relatively low incentive to reduce emissions below the imposed emission cap. Furthermore, emission offset schemes are generally voluntary. The literature portrays them as a self-imposed voluntary emission tax applied to offset the activities of a polluter.[207] Therefore, offsetting emissions in this case means investing in projects to reduce emissions elsewhere. Various offset providers may offer to invest in – for example – forest or renewable energy projects.[208]

4 Literature Review

4.1 Methodology

A literature review is conducted to provide an overview of the state of research on supply chain design models that consider lead times and emission policies. Only publications considering strategic decisions such as facility location are considered, to delimit the focus to relevant contributions on this topic. Furthermore, only forward supply chains are

[207] Cf. WALTHO, C., 2019, p. 324.
[208] Cf. CARO, F. ET AL., 2013, p. 545.

considered in the review process. Closed-loop supply chains,[209] reverse supply chains, and approaches that deal only with tactical or operational decisions are neglected. Moreover, supply chains for biofuels[210] are excluded due to their unique structure.

The literature review is prepared according to the method of VOM BROCKE ET AL.,[211] and two directions are covered. First, literature on supply chain design models that consider lead time is examined. Second, approaches considering emission policies are studied. To identify relevant literature, various search strings are created. For publications on supply chain design considering lead times, combinations of the following keywords are used: “supply chain design,” “lead time,” “optimization model,” “strategic network design,” “responsiveness,” “quoted lead time,” and “order lead time.” To identify publications on supply chain design considering emission policies, the following keywords are used in different combinations: “supply chain design,” “optimization model,” “strategic network design,” “carbon tax,” “carbon cap,” “carbon cap and trade,” “emission cap,” “emission tax,” "emission cap and trade,” “carbon policies,” “emission policies,” “carbon offset,” and "emission offset.” GOOGLE SCHOLAR, EBSCOHOST BUSINESS SOURCE PREMIER, ECONBIZ, and EBSCOHOST ECONLIT are used to perform the searches. Furthermore, forward and backward searches identified the relevant literature.

Regarding the consideration of lead time, 25 publications are identified, published in various scientific journals, conference proceedings, or Ph.D. theses. A further 30 publications are identified that considered emission policies in strategic models for supply chain design. In most studies, lead times are described as unchanging parameters that are unaffected by decisions or are even ignored.[212] Some studies have used lead time to determine

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[209] For publications of closed-loop supply chains considering emission policies see e.g. PAKSOY, T.; ÖZCEYLAN, E.; WEBER, G. W., 2010; CHAABANE, A.; RAMUDHIN, A.; PAQUET, M., 2012; DIABAT, A. ET AL., 2013; FAHIMNIA, B. ET AL., 2013; GAO, N.; RYAN, S. M., 2014; ZEBALLOS, L. J. ET AL., 2014; CHOUDHARY, A. ET AL., 2015; FAREEDUDDIN, M. ET AL., 2015; MOHAJERI, A.; FALLAH, M., 2016; JOHN, S. T.; SRIDHARAN, R.; KUMAR, P. N. R., 2017; MOHAMMED, F. ET AL., 2017; SOLEIMANI, H. ET AL., 2017; XU, Z. ET AL., 2017; ALKHAYYAL, B. A., 2018; HADDAD-SISAKHT, A.; RYAN, S. M., 2018; MOHAMMED, F.; HASSAN, A.; SELIM, S. Z., 2018; SAXENA, L. K.; JAIN, P. K.; SHARMA, A. K., 2018; ALJUNEIDI, T.; BULGAK, A. A., 2020; YUCHI, Q. ET AL., 2019; MOHAMMED, F.; HASSAN, A.; SELIM, S. Z., 2019; SAMUEL, C. N. ET AL., 2020.

[210] For publications of biofuel supply chains considering emission policies see e.g. AKGUL, O.; SHAH, N.; PAPAGEORGIOU, L. G., 2012; GIAROLA, S.; SHAH, N.; BEZZO, F., 2012; IVANOV, B.; DIMITROVA, B.; DOBRUDZHALIEV, D., 2014; MARUFUZZAMAN, M.; EKSIOGLU, S. D.; HERNANDEZ, R., 2014; DUARTE, A.; SARACHE, W.; COSTA, Y., 2016; HOMBACH, L. E. ET AL., 2016; MARUFUZZAMAN, M. ET AL., 2016.

[211] Cf. VOM BROCKE, J. ET AL., 2009, p. 2214.

[212] Cf. MEISEL, F. ET AL., 2016, p. 922.

the number of needed safety stocks,[213] to calculate parameters for an inventory policy,[214] or for inventory management generally.[215] In other research, lead times are used to model either time gaps in material flows[216] or supplier-buyer relationships.[217] Most studies in the supply chain context that include the lead time have focused mainly on operational or tactical aspects without incorporating strategic supply chain design decisions.[218]

Several researchers have reviewed the literature focusing on green supply chains. Examples are SEURING AND MÜLLER,[219] KAINUMA AND TSHIVHASE, [220] XU ET AL.,[221] BANASIK ET AL.,[222] and WALTHO, ELHEDHLI AND GZARA.[223] These reviews are used to enrich the relevant literature on supply chain design that considers emission policies.

4.2 Models that Consider Lead Times

One of the first approaches to consider the influence of lead time on strategic supply chain design decisions is proposed by ARNTZEN ET AL.[224] In their study, minimizing the total time needed for manufacturing, logistics, and distribution is part of the objective function. In addition to lead time, costs are minimized when deciding about the facility location of a strategic network. MELACHRINOUDIS AND MIN propose a multi-objective model that incorporates total profit, transit time from hybrid plants/warehouses to customers, and location incentives. Lead times unrelated to distribution are not considered.[225] CHEONG, BHATNAGAR AND GRAVES use lead times to segment customers according to their expected distribution lead time.[226] Their approach minimizes total cost, and lead times are incorporated in the form of lead-time-dependent lost sales. However, only distribution lead times of the outbound supply chain are considered. Another model is developed by ESKIGUN ET AL.[227] They incorporate (as well as fixed costs of facility location and

[213] See e.g. PETRIDIS, K., 2015.
[214] See e.g. SOURIRAJAN, K.; OZSEN, L.; UZSOY, R., 2007; SABRI, E. H.; BEAMON, B. M., 2000; SOURIRAJAN, K.; OZSEN, L.; UZSOY, R., 2009; KAMINSKY, P.; KAYA, O., 2008.
[215] See e.g. HAMMAMI, R.; NOUIRA, I.; FREIN, Y., 2015; MARTEL, A.; VANKATADRI, U., 1999.
[216] See e.g. CHEN, C.-L.; WANG, B.-W.; LEE, W.-C., 2003; ROBINSON, A. G.; BOOKBINDER, J. H., 2007; ACAR, Y.; KADIPASAOGLU, S.; SCHIPPERIJN, P., 2010; CORREIA, I.; MELO, T., 2016; DO CHUNG, B.; KIM, S. IL; LEE, J. S., 2018; FATTAHI, M.; MAHOOTCHI, M.; MOATTAR HUSSEINI, S. M., 2016.
[217] See e.g. JHA, J. K.; SHANKER, K., 2009.
[218] Cf. HAMMAMI, R.; FREIN, Y., 2013, p. 2761.
[219] Cf. SEURING, S.; MÜLLER, M., 2008.
[220] Cf. KAINUMA, Y.; TSHIVHASE, T., 2019.
[221] Cf. XU, Z. ET AL., 2019.
[222] Cf. BANASIK, A. ET AL., 2018.
[223] Cf. WALTHO, C.; ELHEDHLI, S.; GZARA, F., 2019.
[224] Cf. ARNTZEN, B. C. ET AL., 1995.
[225] Cf. MELACHRINOUDIS, E.; MIN, H., 2000.
[226] Cf. CHEONG, M. L. F.; BHATNAGAR, R.; GRAVES, S. C., 2005.
[227] Cf. ESKIGUN, E. ET AL., 2005.

transportation costs) the lead times as a measure of customer satisfaction. Lead times are included in the target function by using the monetary value of lead time, and only the logistics and distribution lead times are considered in their work. A modified approach, without capacity constraints, is applied to real-world data in a further study.[228]

YOU AND GROSSMANN use the expected lead time as a quantitative measure of supply chain responsiveness. Their mixed integer nonlinear programming (MINLP) model incorporates demand uncertainty and predicts safety stock levels using stock-out probability.[229] It is formulated as a bi-criterion model, solved by the ε-constraint method, maximizing the net present value and restricting the expected lead times. The model y includes logistics, distribution, and manufacturing lead times; uncertainties are taken into account by stock-out-related delays. KOHLER examines the design of global supply chains.[230] This model includes, among others, local-content requirements, tariffs, and taxes; quoted OTDLT are guaranteed. HAFEZALKOTOB proposes a mixed-integer linear programming (MILP) model that includes manufacturing, logistics, and distribution lead times.[231] The Lp-Metrics method is used to minimize total cost and lead times, and the capacity planning of facilities is considered. KOHLER develops an MILP approach considering global aspects like country-specific taxes, tariffs, local content regulations, and exchange rates.[232] Furthermore, the supplier, manufacturing, logistics, and distribution lead times are used to determine cycle times. The bi-objective model, maximizing free cash flow and minimizing cycle times, is solved by applying the ε-constraint method.

BOGASCHEWSKY AND KOHLER propose a global supply chain design model, including all types of lead times and carbon footprint.[233] Their model addresses – besides the maximization of free cash flow – the minimization of cycle times and the carbon footprint as further objectives. Another approach proposed by YOU AND GROSSMANN considers manufacturing, logistics, and distribution lead times.[234] They considered multi-periods and multi-products and aim to minimize total cost and lead times. The bi-objective MINLP model is solved by applying the ε-constraint method. Transportation and distribution lead

[228] Cf. ESKIGUN, E. ET AL., 2007.
[229] Cf. YOU, F.; GROSSMANN, I. E., 2008.
[230] Cf. KOHLER, K., 2008.
[231] Cf. HAFEZALKOTOB, A. ET AL., 2008.
[232] Cf. KOHLER, K., 2009.
[233] Cf, BOGASCHEWSKY, R.; KOHLER, K., 2010.
[234] Cf. YOU, F.; GROSSMANN, I. E., 2011.

times are included in the model by CARDONA-VALDÉS. ÁLVAREZ AND OZDEMIR.[235] This model minimizes the cost of opening distribution centers, the expected transportation costs, and the sum of the maximum transportation and distribution lead time from plants to customers. The stochastic optimization model further includes demand uncertainty. VENKATESAN AND KUMANAN propose a model that considers the minimization of supply chain cost, demand fulfillment lead time, and the maximization of volume flexibility.[236] To calculate demand fulfillment lead time, they incorporate manufacturing, logistics, and distribution lead times. BABAZADEH AND RAZMI develop a robust stochastic programming approach to design a supply network under operational and disruption risks.[237] They restrict distribution lead times to customer-specific quoted lead times. The objective is to minimize total costs, and they consider the possibilities of alliances between companies.

A model developed by SADJADY AND DAVOUDPOUR minimizes the total costs, including the costs related to transportation, inventory holdings, opening and operating facilities, and lead time.[238] Only distribution lead times between warehouses and customers are included. LIU AND PAPAGEORGIU propose a multi-objective approach.[239] They observe costs, responsiveness, and customer service levels simultaneously by incorporating total costs, flow time, and lost sales as the objectives. In this approach, total flow time consists of the distribution lead time between formulation plants and markets. The MILP optimization models consist of two echelons and are solved by applying the ε-constraint and lexicographic minimax methods. ZHANG, LUO AND HUANG developed a bi-objective model for dispersed manufacturing in China. [240] The approach considers trade-offs between lead times and costs, which represent the objective functions. Suppliers are not directly included in the model, so supplier lead time is missing. The model is evaluated using a real-world case and is solved by applying the weighted sum method. HAMMAMI and FREIN develop a model with lead time constraints.[241] The global multi-echelon supply chain model considers transportation lead times, delivery lead times, and manufacturing lead times. The MILP model minimizes the total cost and guarantees a lead time shorter than the specific customer lead time requirements. PASANDIDEH, NIAKI AND ASSADI

[235] Cf. CARDONA-VALDÉS, Y.; ÁLVAREZ, A.; OZDEMIR, D., 2011.
[236] Cf. VENKATESAN, S. P.; KUMANAN, S., 2012.
[237] Cf. BABAZADEH, R.; RAZMI, J., 2012.
[238] Cf. SADJADY, H.; DAVOUDPOUR, H., 2012.
[239] Cf. LIU, S.; PAPAGEORGIOU, L. G., 2013.
[240] Cf. ZHANG, A.; LUO, H.; HUANG, G. Q., 2013.
[241] Cf. HAMMAMI, R.; FREIN, Y., 2013.

propose an MINLP model that minimizes total cost and cost variability.[242] They consider uncertain demands, manufacturing lead times, and costs. MARTÍ TANCREZ AND SEIFERT propose a supply chain network design model that includes carbon policies, responsiveness, and demand uncertainty. [243] Lead times for manufacturing and fixed transport lead times are included.

Another approach dealing with restricted order lead times is proposed by MEISEL ET AL..[244] Their two models include all types of lead times and guarantee the delivery of products within a fixed time. As a possibility to reduce lead times, both models allow the combination of make-to-stock and make-to-order production strategies by using a decoupling point. FATTAHI, GOVINDAN AND KEYVANSHOKOOH develop an approach that considers lead-time-dependent customer demand.[245] Demand depends on the distribution lead time of facilities that are assigned to customers. Furthermore, the model considers uncertainty of demand and disruption risks. DIABAT, DEHGHANI AND JABBARZADEH develop a location-inventory model for the design of supply chains.[246] Uncertainties of demands and logistics lead time are incorporated by applying queuing theory. A multi-echelon supply chain design model with lead time constraints is proposed by HAMMAMI ET AL..[247] This approach guarantees specific lead times for each customer's order and the replenishment of various stocks at different stages in the supply chain. They investigate the impact of the promised lead time on order frequency of customers, supply chain design decisions, and costs. Lead times of suppliers and lead times for transportation and manufacturing are taken into account. SILLER proposes a supply chain design model considering supplier, manufacturing, logistics, and distribution lead times under a carbon cap and trade system.[248] The bi-objective model aims at minimizing total cost and the sum of supply chain lead times.

The results of the review of supply chain design models that consider lead times are summarized in Table 4.1.

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[242] Cf. PASANDIDEH, S. H. R.; NIAKI, S. T. A.; ASADI, K., 2015
[243] Cf. MARTÍ, J. M. C.; TANCREZ, J.-S.; SEIFERT, R. W., 2015.
[244] Cf. MEISEL, F. ET AL., 2016.
[245] Cf. FATTAHI, M.; GOVINDAN, K.; KEYVANSHOKOOH, E., 2017
[246] Cf. DIABAT, A.; DEHGHANI, E.; JABBARZADEH, A., 2017
[247] Cf. HAMMAMI, R.; FREIN, Y.; BAHLI, B., 2017.
[248] Cf. SILLER, B., 2019.

	Objective	Location Decisions			Model Characteristics								Types of Lead Time					Types of Uncer-tainties			
		Supplier Selection	Prod. Facility Selection	Warehouse Selection	Raw Materials	Multiple Products	Multiple Period	Modes of Logistics	Capacity Planning	Inventories	Global Aspects	Environmental Policies	Supplier LT	Manufacturing LT	Logistics LT	Distribution LT	LT Sensitive Demand	Demand	Cost	Lead Time	Disruptions
Arntzen et al. (1995)	Total Cost / Lead Time		X			X	X	X		X	X			X	X	X					
Melachrinoudis & Min (2000)	Total Profit / Lead Time		X				X								X	X					
Eskigun et al. (2005)	Total Cost			X											X	X					
Cheong, Bhatnagar & Graves (2005)	Total Cost			X						X						X	X				
Eskigun et al. (2007)	Total Cost			X											X	X					
Kohler (2008)	Free Cash Flow		X		X	X	X	X			X		X	X	X	X					
Bogaschewsky & Kohler (2010)	Free Cash Flow		X		X	X	X	X			X	X	X	X	X	X					

		Location Decisions			Model Characteristics								Types of Lead Time					Types of Uncer-tainties			
	Objective	**Supplier Selection**	**Prod. Facility Selection**	**Warehouse Selection**	**Raw Materials**	**Multiple Products**	**Multiple Period**	**Modes of Logistics**	**Capacity Planning**	**Inventories**	**Global Aspects**	**Environmental Policies**	**Supplier LT**	**Manufacturing LT**	**Logistics LT**	**Distribution LT**	**LT Sensitive Demand**	**Demand**	**Cost**	**Lead Time**	**Disruptions**
You & Grossmann (2011)	Total Cost		X		X	X	X							X	X	X					
Cardona-Valdés, Álvarez & Ozdemir (2011)	Total Cost			X											X	X		X			
Venkatesan & Kumanan (2012)	Total Cost / Lead Time / Volume Flexibility		X	X										X	X	X					
Babazadeh & Razmi (2012)	Total Cost		X	X				X	X	X						X		X	X		
Sadjady & Davoud-pour(2012)	Total Cost		X	X				X	X						X	X					
Liu & Papageorgiou (2013)	Total Cost / Lead Time / Lost Sales		X			X	X		X	X						X					
Zhang, Luo & Huang (2013)	Total Cost / Lead Time		X			X								X	X	X					

	Objective	Location Decisions			Model Characteristics							Types of Lead Time					Types of Uncer-tainties			
		Supplier Selection	Prod. Facility Selection	Warehouse Selection	Raw Materials	Multiple Products	Multiple Period	Modes of Logistics	Capacity Planning	Inventories	Global Aspects	Environmental Policies	Supplier LT	Manufacturing LT	Logistics LT	Distribution LT	LT Sensitive Demand	Demand	Cost	Lead Time	Disruptions
Hammami & Frein (2013)	Total Cost	X	X	X						X			X	X	X	X					
Pasandideh, Niaki & Asadi (2015)	Mean Cost / Cost Variance			X		X	X			X				X				X	X	X	
Martí, Tancrez & Seifert (2015)	Total Cost		X					X		X		X		X	X	X					
Meisel et al. (2016)	Total Cost		X	X	X	X		X					X	X	X	X					
Fattahi, Govindan & Keyvanshokooh (2017)	Total Cost		X	X		X	X			X						X	X	X			X
Diabat, Dehghani & Jab-barzadeh (2017)	Total Cost			X						X					X			X		X	
Hammami, Frein & Bahli (2017)	Total Cost	X	X	X						X			X	X	X	X					

		Location Decisions			Model Characteristics								Types of Lead Time					Types of Uncer-tainties			
	Objective	Supplier Selection	Prod. Facility Selection	Warehouse Selection	Raw Materials	Multiple Products	Multiple Period	Modes of Logistics	Capacity Planning	Inventories	Global Aspects	Environmental Policies	Supplier LT	Manufacturing LT	Logistics LT	Distribution LT	LT Sensitive Demand	Demand	Cost	Lead Time	Disruptions
Siller (2019)	Total Cost / Lead Time	X	X	X	X	X	X	X		X		X	X	X	X	X					

Table 4.1: Overview of literature on supply chain design models considering lead time

4.3 Models that Consider Emission Policies

One of the first models considering emission policies is proposed by DIABAT AND SIMCHI-LEVI.[249] Their MILP model covers carbon emissions from transportation and facility operations and ensures meeting a carbon cap while minimizing total cost. ABDDALLAH, DIABAT AND SIMCHI-LEVI propose an MILP model under the cap and trade system.[250] The model covers emissions from raw materials, transportation activities, and facility operations, and minimizes the total cost. BOGASCHEWSKY AND KOHLER propose a global supply chain design model under a carbon cap.[251] The approach maximizes the free cash flow and considers emissions from raw materials, production, and transportation activities. Load-dependent emissions of transportation activities are used in an approach proposed by MERRICK.[252] The objective of this model is to minimize total cost, with emissions regulated under a carbon tax scheme. RAMUDHIN, CHAABANE AND PAQUET address the design of a supply chain under a cap and trade scheme.[253] The bi-objective model aims, in addition to minimizing the total cost, to minimize the emissions from transportation and manufacturing activities. CHAABANE, RAMUDHIN AND PAQUET propose a multi-objective MILP model to minimize total cost and total emission from transportation and production activities.[254] They apply a carbon cap and trade system and illustrate the trade-offs between total cost and total carbon emission.

ABDALLAH ET AL. develop an MIP model that aims at minimizing the total cost of a supply chain, with additional costs of carbon trading taken into account.[255] Their model covers emissions from sourcing, transportation, manufacturing, and facility operation activities. It determined the number of additional carbon credits to sell or buy to deal with the imposed carbon cap. A supply chain design model to consider both a carbon cap and trade system and the additional option of installing photovoltaic systems on rooftops to reduce companies' carbon footprint is proposed by ABDALLAH, DIABAT AND RIGTER. Emissions from raw materials and transportation activities are as well covered as the emissions to operate a facility.[256] BAUD-LAVIGNE, AGARD AND PENZ developed a bi-objective model covering transportation, manufacturing, raw materials, and facility operation

[249] Cf. DIABAT, A.; SIMCHI-LEVI, D., 2009.
[250] Cf. ABDALLAH, T.; DIABAT, A.; SIMCHI-LEVI, D., 2010.
[251] Cf. BOGASCHEWSKY, R.; KOHLER, K., 2010.
[252] Cf. MERRICK, R. J., 2010.
[253] Cf. RAMUDHIN, A.; CHAABANE, A.; PAQUET, M., 2010.
[254] Cf. CHAABANE, A.; RAMUDHIN, A.; PAQUET, M., 2011.
[255] Cf. ABDALLAH, T. ET AL., 2012.
[256] Cf. ABDALLAH, T.; DIABAT, A.; RIGTER, J., 2013.

emissions.[257] They investigate how total costs are affected by applying an emission cap, and how total emissions are affected by capping total cost. ALTMANN presents an MILP supply chain design model that covers emissions from transport and manufacturing activities.[258] Emissions are incorporated in the form of a demand function that is influenced by the number of emissions. Furthermore, an emission offset system is applied to manufacturing emissions. FAHIMA ET AL. propose a supply chain optimization model that incorporates emissions from manufacturing and transportation activities and minimizes total cost.[259] An emission cap is applied on both emission sources; additionally, a carbon tax is raised on transport emissions.

MARTÍ, TANCREZ AND SEIFERT propose a supply chain network design model that considers the carbon footprint and responsiveness trade-offs while minimizing the total cost.[260] Emissions from transport and manufacturing are implemented, and a carbon cap and carbon tax are applied in the model's evaluation. An inventory supply chain model that considers carbon emissions from storage and transportation emissions is developed by ALHAJ, SVETINOVIC AND DIABAT.[261] The MILP model minimizes total cost; a carbon tax is applied to cover emissions; and uncertain demand is considered. MOON, JEONG AND SAHA address the design of a production distribution system and apply an emission offset policy.[262] Emissions from transportation, manufacturing, and storage activities are included in the bi-objective fuzzy model. It aims at maximizing total profit while minimizing total shortages in an environment with uncertain raw material sources. A MILP formulation for a supply chain network design problem minimizing total cost and greenhouse gas emissions is presented by PENG, ABLANDEDO-ROSAS AND FU.[263] They consider carbon emissions from transportation and storage activities and apply emission cap and emission tax policy. SHAW, IRFAN AND SHANKAR develop a supply chain design model considering uncertainties of raw material supply, capacities of plants and warehouses, and demands, while minimizing total costs.[264] They apply chance-constrained programming to handle these uncertainties; an emission cap and trade policy covers the transportation, manufacturing, and facility operation emissions. YANG, GUO AND MA develop a model

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[257] Cf. BAUD-LAVIGNE, B.; AGARD, B.; PENZ, B., 2014.
[258] Cf. ALTMANN, M., 2015.
[259] Cf. FAHIMNIA, B. ET AL., 2015.
[260] Cf. MARTÍ, J. M. C.; TANCREZ, J.-S.; SEIFERT, R. W., 2015.
[261] Cf. ALHAJ, M. A.; SVETINOVIC, D.; DIABAT, A., 2016.
[262] Cf. MOON, I.; JEONG, Y.; SAHA, S., 2016.
[263] Cf. PENG, Y.; ABLANEDO-ROSAS, J. H.; FU, P., 2016.
[264] Cf. SHAW, K. ET AL., 2016.

under an emission tax policy.[265] Emissions from transportation, handling, and facility operation are considered, and the approach aims at minimizing total cost. A multi-objective MILP considering total cost, minimizing environmental aspects such as waste and carbon emissions, and maximizing social impacts (in the form of employment opportunities, community development, and labor conditions, is proposed by ARAMPANTZI AND MINIS.[266] Their approach covers emissions from transportation, manufacturing, storage, and handling activities and the emissions caused by raw materials. They apply goal programming and ε-constraint, which can be interpreted as an emission cap policy. DAS AND SHAW propose an approach considering economic, environmental, and social costs.[267] The MINLP model incorporates uncertainties of raw material supply, demand, and capacity of plants and warehouses by applying chance-constrained programming. Sources of emissions are raw materials and transportation, manufacturing, and handling activities. Furthermore, an emission cap is applied.

GOLPÎRA ET AL. formed a green supply chain design model considering uncertainties in carbon emission amounts and demand.[268] Transportation and manufacturing activities are the emission sources covered, and an emission cap policy is applied. An approach to building supply chain network design is proposed by LI, PENG, and ZHANG.[269] Their model includes emissions from operating facilities as well as transportation and manufacturing activities, and an emission tax is applied. A stochastic programming model in an emission trading environment is proposed by REZAEE ET AL.[270] Uncertainties in demand and emission price are considered, and the model covers transport emissions and manufacturing emissions. An approach based on life-cycle assessment of raw materials to determine the emissions they cause is proposed by URATA ET AL.[271] They apply emission tax to investigate the potential for emission reduction. ZAHIRI, ZHUANG AND MOHAMMADI develop a model for the design of a pharmaceutical supply chain.[272] A fuzzy possibilistic-stochastic programming approach is applied to deal with disruption risks. The multi-objective model includes emissions from transportation and manufacturing activities and applies a cap and trade policy. ZHANG ET AL. propose an approach that

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[265] Cf. YANG, J.; GUO, J.; MA, S., 2016.
[266] Cf. ARAMPANTZI, C.; MINIS, I., 2017.
[267] Cf. DAS, R.; SHAW, K., 2017.
[268] Cf. GOLPÎRA, H. ET AL., 2017.
[269] Cf. LI, X.; PENG, Y.; ZHANG, J., 2017.
[270] Cf. REZAEE, A. ET AL., 2017.
[271] Cf. URATA, T. ET AL., 2017.
[272] Cf. ZAHIRI, B.; ZHUANG, J.; MOHAMMADI, M., 2017.

includes economies of scale.[273] They consider investments to lower emissions in facilities and include emissions from transportation and handling activities. Furthermore, they apply emission tax policy. ZHOU ET AL. investigate the influence of carbon tariffs on supply chain design.[274] They apply an emission cap policy and consider emissions caused by raw materials, transportation, and manufacturing. BUDIMAN AND RAU consider postponement strategies in their green supply chain design approach.[275] They consider raw material, transportation, and manufacturing emissions and apply an emission tax policy to cover the ecological aspects. MISHRA AND SINGH develop a global supply chain design model that includes an emission cap and trade system for each country. Various global dynamics are considered. However, the design of the emission cap and trade system does not vary across the countries in their data example and could thus be interpreted as an uniform, global system. SILLER develops a supply chain design model in a cap and trade environment.[276] Emissions from transportation, manufacturing, handling, and facility operation are covered, and the trade-off between lead time and total costs is investigated. DAS, SHAW AND IFRAN develop a model considering water footprint, solid waste, and carbon footprint.[277] The supply chain design model covers raw material supply, demand, and facility capacity uncertainties and includes the service levels. Emissions from transportation, manufacturing, and handling activities are considered as well as emissions from raw materials and facility operations. An emission cap policy is applied to cover the environmental aspects.

The results of the review of supply chain design models that consider different emission policies are summarized in Table 4.2.

[273] Cf. ZHANG, D. ET AL., 2017.
[274] Cf. ZHOU, Y. ET AL., 2017.
[275] Cf. BUDIMAN, S. D.; RAU, H., 2019.
[276] Cf. SILLER, B., 2019.
[277] Cf. DAS, R.; SHAW, K.; IRFAN, M., 2020.

	Objective	Location Decisions			Model Characteristics								Emission Sources						Emission Policy				Types of Uncertainties					
		Supplier selection	Prod. Facility Selection	Warehouse Selection	Raw Materials	Multi Products	Multi Period	Logistic Modes	Capacity Planning	Inventory planning	Lead Time	Global Aspects	Transportation	Manufacturing	Raw Materials	Storage/Distribution	Handling	Facility Operations	Emission Cap	Emission Offset	Emission Tax	Emission Cap & Trade	Supply	Demand Uncertainty	Capacity	Emission Policy	Emission value	Disruptions
Diabat & Simchi-Levi (2009)	Total Cost		X						X				X					X	X									
Abdallah, Diabat, & Simchi-Levi (2010)	Total Cost	X	X	X		X			X				X		X			X				X						
Bogaschewsky & Kohler (2010)	Free Cash Flow			X	X		X	X	X	X	X		X	X	X				X									
Merrick (2010)	Total Cost			X									X								X							
Ramudhin, Chaabane, & Paquet (2010)	Total Cost / Total Emissions	X	X	X	X	X	X	X					X	X								X						
Chaabane, Ramudhin, & Paquet (2011)	Total Cost / Total Emissions	X	X		X	X	X	X					X	X	X			X				X						

	Objective	Location Decisions			Model Characteristics								Emission Sources						Emission Policy				Types of Uncertainties					
		Supplier selection	Prod. Facility Selection	Warehouse Selection	Raw Materials	Multi Products	Multi Period	Logistic Modes	Capacity Planning	Inventory planning	Lead Time	Global Aspects	Transportation	Manufacturing	Raw Materials	Storage/Distribution	Handling	Facility Operations	Emission Cap	Emission Offset	Emission Tax	Emission Cap & Trade	Supply	Demand Uncertainty	Capacity	Emission Policy	Emission value	Disruptions
Abdallah et al. (2012)	Total Cost	X	X	X	X	X			X				X	X	X							X						
Abdallah, Diabat & Rigter (2013)	Total Cost	X	X		X	X							X		X			X				X						
Baud-Lavigne, Agard & Penz (2014)	Total Cost / Total Emissions	X	X	X	X	X			X				X	X	X			X			X	X						
Altmann (2015)	Discounted free Cash Flow		X		X	X	X						X	X						X								
Fahimnia et al. (2015)	Total Cost		X	X	X	X	X	X		X			X	X					X		X							
Martí, Tancrez, & Seifert (2015)	Total Cost		X					X			X		X	X					X		X							

		Location Decisions			Model Characteristics								Emission Sources						Emission Policy				Types of Uncertain-ties					
	Objective	**Supplier selection**	**Prod. Facility Selection**	**Warehouse Selection**	**Raw Materials**	**Multi Products**	**Multi Period**	**Logistic Modes**	**Capacity Planning**	**Inventory planning**	**Lead Time**	**Global Aspects**	**Transportation**	**Manufacturing**	**Raw Materials**	**Storage/Distribution**	**Handling**	**Facility Operations**	**Emission Cap**	**Emission Offset**	**Emission Tax**	**Emission Cap & Trade**	**Supply**	**Demand Uncertainty**	**Capacity**	**Emission Policy**	**Emission value**	**Disruptions**
Alhaj, Sveti-novic & Diabat (2016)	Total Cost			X									X		X							X		X				
Moon, Jeong & Saha (2016)	Total Profit / Total Shortage			X	X		X			X			X	X		X				X			X					
Peng, Ablanedo-Rosas & Fu (2016)	Total Cost / Total Emissions		X				X			X			X			X			X		X							
Shaw et al. (2016)	Total Cost		X	X									X	X				X				X	X	X	X			
Yang, Guo & Ma (2016)	Total Cost			X									X				X	X			X							
Arampantzi & Minis (2017)	Total Cost/Total Emissions/Work Opportunities		X	X	X	X	X	X	X	X		X	X	X	X	X	X		X									

	Objective	Location Decisions			Model Characteristics								Emission Sources						Emission Policy				Types of Uncertainties					
		Supplier selection	Prod. Facility Selection	Warehouse Selection	Raw Materials	Multi Products	Multi Period	Logistic Modes	Capacity Planning	Inventory planning	Lead Time	Global Aspects	Transportation	Manufacturing	Raw Materials	Storage/Distribution	Handling	Facility Operations	Emission Cap	Emission Offset	Emission Tax	Emission Cap & Trade	Supply	Demand Uncertainty	Capacity	Emission Policy	Emission value	Disruptions
Das & Shaw (2017)	Total Cost		X	X									X	X	X		X		X				X	X	X			
Golpîra et al. (2017)	Total Cost/Total Emission	X	X										X	X							X			X			X	
Li, Peng, & Zhang (2017)	Total Cost	X	X	X	X	X	X			X			X	X				X			X							
Rezaee et al. (2017)	Total Cost	X	X	X	X	X	X	X	X				X	X								X		X		X		
Urata et al. (2017)	Total Cost		X		X										X						X							
Zahiri, Zhuang & Mohammadi (2017)	Total Cost/Social Impact/Total Emissions/ Resilience		X	X		X	X	X		X			X	X								X						X

	Objective	Location Decisions			Model Characteristics								Emission Sources						Emission Policy				Types of Uncertainties					
		Supplier selection	Prod. Facility Selection	Warehouse Selection	Raw Materials	Mulit Products	Mulit Period	Logistic Modes	Capacity Planning	Inventory planning	Lead Time	Global Aspects	Transportation	Manufacturing	Raw Materials	Storage/Distribution	Handling	Facility Operations	Emission Cap	Emission Offset	Emission Tax	Emission Cap & Trade	Supply	Demand Uncertainty	Capacity	Emission Policy	Emission value	Disruptions
Zhang et al. (2017)	Total Cost			X			X		X				X				X				X							
Zhou et al. (2017)	Total Cost		X		X	X		X					X	X	X				X									
Budiman & Rau (2019)	Total Cost		X	X	X	X		X					X	X	X						X							
Mishra & Singh (2019)	Total Cost		X	X		X	X			X		X	X	X		X						X						
Siller (2019)	Total Cost	X	X		X	X	X	X		X	X		X	X			X	X				X						
Das, Shaw & Irfan (2020)	Total Cost		X	X	X	X	X	X		X			X	X	X		X	X	X				X	X	X			

Table 4.2: Literature overview of supply chain design models that consider emission policies

4.4 Review Results

As shown in Table 4.3, only three publications that consider lead times and an emission policy are identified.

	Objective	Location Decisions			Emission Sources						Emission Policy				Types of Lead Time			
		Supplier selection	**Prod. Facility Selection**	**Warehouse Selection**	**Transportation**	**Manufacturing**	**Raw Materials**	**Storage/Distribution**	**Handling**	**Facility Operations**	**Emission Cap**	**Emission Offset**	**Emission Tax**	**Emission Cap & Trade**	**Supplier LT**	**Manufacturing LT**	**Transportation LT**	**Distribution LT**
Bogaschewsky & Kohler (2010)	Free Cash Flow			X	X	X	X				X				X	X	X	X
Martí, Tancrez, & Seifert (2015)	Total Cost		X		X	X					X		X			X	X	X
Siller (2019)	Total Cost	X	X	X	X	X			X	X				X	X	X	X	X

Table 4.3: Literature on supply chain design models considering lead times and emission policies

Through the review, several gaps in research are identified. They are as follows:

- Most publications considering lead times in supply chain design focus on a specific type of lead time. Supplier lead time tends to be neglected. Since supplier lead time can greatly affect the performance of a supply chains,[278] it should be incorporated in supply chain design models.
- In many of the examined publications, supplier selection is not explicitly considered. Suppliers are a crucial component of the supply chain in terms of reliability and efficient supply. Therefore, suppliers' capabilities – such as delivery, flexibility, and quality – are essential for supplier lead time, and supplier selection is a strategic decision.[279]
- Due to the congestion effect, capacity planning is a crucial decision at the strategic level. Congestion effects may negatively affect lead times and the flexibility of manufacturers.[280] Most supply chain design models that are examined neglect capacity planning decisions.

[278] Cf. So, K. C.; Zheng, X., 2003, p. 169f; Heydari, J., 2014, p. 89.
[279] Cf. Sarkis, J.; Talluri, S., 2002, p. 18.
[280] Cf. Rajagopalan, S.; Yu, H. L., 2001, p. 365.

- In most models that consider emission policies in supply chain design, only certain emission sources are considered. Stricter policies mean that gathering all emission sources becomes more critical. Many countries are discussing harsher consequences to reach the goals of the Paris Agreement. With stricter emission policies, the costs from short-term changes in a supply chain structure can become prohibitively high. Capturing all potential emission sources in supply chain models, therefore, seems to be valuable.
- With short product life-cycles, OTDLT plays an essential role, and the total lead times must be considered.[281] Regarding lead-time-sensitive customers, the identified approaches only consider delivery lead time to assign warehouses to each customer. Therefore, an approach considering OTDLT in the case of time-sensitive customers should be considered.
- No approach could be identified that considers different country-specific emission policies. Emission policies can be harsh regulations that affect companies in a costly manner; hence, it can be beneficial for companies to move their operations to unconstrained countries. This effect is called “carbon leakage” and can lead to a net increase of total emissions even if some countries apply burdensome environmental regulations.[282]
- Companies face uncertainty in terms of the future design of environmental policies. With greater knowledge of climate change among the public, governments tend to tighten environmental standards and regulations. Only one publication could be identified that considers uncertainty in prices for carbon allowances. Therefore, investigating uncertainties in the design of environmental policies could be beneficial.

According to the literature review results, this work provides several approaches to tackle some of the identified issues. Chapter 5 presents a model considering lead times and emission policies to investigate the trade-off between total cost, total emission, and OTDLT. The model presented in Chapter 6 investigates the effect of OTDLT-sensitive customers and the influence of emission policies. Chapter 7 proposes an approach considering OTDLT and uncertainties in the design of environmental

[281] Cf. Christopher, M., 1986, p. 66.
[282] Cf. Eichner, T.; Pethig, R., 2011, p. 767.

policies. Finally, Chapter 8 deals with the influences of country-specific emission policies and their influence on OTDLT and total cost.

5 Supply Chain Design Considering Lead Times and Emission Policies

5.1 Relevance and Assumptions

SHAPIRO[283] identifies lead time and cost control as areas of marketing and manufacturing that need cooperation but can cause potential conflicts. The importance of lead times is underlined because shorter lead time attracts more customers and therefore causes a higher demand.[284] Furthermore, short lead time is becoming a major criterion for competitive advantage.[285] However, faster modes of transportation or keeping larger inventories can affect supply chain costs by shortening OTDLT. In complex supply chains, inventory costs can make up a significant proportion of total supply chain costs.[286] As described in Chapter 2.4, lead times are an essential strategy for companies to differentiate themselves. A model is proposed here that can investigate the trade-offs between total supply chain costs and OTDLT. However, customers have also become familiar with the concept of carbon footprint, and concerns about climate change are growing.[287] Treaties like the Paris Agreement pressurize governments to tighten their emissions policies. Hence, standard emission policies – like emission cap, emission tax, emission cap and trade, and emission offset – are incorporated in the proposed multi-objective model. These variables help in evaluating the influences of lead time and emission policies on the design of a supply chain network.

For multi-objective problems, literature discusses several techniques, such as goal programming, compromise programming, or the reference point method.[288] The compromise programming approach is used to combine the objectives of minimizing both total cost and OTDLT in this study. Due to the different scales of the objectives, they must be normalized,[289] and the weighted Lp-metric method is applied for this purpose. For the

[283] Cf. SHAPIRO, B. P., 1977, p. 105ff.
[284] Cf. PEKGÜN, P.; GRIFFIN, P.; KESKINOCAK, P., 2008, p. 12.
[285] Cf. HSU, S.-L.; LEE, C. C., 2009, p. 398; HAMMAMI, R.; FREIN, Y., 2014, p. 466.
[286] Cf. KAMINSKY, P.; KAYA, O., 2008, p. 276.
[287] Cf. GROENING, C.; INMAN, J. J.; ROSS JR., W. T., 2015, p. 263.
[288] Cf. ROMERO, C.; TAMIZ, M.; JONES, D. F., 1998, p. 986.
[289] Cf. MASUD, A. S. M.; RAVINDRAN, R. A., 2008, p. 5–4; MARLER, R. T.; ARORA, J. S., 2005, p. 553ff; GRODZEVICH, O.; ROMANKO, O., 2006, p. 93ff.

application of this method, reference points are calculated by solving the model for every single objective function. Then the weighted distances between these reference points and the feasible objective region are minimized. By applying the weighted Lp-metrics method, the multi-objective problem can be transformed into a single objective problem.[290] Variable Z_1 is the objective value for total supply chain cost and variable Z_2 represents the value for the OTDLT. The Z_1^* term represents the optimal value of total supply chain costs when the model is solved with only the cost objective, whereas Z_2^* is the objective value for OTDLT when only the time objective is considered. The relevant Lp-metrics are:

$$Min\ Z_3 = \left[\varpi \frac{Z_1 - Z_1^*}{Z_1^*} + (1-\varpi)\frac{Z_2 - Z_2^*}{Z_2^*}\right]^{\frac{1}{p}} \quad (5.1)$$

The terms $\frac{Z_1 - Z_1^*}{Z_1^*}$ and $\frac{Z_2 - Z_2^*}{Z_2^*}$ derive relative deviations from optimal solutions.

The value of p determines the type of distance. For $p = 1$, all deviations from the ideal objective value Z^* are considered in direct proportion to their magnitudes. For $2 \leq p < \infty$, larger deviations carry a higher weight in Lp. When $p = \infty$, only the largest deviation is considered, which leads to a purely “individual utility,” where all weighted deviations are equal.[291] For the analysis of the following model, p is set to the value 1.

The proposed model has the following characteristics and assumptions:

- It is a discrete deterministic model.
- There are a finite number of planning periods, potential suppliers, production facilities, and warehouses.
- The number of customer regions is fixed.
- The planning horizon covers several strategic planning periods.
- Three logistic modes are available, and full truck loads are assumed for each transportation process. Logistic modes differ in cost, speed, and generated emissions. Logistic mode 1 offers low cost, emissions, and speed, whereas logistic mode 3 offers high cost, emission, and speed. Logistic mode 2 is characterized by medium cost, emissions, and speed.
- Capacities of suppliers are restricted.

[290] Cf. Miettinen, K., 1998, p. 97ff.
[291] Cf. Coello, C. A. C. et al., 2007, p. 32f.

- Capacities of production facilities and warehouses are restricted to the chosen capacity option.
- The same quality of production and handling processes is assumed at all suppliers, production facilities, and warehouses.
- Emission policy parameters such as emission cap, tax rate, or emission allowance price do not vary over time.

5.2 Model Development

5.2.1 Model with no Emission Policy

The formulation of the optimization model is built on the approach of SILLER[292] and is based on the following notation:

$$\begin{aligned} Z_1 = & \sum_{s}^{S} SC_s\, y_s^{Su} + \sum_{f}^{F}\sum_{o}^{O} FC_{fo}\, y_{fo}^{Fa} + \sum_{w}^{W}\sum_{o}^{O} WC_{wo}\, y_{wo}^{Wa} \\ & + \sum_{s}^{S}\sum_{f}^{F}\sum_{m}^{M}\sum_{p}^{P}\sum_{l}^{L}\sum_{t}^{T} PC_{smt}\, x_{sfmplt} \\ & + \sum_{f}^{F}\sum_{w}^{W}\sum_{p}^{P}\sum_{l}^{L}\sum_{t}^{T} MC_{fpt}\, x_{fwplt} \\ & + \sum_{w}^{W}\sum_{c}^{C}\sum_{p}^{P}\sum_{l}^{L}\sum_{t}^{T} HC_{wpt}\, x_{wcplt} \\ & + \sum_{w}^{W}\sum_{p}^{P}\sum_{t}^{T}\sum_{c}^{C} SC_{wpt} \frac{\left(h_{wp(t-1)c} + h_{wptc}\right)}{2} \\ & + \sum_{s}^{S}\sum_{f}^{F}\sum_{m}^{M}\sum_{p}^{P}\sum_{l}^{L}\sum_{t}^{T} TC_{sfmlt}\, x_{sfmplt} \\ & + \sum_{f}^{F}\sum_{w}^{W}\sum_{p}^{P}\sum_{l}^{L}\sum_{t}^{T} TC_{fwplt}\, x_{fwplt} \\ & + \sum_{w}^{W}\sum_{c}^{C}\sum_{p}^{P}\sum_{l}^{L}\sum_{t}^{T} TC_{wcplt}\, x_{wcplt} \end{aligned} \tag{5.2}$$

$$Z_2 = MaxLT \tag{5.3}$$

The first objective function (5.2) aims at minimizing total supply chain cost. The first three terms determine the fixed costs of selecting suppliers and establishing production facilities and warehouses. The fourth term represents purchasing costs for raw materials, the fifth term manufacturing, and the sixth term sums up the warehouse handling costs.

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[292] SILLER, B., 2019.

The seventh term represents the stocking costs over the planning horizon in the form of the average number of stock-keeping units between two successive periods. The last three terms represent transportation costs between suppliers and production facilities, between production facilities and warehouses, and between warehouses and customers. The second objective (5.3) aims at minimizing the maximum OTDLT to a customer.

$$D_{cpt} = \sum_{w}^{W} \sum_{l}^{L} x_{wcplt} \qquad \forall c \in C, p \in P, t \in T \qquad (5.4)$$

$$\sum_{c}^{C} \sum_{l}^{L} x_{wcplt} + \sum_{c}^{C} h_{wptc} = \sum_{f}^{F} \sum_{l}^{L} x_{fwplt} + \sum_{c}^{C} h_{wp(t-1)c} \qquad \forall w \in W, p \in P, t \in T \qquad (5.5)$$

$$\sum_{w}^{W} \sum_{p}^{P} \sum_{l}^{L} x_{fwplt} \, BOM_{mp} = \sum_{s}^{S} \sum_{p}^{P} \sum_{l}^{L} x_{sfmplt} \qquad \forall f \in F, m \in M, t \in T \qquad (5.6)$$

$$\sum_{f}^{F} \sum_{p}^{P} \sum_{l}^{L} x_{sfmplt} \leq Cap_{sm}^{Su} y_{s}^{Su} \qquad \forall s \in S, m \in M, t \in T \qquad (5.7)$$

$$\sum_{w}^{W} \sum_{p}^{P} \sum_{l}^{L} x_{fwplt} \leq \sum_{o}^{O} Cap_{fo}^{Fa} \, y_{fo}^{Fa} \qquad \forall f \in F, t \in T \qquad (5.8)$$

$$\sum_{p}^{P} \sum_{c}^{C} h_{wptc} \leq \sum_{o}^{O} Cap_{wo}^{Wa} \, y_{wo}^{Wa} \qquad \forall w \in W, t \in T \qquad (5.9)$$

$$\sum_{c}^{C} \sum_{p}^{P} \sum_{l}^{L} x_{wcplt} \leq \sum_{o}^{O} Cap_{wo}^{Wa} \, y_{wo}^{Wa} \qquad \forall w \in W, t \in T \qquad (5.10)$$

$$\sum_{o}^{O} y_{fo}^{Fa} \leq 1 \qquad \forall f \in F \qquad (5.11)$$

$$\sum_{o}^{O} y_{wo}^{Wa} \leq 1 \qquad \forall w \in W \qquad (5.12)$$

Constraint (5.4) ensures that each customer's demand for a specific product is fulfilled in every period. Product flows between production facilities and warehouses and stocks at each warehouse are determined in constraint (5.5). Constraint (5.6) determines the production amount of each product, the raw material flows between suppliers and production facilities, and the number of procured materials from suppliers according to the specific bill of materials. Constraints (5.7) to (5.10) are the capacity constraints of suppliers, production facilities, and warehouses. In (5.11) and (5.12), it is ensured that only one capacity option for each production facility and each warehouse is chosen.

$$MaxLT \geq OTD_{cpt} \qquad \forall c \in C, p \in P, t \in T \qquad (5.13)$$

$$\begin{aligned} OTD_{cpt} \geq\ & LT^{Su}_{smt}\delta^{SF}_{sfmpltc} + LT^{Fa}_{fpt}\delta^{FW}_{fwpltc} \\ & + LT^{Wa}_{wpt}x_{wcplt} + LT_{sfmlt}\delta^{SF}_{sfmpltc} \\ & + LT_{fwplt}\delta^{FW}_{fwpltc} + LT_{wcplt}x_{wcplt} \end{aligned} \qquad \begin{aligned} &\forall s \in S, f \in F, w \in W, \\ &c \in C, m \in M, \\ &p \in P, l \in L, t \in T \end{aligned} \qquad (5.14)$$

$$\sum_{l}^{L} x_{wcplt} - h_{wp(t-1)c} = \sum_{f}^{F}\sum_{l}^{L} \delta^{FW}_{fwpltc} \qquad \begin{aligned} &\forall w \in W, p \in P, t \in T, \\ &c \in C \end{aligned} \qquad (5.15)$$

$$x_{fwplt} \geq \sum_{c}^{C} \delta^{FW}_{fwpltc} \qquad \begin{aligned} &\forall, f \in F, w \in W, \\ &p \in P, l \in L, t \in T \end{aligned} \qquad (5.16)$$

$$\sum_{w}^{W}\sum_{l}^{L} \delta^{FW}_{fwpltc} BOM_{mp} = \sum_{s}^{S}\sum_{l}^{L} \delta^{SF}_{sfmpltc} \qquad \begin{aligned} &\forall f \in F, p \in P, c \in C, \\ &m \in M, t \in T \end{aligned} \qquad (5.17)$$

$$x_{sfmplt} \geq \sum_{c}^{C} \delta^{SF}_{sfmpltc} \qquad \begin{aligned} &\forall s \in S, f \in F, m \in M, \\ &p \in P, l \in L, t \in T \end{aligned} \qquad (5.18)$$

$$\begin{aligned} &x_{sfmplt}, x_{fwplt}, x_{wcplt}, h_{wptc}, \delta^{SF}_{sfmpltc}, \\ &\delta^{FW}_{fwpltc}, OTD_{cpt} \geq 0 \end{aligned} \qquad \begin{aligned} &\forall s \in S, f \in F, w \in W, \\ &c \in C, m \in M, p \in P, \\ &l \in L, t \in T \end{aligned} \qquad (5.19)$$

$$y^{Su}_{s}, y^{Fa}_{fo}, y^{Wa}_{wo} \in [0;1] \qquad \forall s \in S, f \in F, w \in W \qquad (5.20)$$

In (5.13), the maximum OTDLT is guaranteed. To ensure linearity of the model, the $max\ (OTD_{cpt})$ function is linearized. Constraint (5.14) calculates the specific OTDLT for each product requested by a customer in each period. The OTDLT consists of supplier lead time for raw materials used for products that are not in stock to serve the customer's request, the manufacturing lead time for the additional needed products, and the handling lead time in warehouses. Furthermore, the transportation and delivery lead time for these raw materials and products are taken into account. In (5.15), the number of products needed above the current stock to meet customer demand is calculated. Constraint (5.16) ensures that these additional products are in the transportation flows between production facilities and warehouses. In (5.17), the needed number of raw materials to produce the additional products is calculated, and (5.18) ensures that these materials are within the transportation flows between supplier and production facilities. Constraint (5.19) is a non-negativity constraint, and (5.20) determines the binary variables.

5.2.2 Models with Various Emission Policies

$$E_t = \sum_{f}^{F}\sum_{o}^{O} FE_{fot} y_{fo}^{Fa} + \sum_{w}^{W}\sum_{o}^{O} WE_{wot}\, y_{wo}^{Wa} + \sum_{s}^{S}\sum_{f}^{F}\sum_{m}^{M}\sum_{p}^{P}\sum_{l}^{L} PE_{smt}\, x_{sfmplt} + \sum_{f}^{F}\sum_{w}^{W}\sum_{p}^{P}\sum_{l}^{L} ME_{fpt}\, x_{fwplt} + \sum_{w}^{W}\sum_{c}^{C}\sum_{p}^{P}\sum_{l}^{l} HE_{wpt}\, x_{wcplt} + \sum_{w}^{W}\sum_{p}^{P}\sum_{c}^{C} SE_{wpt} \frac{\left(h_{wp(t-1)c} + h_{wptc}\right)}{2} + \sum_{s}^{S}\sum_{f}^{F}\sum_{m}^{M}\sum_{p}^{P}\sum_{l}^{L} TE_{sfmlt}\, x_{sfmplt} + \sum_{f}^{F}\sum_{w}^{W}\sum_{p}^{P}\sum_{l}^{L} TE_{fwplt}\, x_{fwplt} + \sum_{w}^{W}\sum_{c}^{C}\sum_{p}^{P}\sum_{l}^{L} TE_{wcplt}\, x_{wcplt} \quad \forall t \in T \quad (5.21)$$

The number of emissions in each period must are necessary to include different emission policies. Therefore, constraint (5.21) calculates total emission per period. The first two terms calculate the emissions for operating a production facility or warehouse in period t. Terms three, four, and five determine the emissions from purchasing, manufacturing, and handling activities. The sixth term represents the emissions from stocking. The average number of goods in stock between successive periods is used for the calculation to cover periodical fluctuations. The last three terms represent the emission from transportation activities.

$$E_t \le ECap \quad \forall t \in T \quad (5.22)$$

$$E_t \ge 0 \quad \forall t \in T \quad (5.23)$$

To incorporate the effect of an emission cap into the model, in constraint (5.22) it is ensured that the number of emissions is less than or equal to the applied emission cap in each period. Constraint (5.23) is a non-negativity constraint.

The cost objective needs to include (in addition to fixed and variable costs for supply chain activities) a further term to determine the amount of emission tax. Costs of taxation are calculated by the emitted emissions in a period multiplied by the specific tax rate. Formula 5.24 represents the mathematical formulation of the cost objective, including a emission tax.

$$
\begin{aligned}
Z_1 = {} & \sum_{s}^{S} SC_s \, y_s^{Su} + \sum_{f}^{F}\sum_{o}^{O} FC_{fo} \, y_{fo}^{Fa} + \sum_{w}^{W}\sum_{o}^{O} WC_{wo} \, y_{wo}^{Wa} \\
& + \sum_{s}^{S}\sum_{f}^{F}\sum_{m}^{M}\sum_{p}^{P}\sum_{l}^{L}\sum_{t}^{T} PC_{smt} \, x_{sfmplt} \\
& + \sum_{f}^{F}\sum_{w}^{W}\sum_{p}^{P}\sum_{l}^{L}\sum_{t}^{T} MC_{fpt} \, x_{fwplt} \\
& + \sum_{w}^{W}\sum_{c}^{C}\sum_{p}^{P}\sum_{l}^{L}\sum_{t}^{T} HC_{wpt} \, x_{wcplt} \\
& + \sum_{w}^{W}\sum_{p}^{P}\sum_{t}^{T}\sum_{c}^{C} SC_{wpt} \frac{\left(h_{wp(t-1)c} + h_{wptc}\right)}{2} \\
& + \sum_{s}^{S}\sum_{f}^{F}\sum_{m}^{M}\sum_{p}^{P}\sum_{l}^{L}\sum_{t}^{T} TC_{sfmlt} \, x_{sfmplt} \\
& + \sum_{f}^{F}\sum_{w}^{W}\sum_{p}^{P}\sum_{l}^{L}\sum_{t}^{T} TC_{fwplt} \, x_{fwplt} \\
& + \sum_{w}^{W}\sum_{c}^{C}\sum_{p}^{P}\sum_{l}^{L}\sum_{t}^{T} TC_{wcplt} \, x_{wcplt} + \sum_{t}^{T} \Omega^{Tax} E_t
\end{aligned}
\qquad (5.24)
$$

The cost objective has to be altered to apply an emission cap and trade policy. In formula (5.25), an additional term calculates the cost or benefits of buying or selling additional emission credits. The additional needed or surplus emission credits are calculated in constraint (5.26). Variable α_t^- determines the surplus allowances and α_t^+ specifies the allowances that must be bought on the market. In constraint (5.27), their non-negativity is ensured.

$$Z_1 = \sum_{s}^{S} SC_s\, y_s^{Su} + \sum_{f}^{F}\sum_{o}^{O} FC_{fo}\, y_{fo}^{Fa} + \sum_{w}^{W}\sum_{o}^{O} WC_{wo}\, y_{wo}^{Wa}$$
$$+ \sum_{s}^{S}\sum_{f}^{F}\sum_{m}^{M}\sum_{p}^{P}\sum_{l}^{L}\sum_{t}^{T} PC_{smt}\, x_{sfmplt}$$
$$+ \sum_{f}^{F}\sum_{w}^{W}\sum_{p}^{P}\sum_{l}^{L}\sum_{t}^{T} MC_{fpt}\, x_{fwplt}$$
$$+ \sum_{w}^{W}\sum_{c}^{C}\sum_{p}^{P}\sum_{l}^{L}\sum_{t}^{T} HC_{wpt}\, x_{wcplt}$$
$$+ \sum_{w}^{W}\sum_{p}^{P}\sum_{t}^{T}\sum_{c}^{C} SC_{wpt}\, \frac{\left(h_{wp(t-1)c} + h_{wptc}\right)}{2}$$
$$+ \sum_{s}^{S}\sum_{f}^{F}\sum_{m}^{M}\sum_{p}^{P}\sum_{l}^{L}\sum_{t}^{T} TC_{sfmlt}\, x_{sfmplt}$$
$$+ \sum_{f}^{F}\sum_{w}^{W}\sum_{p}^{P}\sum_{l}^{L}\sum_{t}^{T} TC_{fwplt}\, x_{fwplt}$$
$$+ \sum_{w}^{W}\sum_{c}^{C}\sum_{p}^{P}\sum_{l}^{L}\sum_{t}^{T} TC_{wcplt}\, x_{wcplt} + \sum_{t}^{T} \Omega^{CAT}\,(\alpha_t^{+} - \alpha_t^{-}) \tag{5.25}$$

$$E_t + \alpha_t^{-} = ECap + \alpha_t^{+} \qquad \forall t \in T \tag{5.26}$$

$$\alpha_t^{-}, \alpha_t^{+}, E_t \geq 0 \qquad \forall t \in T \tag{5.27}$$

The total cost objective has to be altered to include an emission offset policy into the model. In addition to the terms for fix and variable costs in objective (5.28), there is a term accounting for the cost of buying additional emission permits by a price of Ω^{Off}.

$$Z_1 = \sum_s^S SC_s\, y_s^{Su} + \sum_f^F \sum_o^O FC_{fo}\, y_{fo}^{Fa} + \sum_w^W \sum_o^O WC_{wo}\, y_{wo}^{Wa}$$
$$+ \sum_s^S \sum_f^F \sum_m^M \sum_p^P \sum_l^L \sum_t^T PC_{smt}\, x_{sfmplt}$$
$$+ \sum_f^F \sum_w^W \sum_p^P \sum_l^L \sum_t^T MC_{fpt}\, x_{fwplt}$$
$$+ \sum_w^W \sum_c^C \sum_p^P \sum_l^L \sum_t^T HC_{wpt}\, x_{wcplt}$$
$$+ \sum_w^W \sum_p^P \sum_t^T \sum_c^C SC_{wpt} \frac{\left(h_{wp(t-1)c} + h_{wptc}\right)}{2}$$
$$+ \sum_s^S \sum_f^F \sum_m^M \sum_p^P \sum_l^L \sum_t^T TC_{sfmlt}\, x_{sfmplt}$$
$$+ \sum_f^F \sum_w^W \sum_p^P \sum_l^L \sum_t^T TC_{fwplt}\, x_{fwplt}$$
$$+ \sum_w^W \sum_c^C \sum_p^P \sum_l^L \sum_t^T TC_{wcplt}\, x_{wcplt} + \sum_t^T \Omega^{Off}\, \beta_t \tag{5.28}$$

The number of additionally needed allowances is calculated in constraint (5.29).

$$E_t = ECap + \beta_t \qquad \forall t \in T \tag{5.29}$$
$$\beta_t, E_t \geq 0 \qquad \forall t \in T \tag{5.30}$$

The additional needed number of allowances β_t is determined by the number of emitted emissions that exceed the applied emission cap. Constraint (5.30) ensures the non-negativity of β_t.

5.3 Data Generation Process

For each test instance, the following data is required to be produced:

- Customer demands for each final product and each scenario.
- Bill of processes that indicates which processes are needed for final products.
- Capacity of warehouses, production facilities, and suppliers.
- Fixed costs, such as supplier selection costs, costs for opening a production facility, and costs for opening a warehouse.
- Variable costs, such as production costs per unit, handling costs per unit, purchasing costs per unit and transportation costs per unit.

- Lead times, such as supplier lead times per unit, manufacturing lead times per unit, handling lead times per unit, and transportation lead times per unit and link.
- Emissions from purchasing, manufacturing, handling, stocking, and transportation activities, as well as from operating production facilities and warehouses.

Each demand realization is randomly generated using the distribution $U[5000, 20000]$ for each customer, product, and period. The maximum demand of all customers for final products is calculated for the different periods to determine the capacities. Warehouses capacity must allow for the maximum periodic demand. Afterward, the needed capacity is divided by the number of possible warehouses and multiplied by a random number generated from the distribution $U[1, 5]$. The capacity of production facilities is determined similarly. The minimum capacity of all warehouses must guarantee that all demanded final products can be produced. Then, this capacity value is divided by the number of production facilities and for each facility multiplied by a random number from the distribution $U[1, 5]$.

Regarding the bill of materials, it is assumed that different amounts of supplier material are needed for every final product. An integer value from distribution $U[1, 3]$ is assigned to determine the bill of materials for every raw material and the final product. Then it is checked whether every raw material is assigned and if any final product needs more than one raw material. If these checks are not successful, the procedure is repeated. Suppliers' capacity is calculated by the actual demand for finished products multiplied by the needed raw materials. This quantity is divided by the number of suppliers. Finally, the capacity for each supplier is multiplied by a randomly generated number from a uniform distribution $U[1, 5]$.

Most fixed costs are dependent on the capacity of a facility. Therefore, a formula similar to the suggestion of CORTINHAL AND CAPTIVO[293] is used:

$$f_i = U[x_1, y_1] + U[x_2, y_2] * \sqrt{a_i}$$

$U[x_1, y_1]$ and $U[x_2, y_2]$ are uniform distributions in the range $[x_1, y_1]$ and $[x_2, y_2]$, and a_{io} is the capacity of the specific facility with capacity option o. It is assumed that there

[293] Cf. CORTINHAL, M. J.; CAPTIVO, M. E., 2003, p. 345.

are different capacity options. For the data generation of the fixed costs, the following formulations are used:

- Costs for selecting a supplier: $U[5000 * S, 10000 * S] + U[500, 1200] * \sqrt{a_s}$
- Setup costs of a production facility: $U[12500 * F, 250000 * F] + U[1500, 4500] * \sqrt{a_{fo}}$
- Setup costs of a warehouse: $U[8000 * W, 16000 * W] + U[1100, 3300] * \sqrt{a_{wo}}$

An approach similar to MELKOTE AND DASKIN [294] is used to locate suppliers, production facilities, warehouses, and customers. In this approach, every location is represented by a node on a 10,000 x 10,000 grid, where x and y coordinates are randomly generated within the distribution $U[0, 10000]$. The distance between two locations is measured with the Euclidean distance method. Transportation costs are calculated by multiplying the distance with a cost factor for the different logistic modes. In this evaluation, three modes of logistics are assumed with costs of $[0.03, 0.4, 2.5]$. The value of the distance multiplied by the transportation cost factor is multiplied by a capacity factor for each product and raw material. This value is divided by the assumed capacity of every mode represented by [300, 40, 90]. The raw material factor is generated from the uniform distribution $U[0.01, 0{,}075]$ and the factor for final products from uniform distribution $U[0.075, 0.20]$.

Purchasing costs are calculated by determining a price for each raw material from uniform distribution $U[0.1, 0.9]$. This value is multiplied by a factor for each supplier from uniform distribution $U[0.5, 3]$. The value is multiplied by a random number from uniform distribution $U[0.9, 1.1]$ to take periodic price shifts into account for each period. Production costs are generated from the distribution $U[0.5, 7]$ for each product, multiplied by a random number from $U[1, 5]$ for each production facility; to cover periodic differences the values are also multiplied by a number from $U[0.9, 1.1]$. Handling costs for each final product are generated from a uniform distribution $U[0.01, 1]$. This value is multiplied by a factor from distribution $U[0.05, 0.9]$ for each warehouse to take differences in warehouses into account, and with a value of $U[0.9, 1.1]$ for each period to cover periodic differences. Finally, stocking costs are generated from a uniform distribution $U[3, 12]$,

[294] Cf. MELKOTE, S.; DASKIN, M. S., 2001, p. 484.

which is multiplied for each warehouse by a number from uniform distribution $U[1, 4]$ and $U[0.9, 1.1]$ for each period.

Transportation lead times are calculated by dividing the distance between two locations with a factor for the logistic mode, represented by [20, 80, 600]. This value represents the transportation lead times between production facilities, warehouses, and customers, divided by the minimum demand of all customers in all periods. For the transportation lead times between suppliers and production facilities, the value is divided by the minimum demand multiplied by the bill of material for the specific product to generate differences for each raw material.

Supplier lead times, production lead times, and handling lead times are converse to the equivalent cost. The most expensive process is also the fastest process. Procurement lead times are calculated by 1 minus the procurement costs of the supplier for the specific material in a specific period, divided by the maximum cost for this material. The value is divided by 20. Manufacturing and handling lead times are calculated in the same way, but values for manufacturing lead times are divided by 10, and for handling lead times they are divided by 100.

A function equivalent to the function for the fixed costs is used to generate emissions for operating production facilities and warehouses:

- Operation emissions of production facilities: $[50 * F, 100 * F] + U[0.25, 2.5] * \sqrt{a_{fo}}$
- Operation emissions of warehouses: $U[25 * W, 75 * W] + U[0.15, 1.5] * \sqrt{a_{wo}}$

For periodic differences, the generated values are multiplied by a value of uniform distribution $U[0.9, 1.1]$ for each period.

Emissions for raw materials are calculated by determining the emissions for each material from uniform distribution $U[0.0001, 0.0002]$. To cover different emissions from different suppliers, these values are multiplied by a number from uniform distribution $U[1,3]$ for each supplier, and to include periodic differences, also by a value of uniform distribution $U[0.9, 1.1]$ for each period. For the production emissions for each final product, a value of uniform distribution $U[0.002, 0.05]$ is generated. For each production facility, these numbers are multiplied by a value of uniform distribution $U[1, 3]$ and then multiplied by $U[0.9, 1.1]$ for each period. Handling emissions per product are generated from

$U[0.00015, 0.0015]$, multiplied for each warehouse by U[1, 3] and for each period by $U[0.9, 1.1]$. Emissions from stock-related activities are generated for each product from uniform distribution U[0.001, 0.03], multiplied for each warehouse by a value from U[1, 3]; to cover periodic shifts, the emission values are also multiplied by a value from U[0.9, 1.1] for each period. Transportation emissions are determined by multiplying the distance with an emission factor for the various logistic modes. In this evaluation, three logistic modes are assumed, with emissions of $[0.0002, 0.015, 0.02]$. The values for distance and transportation emission factors are multiplied by the capacity factor for each product and each raw material, which is divided by the assumed capacity of every mode.

5.4 Numerical Results

5.4.1 Data for Evaluating the Models

The models described in Chapter 5.2 are evaluated using an example based on the data generator in Chapter 5.3. This example includes six potential suppliers, four possible locations for production facilities, four potential locations for warehouses, and 10 customer regions. Furthermore, three types of logistic modes are considered as well as three types of raw material. There are three planning periods and two capacity options for production facilities and warehouses, and one final product is considered for simplicity.

The locations of suppliers, production facilities, warehouses, and customer regions are shown in Fig. 5.1. The bubble size differs according to the maximum capacity – or in the case of customers, the demand for all planning periods – of each location.

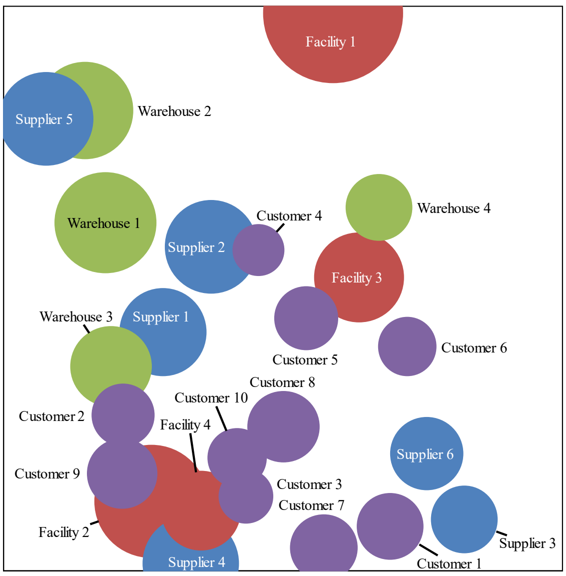

Figure 5.1: Locations of suppliers, production facilities, warehouses, and customers

Since all models described in Chapter 5.2 are MILP, a standard solver can be used to find the optimal solutions. Therefore, all models are solved using IBM ILOG CPlex on an Intel Core i7-8750H 2.2 GHz machine with 16 GB Ram under Windows 10.

5.4.2 Results with Varying Weighting Factor

The results for varying weighting factors are examined first. The following parameters are used to compare the results from the model without emission policies to the results from models with emission policies:[295]

- Emission cap for emission cap policy is set to 19,000 emission units per period.
- Emission cap for emission cap and trade and offset policy is set to 15,000 emission units per period.
- Tax rate, emission credit price, and emission allowance price are all set to 75 monetary units per unit of emission in each period.

As shown in Fig. 5.2 a), the total costs are initially only slightly affected by an increasing weighting factor ϖ. Only when the emission cap policy is in charge does the total cost decrease even with a low weighting factor. Only the emission tax policy increases the total cost in every case. Under an emission cap policy, the total costs are always below that under no emission policy. Emission cap and trade policy results for total cost are lower than the results when no emission policy is applied, starting from ϖ of 0.5. The reason is the possibility of gaining additional income by selling unused emission credits.

Reduced total cost is associated with an increased maximum OTDLT, as shown in Fig. 5.2 b). With a lower weighting factor ϖ, OTDLT is initially relatively stable. Starting from weighting factor 0.5, OTDLT increases. Under the emission tax policy, OTDLT increases slightly less than in the case of no applied emission policy. Every other emission policy leads to a larger increase in OTDLT. However, with a weighting factor of 0.9, the results of emission offset policy and no emission policy are the same for total cost and total emission. The emission cap policy leads to higher OTDLT when OTDLT is emphasized because the strict regulation restricts the number of generated emissions in every period. Emission cap and trade policy leads to the highest OTDLT with an increasing weighting factor. This can be explained by the stronger incentive to reduce emission amounts to gain additional income and the nature of the Lp-metrics method.

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[295] Detailed results of the examinations in Chapter 5.4 can be found in appendix A.

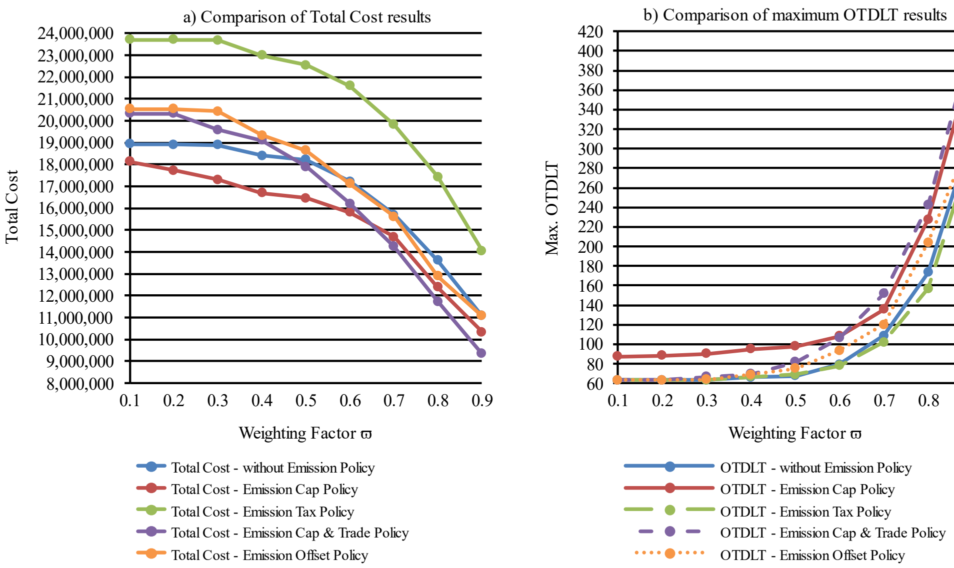

Figure 5.2: Comparison of total cost and maximum OTDLT

Every emission policy reduces the emission levels compared to the results without an emission policy applied, as illustrated in Fig. 5.3. In the trade-off case, the emission cap policy achieves the lowest total emission with a low ϖ. Starting from weighting factor 0.6, the emission cap and trade policy leads to greater reductions in total emission. With a ϖ of 0.9, the same total emission results are obtained under no applied emission policy, emission tax, and the offset policy.

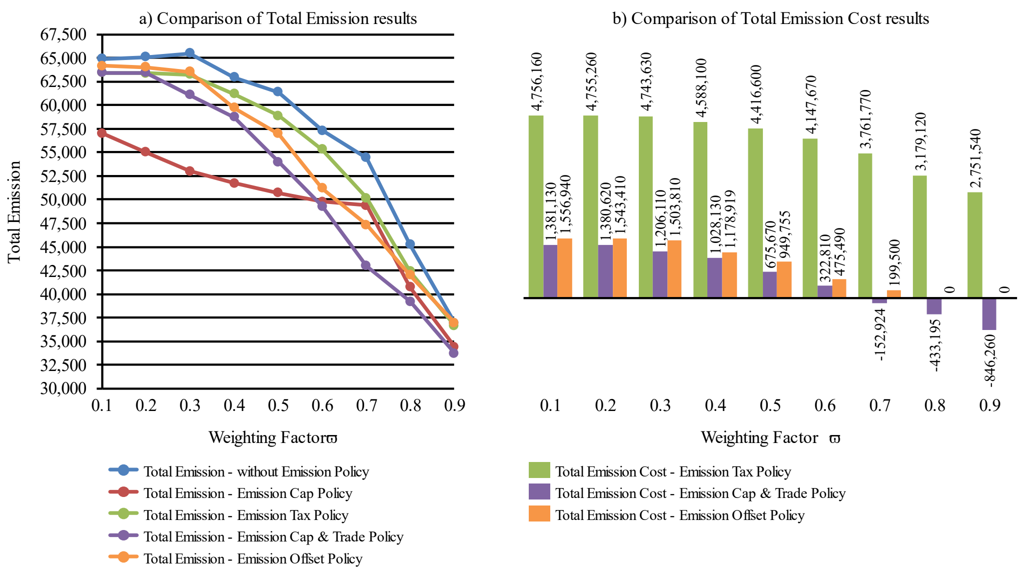

Figure 5.3: Comparison of total emission and total emission cost

The market-based emission policies result in different total emission costs, as shown in Fig. 5.3 b). Emission tax policy always causes the highest total emission cost because every generated emission unit is priced. The emission cap and trade policy and the emission offset policy result in significantly lower emission costs. In all observed weighting factor variations, total emission costs are less than 50% compared to the costs under the emission tax policy. Only emissions that exceed the imposed cap are priced under these policies. Therefore, with high weight on total cost, there are no additional costs for emission allowances under the emission offset policy. The underlying market mechanism for emission cap and trade policy can become a subsidy system, and companies can gain additional revenues by selling their excess emission credits.

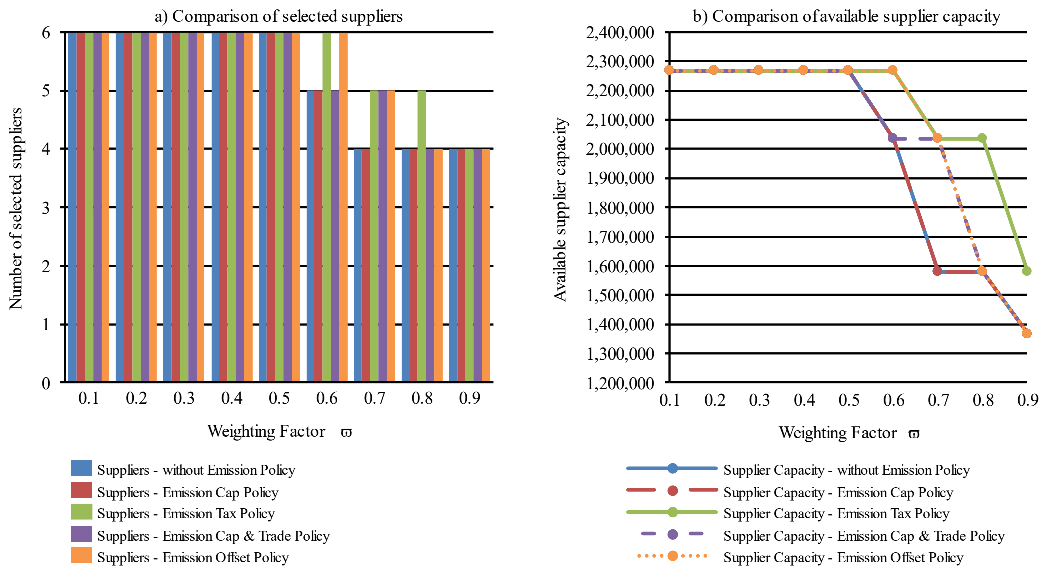

Figure 5.4: Comparison of number of selected suppliers and available supplier capacity

In the given example, more suppliers are selected with a lower weighting factor, as shown in Fig. 5.4 a). A reduction in the number of suppliers is observed with ϖ of 0.6. For the emission tax and offset policy, this effect occurs at higher ϖ. The number of selected suppliers is similar under either an emission cap or no emission policy. A higher number of suppliers can offer the opportunity to source raw materials in parallel from different suppliers. This multiple sourcing approach can reduce the procurement lead time.

Available supplier capacity is reduced with higher ϖ for market-based emission policies, relative to under an emission cap or no emission policy. For emission tax, other suppliers are selected for ϖ of 0.9 to contract a higher supplier capacity.

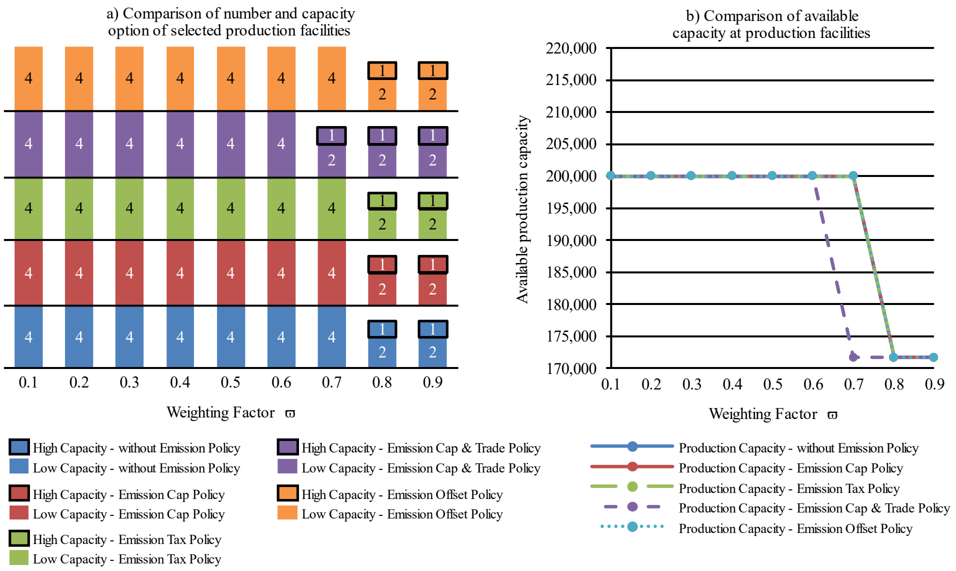

Figure 5.5: Comparison of number of selected production facilities and available production capacity

The number and capacity of established production facilities vary with the weighting factor, as shown in Fig. 5.5 a). It can be stated that Only with a strong emphasis on total cost are fewer production facilities established. The use of many production facilities offers the opportunity to parallel-process orders, which can reduce manufacturing lead times. The results are similar between all examined policy options, except that the emission cap and trade policy lowered the number of production facilities even at ϖ of 0.7. In contrast, all other policies reduce the number of established facilities with ϖ of 0.8. These effects are also examined by comparing the available capacity of production facilities, as shown in Fig. 5.5 b).

The number and capacity of selected warehouses are illustrated in Fig. 5.6 a) and b). The results depend on the emission policy examined. Between ϖ of 0.4 and 0.7, three warehouses are established. Otherwise, all four available warehouses are established. For the emission cap and trade policy, only three warehouses are established with ϖ of 0.3; under the emission tax policy, only three warehouses are established with ϖ of 0.8. This aspect influences available warehouse capacity: with a strong emphasis on OTDLT, more warehouse capacity is required to guarantee lower lead times. In contrast, an emphasis on total cost can lead to warehouse capacity decreases.

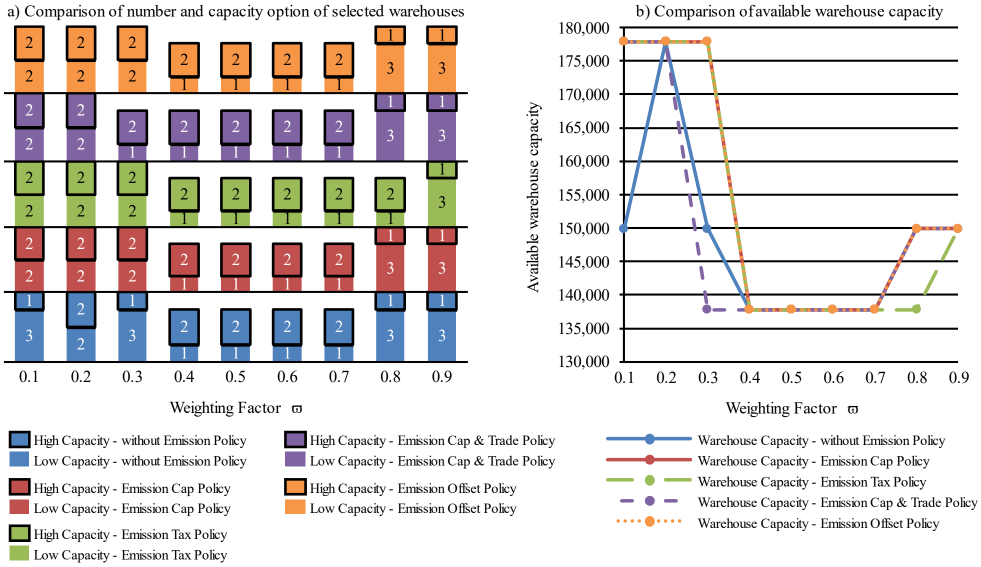

Figure 5.6: Comparison of number of established warehouses and available warehouse capacity

Variation of the weighting factor influences the choice of logistic modes. These changes are illustrated in Fig. 5.7. For better comparability, the raw materials shipped from suppliers to production facilities are scaled according to the bill of materials. The use of logistic mode 3, characterized as the fastest but most expensive and emission-intensive logistic mode in the given example, decreases with increasing emphasis on total cost. Logistic mode 1 is the cheapest, slowest, and most environmentally friendly mode. Initially, it slightly decreases with increasing weighting factors and then vastly increases when no emission policy or price-based emission policies are applied. For price-based emission policies with ϖ of 0.9, only logistic mode 1 is chosen. Applying an emission cap policy leads to a high percentage of goods shipped by logistic mode 2, with low ϖ. The shares of mode 2 and 3 decrease with increasing weighting factors, whereas the share of logistic mode 1 increases.

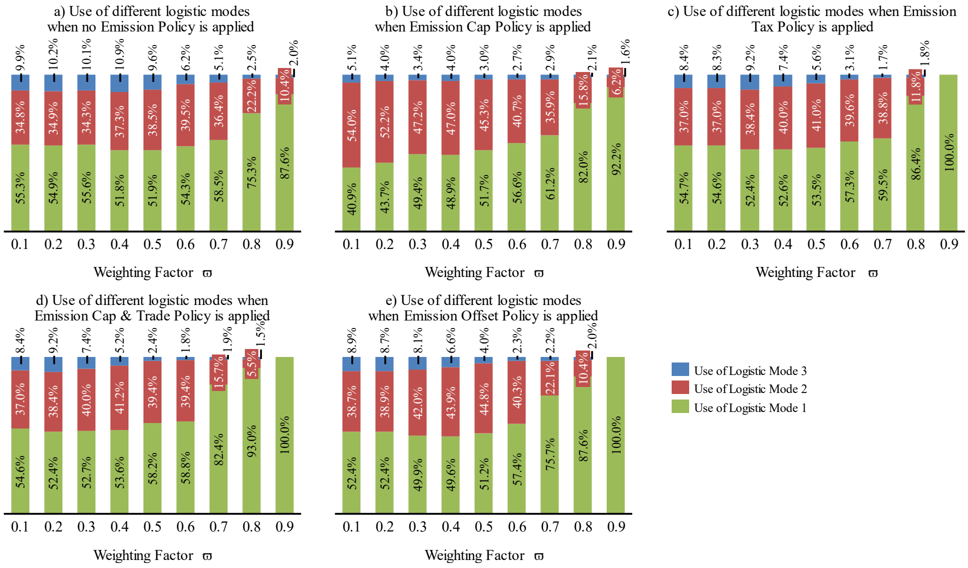

Figure 5.7: Share of different logistic modes with varying ϖ

With increasing ϖ, average units in stock also decrease, as shown in Fig. 5.8 a). An exception is the emission cap policy. Under this policy, average stocks increase with a higher weighting factor and are only strongly decreasing at ϖ of 0.9. The greater use of logistic mode 2 under this regulation explains this effect: with a faster logistic mode, lower OTLDT can be achieved even when fewer goods are in stock. With price-based emission policies or when no emission policy is applied, average units in stock decrease with increasing ϖ. This point also reflects the lower achieved OTDLT and the decrease in total cost.

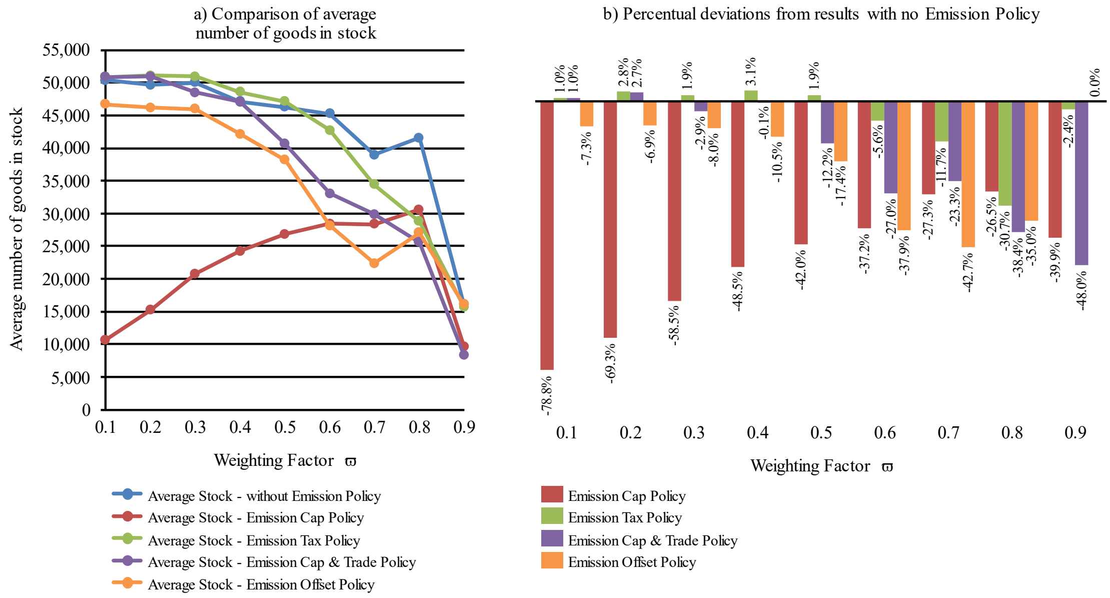

Figure 5.8: Comparison of average number of goods in stock and percentual deviations from results without emission policy

As shown in Fig. 5.8 b), in most cases, applying an emission policy leads to lowered stocks. For emission tax and the cap and trade policy, an emphasis on OTDLT leads to slightly higher stocks compared to the situation without an emission policy. However, where the emphasis is on total cost, stocks strongly decrease. The emission cap policy seems to have the strongest impact on average stocks.

5.4.3 Results with Varying Emission Cap

This section examines the influence of emission cap levels under the emission cap, emission cap and trade, and emission offset policies. Solutions with varying emission caps are examined. The weighting factor is fixed to 0.5, and emission prices are 75 monetary units. For the emission cap and trade policy also the situation of an emission cap dependent emission credit price is investigated. It is assumed that the emission credit price is calculated as follows:

$$\Omega^{CAT} = 75 + (15000 - ECap) * 0.0075.$$

Fig. 5.9 shows the results for total cost (5.9 a)) and OTDLT (5.9 b)) with varying imposed emission caps per period. For market-based emission policies, total costs decrease with an increasing emission cap, whereas OTDLT increases.

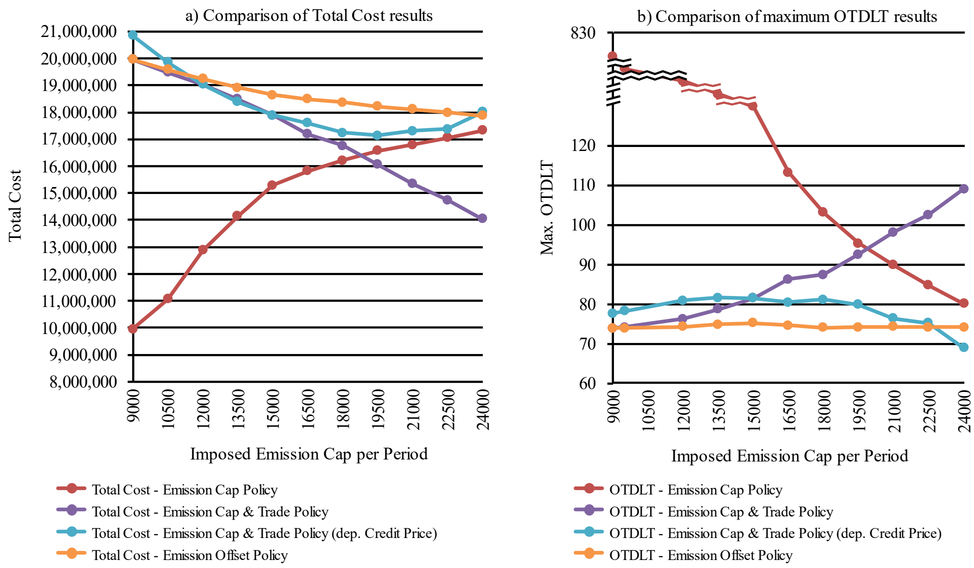

Figure 5.9: Comparison of total cost and maximum OTDLT with varying emission cap per period

The emission cap and trade policy with cap-dependent emission credit price leads to decreasing total cost with increasing emission cap. However, with an imposed cap of 21,000, the emission price decline leads to lower income from selling emissions. Therefore, total cost increase and OTDLT decreases. For the emission cap policy, increases in the imposed emission cap lead to increases in total cost because of decreasing OTDLT.

With an imposed cap of 15,000, this effect is weaker, with less of an increase in total cost and decrease in OTDLT, respectively.

An increasing emission cap has little influence under the emission offset policy. The OTDLT is stable and the total cost decrease only slightly. This effect is explainable by the relatively low influence of the emission cap on the optimal total cost value for the emission offset model. The gap between trade-off value and optimal value increases only slightly with a higher imposed emission cap. In contrast, the optimal total cost value for the emission cap and trade model is highly affected. The possibility of additional revenues by selling excess emission credits leads to an increasing gap between optimal and trade-off total cost value with an increasing emission cap.

Total emission are affected similarly to total cost when the imposed emission cap varies, as shown in Fig. 5.10 a). For emission cap policy, an increasing cap per period leads to vastly increasing total emissions.

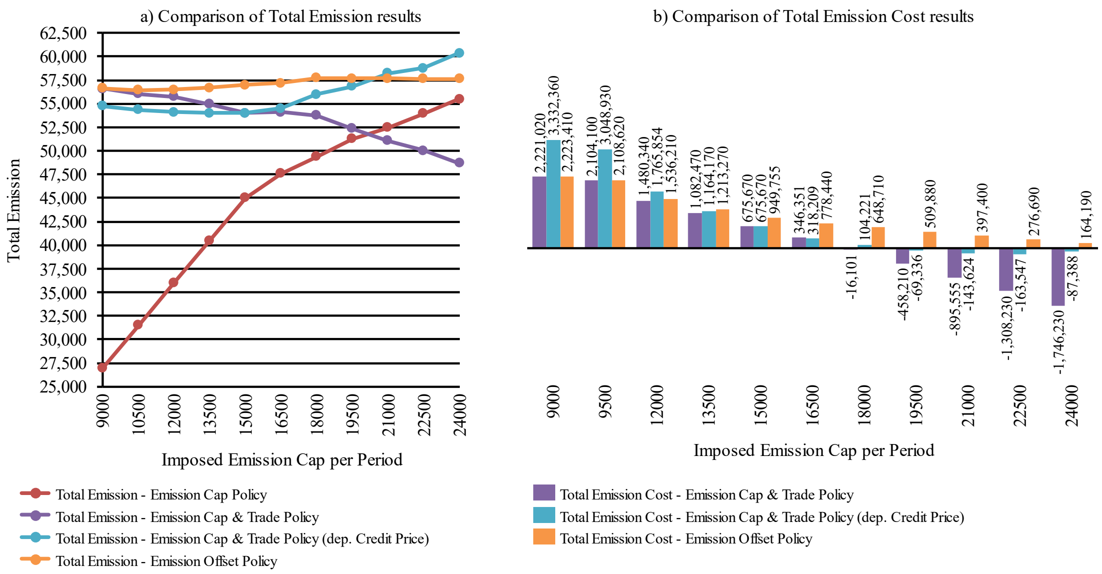

Figure 5.10: Comparison of total emission and total emission cost with varying emission cap per period

For an imposed emission cap higher than 15,000, the increase is weaker. In contrast, the emission offset policy leads to relatively stable total emission, with only slight fluctuations. The emission cap and trade policy results depend mainly on the emission credit price. Stable prices lead to almost linearly decreasing total emissions. This effect can be explained by the functionality of Lp-metrics, as mentioned above. However, a cap-dependent emission credit price leads under a low cap to a low total emission, whereas with a cap above 13,500 it leads to a high total emission. Since a higher cap indicates lower prices for emission credits, the incentive to reduce emissions weakens.

The number of selected suppliers with different imposed emission caps is illustrated in Fig. 5.11 a).

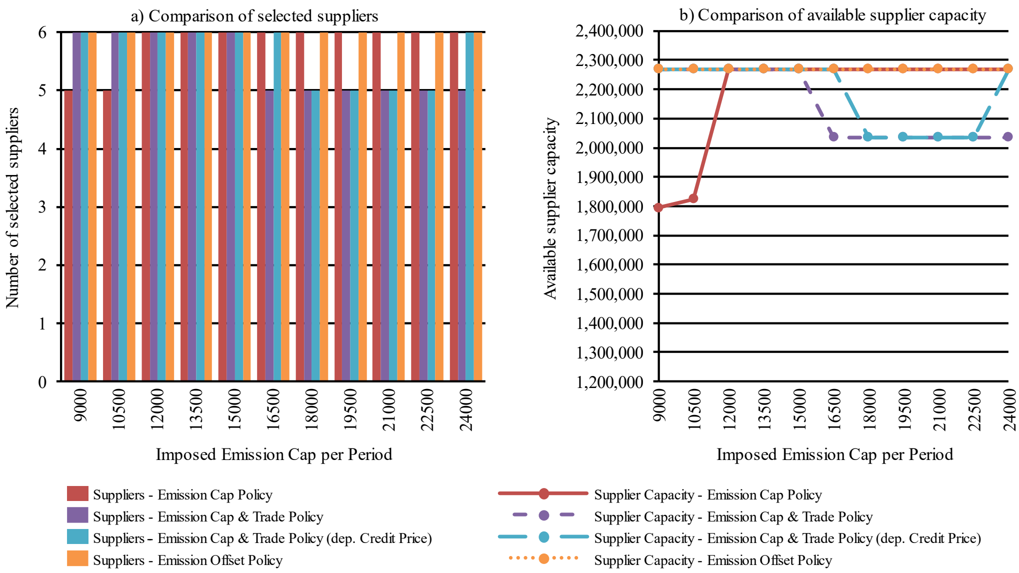

Figure 5.11:Comparison of number of selected suppliers and available supplier capacity with varying emission cap per period

Under an emission cap policy with low imposed caps, five suppliers are selected. This is a change from an imposed cap of 12,000 emission units; at the latter point, all available suppliers are contracted. In addition, different suppliers are contracted in low-cap settings, as Fig. 5.11 b) illustrates. Under the emission offset policy, the variation of the cap does not influence the number of selected suppliers and available supplier capacity. All available suppliers are selected with a low imposed cap under the emission cap and trade policy. With an emission cap of 16,500 units, the number of contracted suppliers is reduced to five. When emission credit prices are cap-dependent, with a cap higher than 16,500 emission units the number of suppliers is reduced to five. With a high imposed cap of 24,000 emission units, six suppliers are contracted under this policy, resulting in increased total cost and total emission but lower OTDLT.

The decisions on production facilities are illustrated in Fig. 5.12 a), and the available production capacity is shown in 5.12 b). The price-based emission policies, emission cap and trade, and emission offset do not influence these decisions according to variations in the emission cap. Only the strict command and control policy influences the selected sites' capacity levels. In the case of a low emission cap, it seems beneficial to open fewer production facilities with higher capacity levels. In contrast, more and smaller production facilities under a higher imposed cap may offer flexibility and OTDLT advantages due to parallel processing.

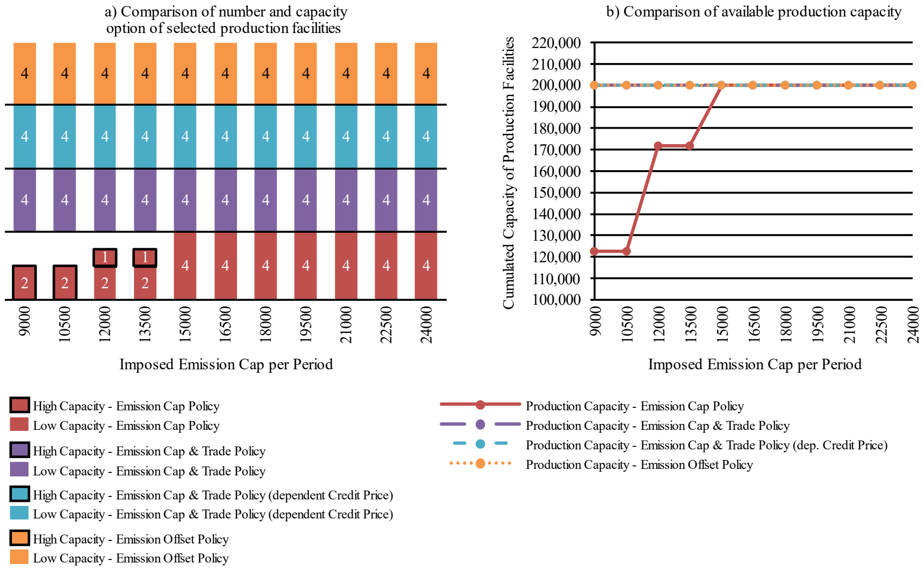

Figure 5.12: Comparison of number of selected production facilities and available production capacity under varying emission cap

Similar observations can be made when examining the number and capacity option of selected warehouses. As Fig. 5.13 a) and b) show, no changes occur in capacity levels and opened warehouses under different imposed emission caps for the market-based emission policies.

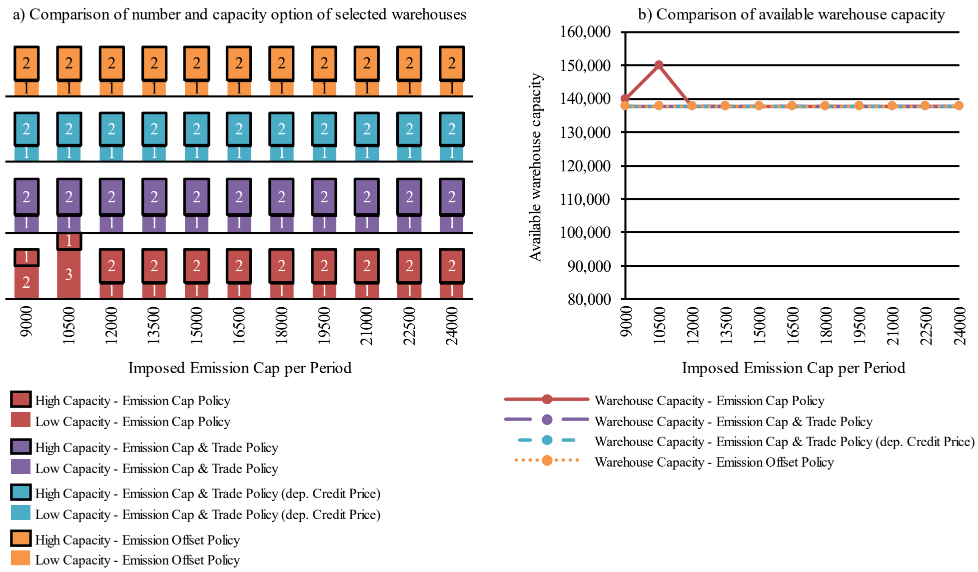

Figure 5.13: Comparison of number of established warehouses and available warehouse capacity with varying emission cap per period

Only the emission cap policy influences this decision when the imposed emission cap is sufficiently low. With emission caps of 9,000 and 10,500, different warehouses are established. Thereafter, the same configuration as for market-based emission policy schemes is chosen.

Furthermore, the logistic modes chosen for goods transportation are influenced mainly by the emission cap policy with varying caps. Fig. 5.13 shows the different shares of logistic mode use under the examined emission policies. Compared to the emission cap policy, the use of different logistic modes s barely influenced by an emission cap with market-based emission policies.

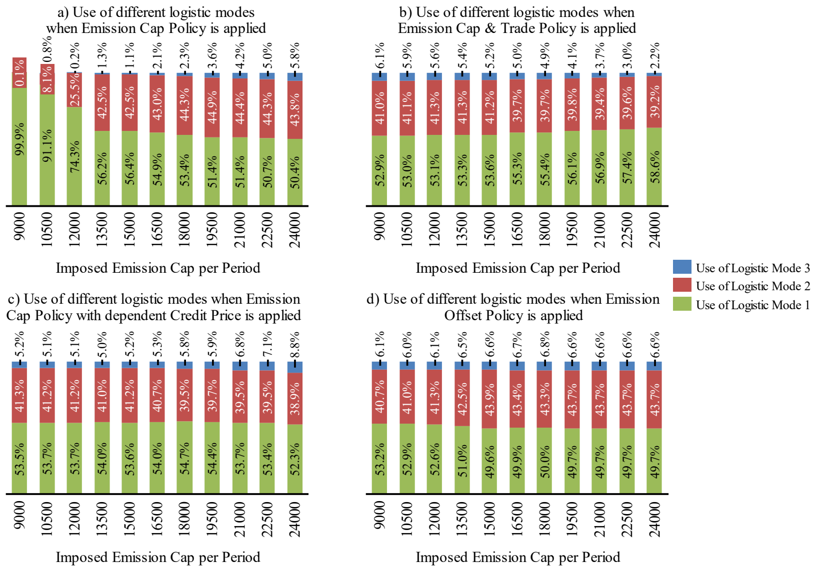

Figure 5.14: Share of selected logistic modes under different emission policies with varying emission cap

The use of logistic mode 1 increases, whereas the use of logistic modes 2 and 3 decreases with increasing height of the imposed cap under the emission cap and trade policy. With cap-dependent emission credit prices under this regulation, the use of logistic mode 1 is relatively stable; logistic mode 2 decreases slightly, and logistic mode 3 increases. Under the offset scheme, the share of goods transported with logistic modes 2 and 3 increases with higher emission caps, whereas logistic mode 1 is used less. The same pattern occurred for the emission cap policy, but the effect is more substantial with a low imposed cap. Due to the harsh regulations, it seems impossible to use more emission-intensive logistic modes.

The number of goods in stock is illustrated in Fig. 5.15 a). With low imposed emission cap per period, average stock levels are similar for the price-based emission policies. With an increasing cap, the average number of goods in stock decreases under the emission offset policy and the emission cap and trade policy with a stable emission credit price. Under the emission offset policy, the lower stock levels are compensated for by faster logistic modes. Therefore, no significant change in OTDLT is observed. By contrast, as mentioned before, under the emission cap and trade regulation with fixed credit price, OTDLT increases. Possible reasons include the smaller share of fast logistic modes and the lower average stock levels with higher emission caps imposed. Regarding different caps under the emission cap policy, a low cap is associated with low stock levels, which – in addition to the limited use of fast logistic modes – leads to higher OTDLT. With increasing caps imposed, the stock levels increase.

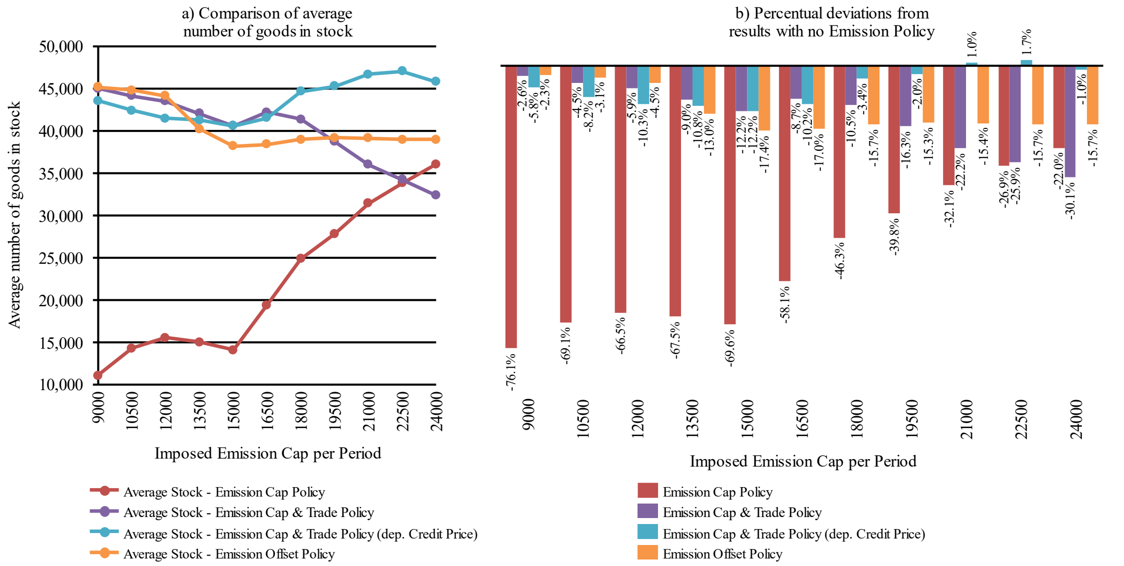

Figure 5.15: Comparison of average number of goods in stock with varying emission cap and percentual deviations from results without emission policy

Fig. 5.15 b) shows that the average stock levels are reduced under each emission policy compared to the solution without policies applied. Only the cap and trade policy with dependent credit price leads, in some cases, to slightly higher stocks when a high cap is imposed. A higher emission cap, in this case, leads to a lower price on emissions. Therefore, the incentive to reduce emissions is lower, resulting in higher total emissions and lower OTDLT.

5.4.4 Results with Varying Emission Price

The weighting factor is fixed at 0.5, and the emission cap for emission offset and emission cap and trade policy is set to 15,000 emission units to examine the influence of different prices for emissions. Under the emission cap policy, no prices on emissions are applied. Therefore, this policy is neglected in this section.

Fig. 5.16 shows total cost and maximum OTDLT under emission tax, emission cap and trade, and emission offset policy when emission prices vary. Under emission tax regulation, the total costs increase almost linearly with increasing tax rates. Furthermore, maximum OTDLT is relatively stable. This can be explained by increasing optimal total cost, whereas optimal OTDLT as a reference point is not affected in the Lp-metrics method. Under cap and trade policy and offset policy, OTDLT is significantly influenced by emission credit or allowance prices. With higher prices on emission allowances, OTDLT increases by up to 26%, but total costs are only slightly affected when an emission offset policy is applied. Under the emission cap and trade scheme, the trade-off between OTDLT and total cost is more substantial. Maximum OTDLT at first increases slightly, but with increasing emission credit price, it can rise by about 60%. On the other hand, total cost can be lowered with higher prices due to selling excess emission credits, leading to a stronger incentive to reduce total emission.

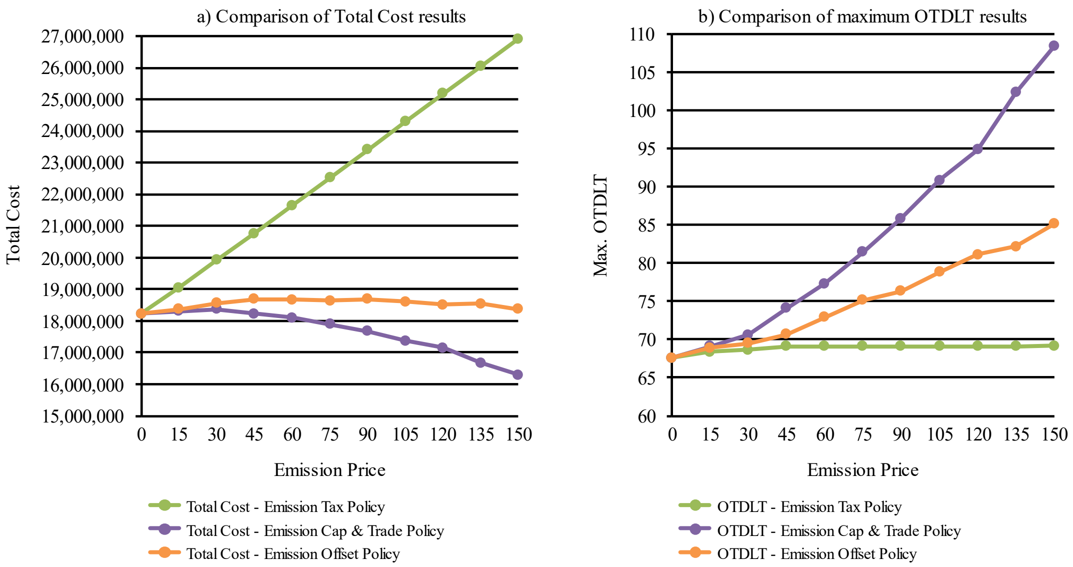

Figure 5.16: Comparison of total cost and maximum OTDLT with varying emission prices

The influence of the price on total emission is illustrated in Fig. 5.17 a). A higher price, under all market-based emission policies, leads to reduced total emission. The higher total emission cost is illustrated in Fig. 5.17 b). Highest increase of total cost is caused by emission tax policy. Nonetheless, total emission reduction is relatively tiny in the trade-off setting, compared to the emission offset and cap and trade policy.

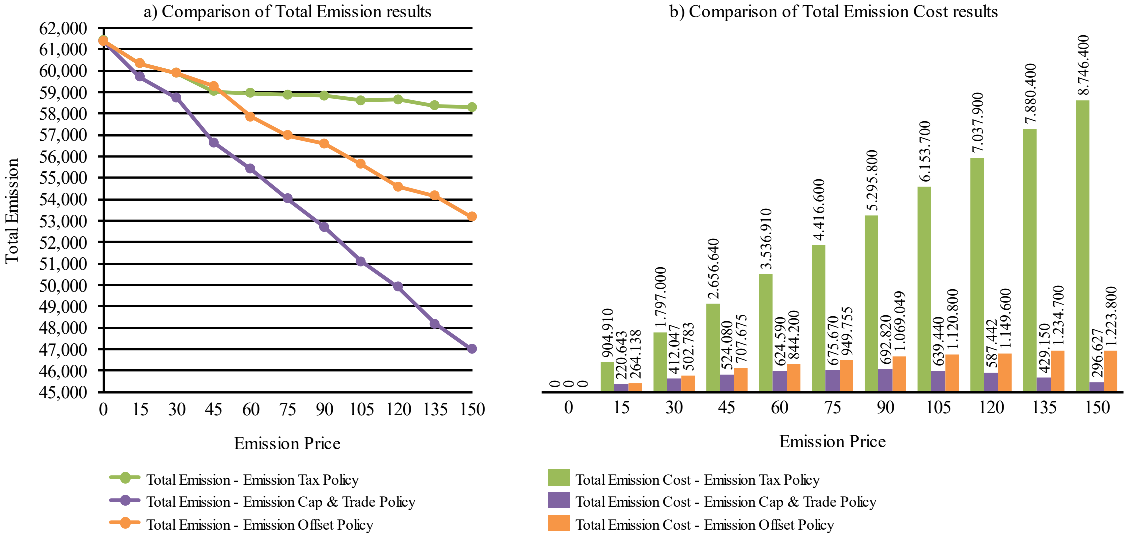

Figure 5.17: Comparison of total emission and total emission cost with varying emission prices

In contrast to increased total cost and total emission, OTDLT remains stable under emission tax policy. The emission offset policy has a moderate effect on total emissions and causes significantly lower total emission costs than did the tax regime. With emission cap and trade, total emissions can be reduced by about 23% under high emission credit prices. Total emission cost is marginally affected by the price. A higher emission credit price does not necessarily lead to higher total emission cost because of the strong incentive to reduce emissions to gain additional revenue by selling excess credits. Furthermore, a decrease in total cost is observed, but this is a result of increasing OTDLT.

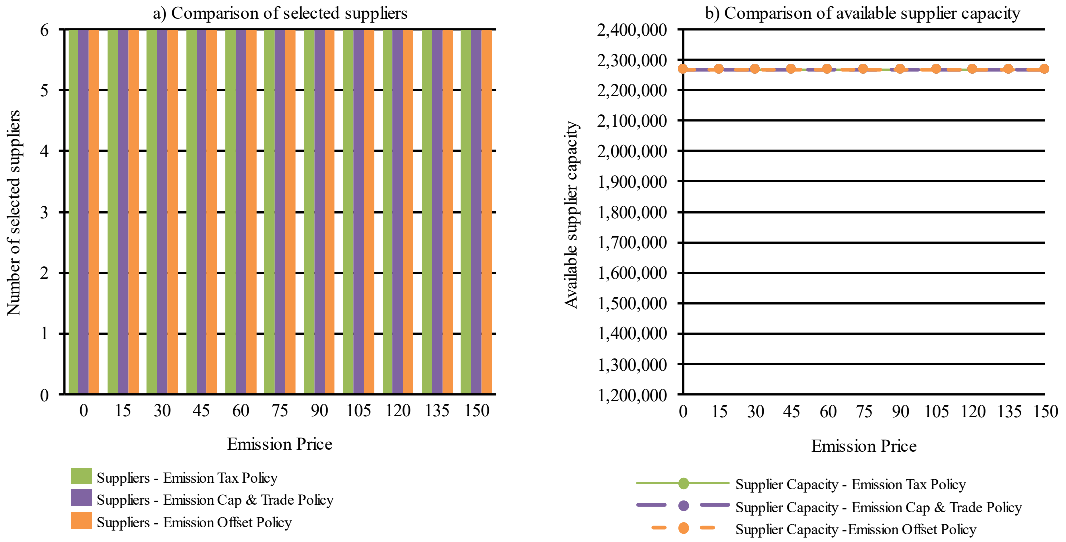

Figure 5.18: Comparison of number of selected suppliers and available supplier capacity with varying emission prices

As shown in Fig 5.18, emission prices do not influence the number of selected suppliers. For all observed emission policies, no changes in available supplier capacity could be determined.

Emission prices also do not influence production and warehouse capacity, as illustrated in Fig. 5.19. Therefore, there are no changes in location decisions about production facilities and warehouses. The weighting factor is the most influential factor for such a decision in this model context. However, it is essential to note that the emission credit price is not independent of the imposed emission cap due to the market-based nature of this policy. Therefore, the results for the emission cap and trade policy with dependent credit price (see Chapter 5.4.3) seem more realistic than emission credit price variation with a fixed emission cap.

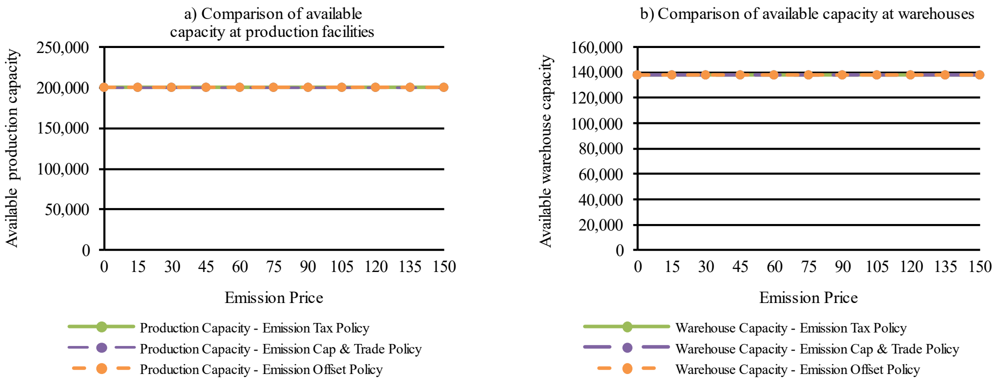

Figure 5.19: Comparison of available production and warehouse capacity with varying emission prices

Regarding the influence of emission prices on the use of logistic modes, the results strongly depend on the applied policy, as shown in Fig. 5.20. The use of logistic mode 3 decreases slightly, whereas the share of logistic modes 1 and 2 slightly increases under the emission tax policy. However, the changes are rather small compared to those associated with other policies. When the emission cap and trade policy is applied, the share of logistic mode 3 decreases from 9.6% to 1.4% with higher emission prices. The use of logistic mode 1 rises constantly, and the share of logistic mode 2 fluctuates between 38.5% and 41.4% with higher emission prices. The share of logistic mode 3 decreases with higher emission prices under the emission offset policy, but not below 4.8%. Logistic mode 2 rises constantly up to 46.4%. Interestingly, the share of logistic mode 1 decreases with higher emission prices.

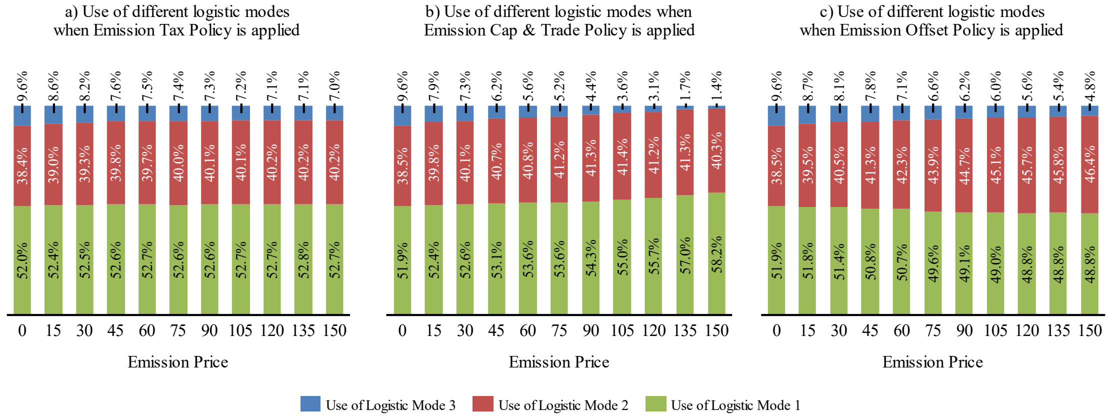

Figure 5.20: Share of selected logistic modes under different emission policies with varying emission prices

Fig. 5.21 illustrates the average number of goods in stock and percentual deviations from results without an emission policy.

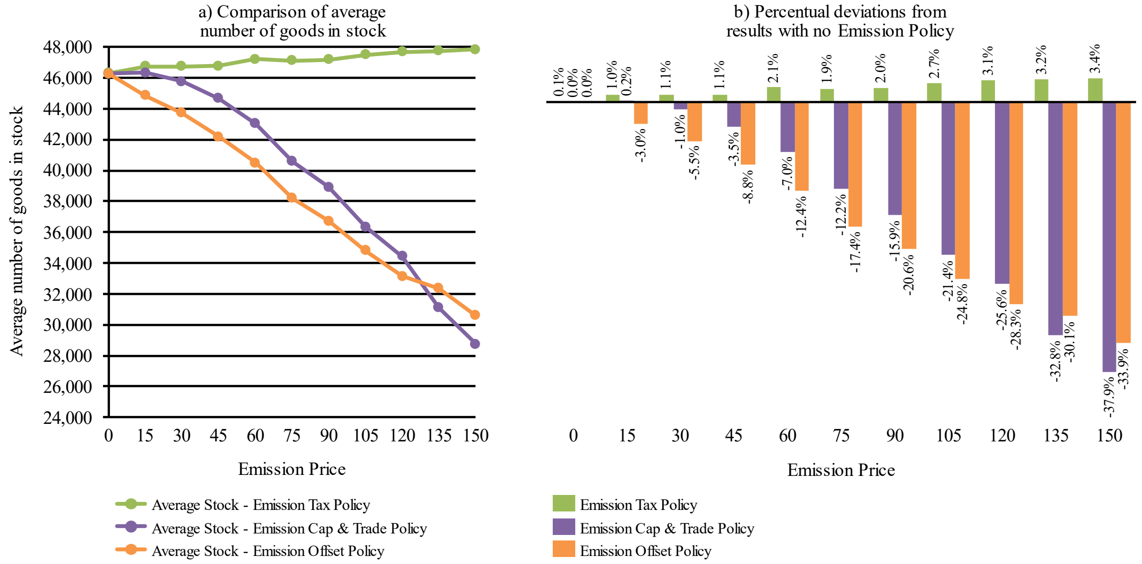

Figure 5.21: Comparison of average number of goods in stock with varying emission prices and percentual deviations from results without emission policy

Under the emission tax policy, the average amount of goods in stock increases with a higher tax rate. Deviations in results without an emission policy are at most 3%. It seems that the use of ecological logistic modes becomes feasible with slightly higher stock levels. Therefore, under the emission tax scheme, there are only minor changes in maximum OTDLT. Stock levels decrease up to 37.9% and 39.9%, respectively, under the emission cap and trade and emission offset policies. Under emission cap and trade regulation, more ecologically friendly logistic modes are used, and the average number of goods in stock decreases with increasing emission prices. Therefore, OTDLT increases notably. Under an emission offset scheme, stocks also decrease, but due to the higher share of logistic mode 2 the effect on OTDLT is lowered.

5.4.5 Conclusion

As seen before, the weighting factor greatly influences total cost, OTDLT, and total emission. The percentual deviations are illustrated in Fig. 5.22 for results without any emission policy applied.

With low ϖ, OTDLT results are relatively stable. Total cost are constantly increased, compared to the optimal value when OTDLT is not considered. A high ϖ leads to a difference of 68.8% between the trade-off solution and the optimal value. This point unpins the importance of considering lead times even during strategic decisions. With higher weight on OTDLT, total cost nearly triple in comparison to the optimal cost value. The changes in OTDLT are also significant when total cost is the crucial criterion.

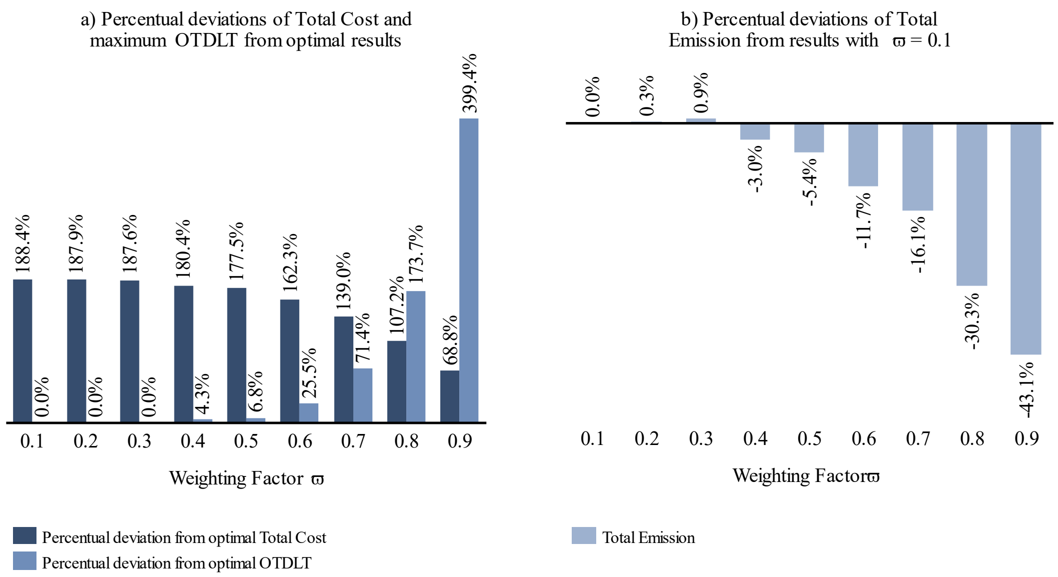

Figure 5.22: Percentage changes of results without emission policies under varying weighting factor

Therefore, it seems to be essential to find a good trade-off that fits a company's goals. Total emissions can be reduced by more than 40%, but this can substantially increase OTDLT. In contrast to the examined changes in emission policies (namely the cap and the price variations), the weighting factor strongly influences the supply chain network design. In some cases, emission policies can strengthen these effects, but the trade-off between total cost and OTDLT is the determining factor for the network configuration. Fig. 5.23 shows the network design for ϖ of 0.1 and 0.9.

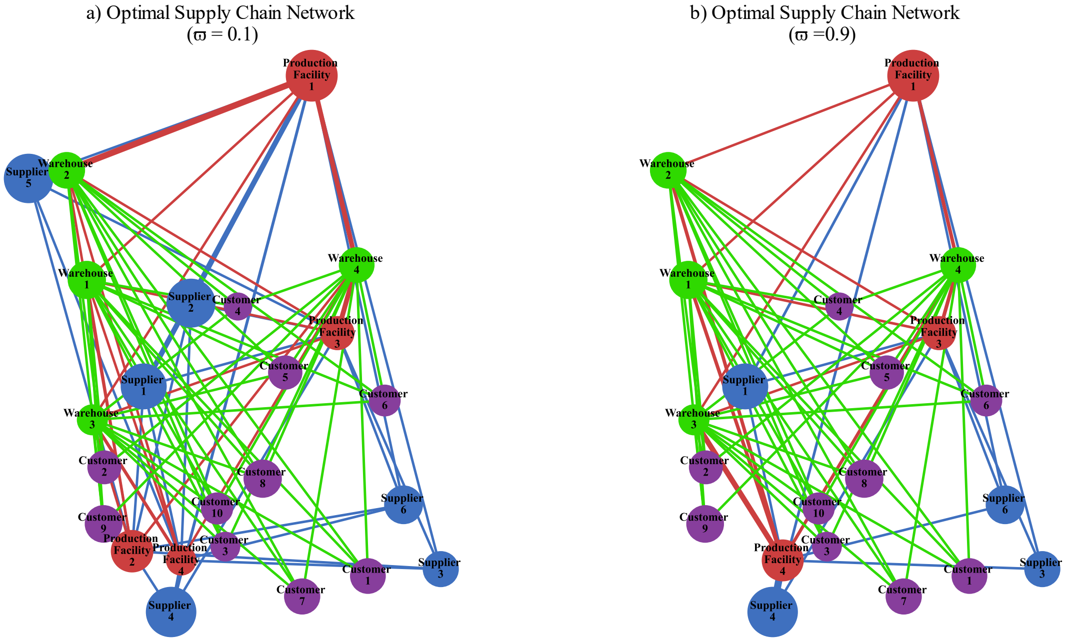

Figure 5.23: Supply chain network design without emission policies

With an emphasis on total cost, fewer suppliers and production facilities are selected. Warehouses seem to be more critical in order to limit the increase of OTDLT. Furthermore, the choice of logistic modes and stock levels seem to be crucial for decreasing the total cost and total emission. To achieve low OTDTL, the share of faster logistic modes rises, as does the number of goods in stock.

The effects on total cost and OTDLT are amplified regarding the different emission policies examined, as shown in Fig. 5.24.

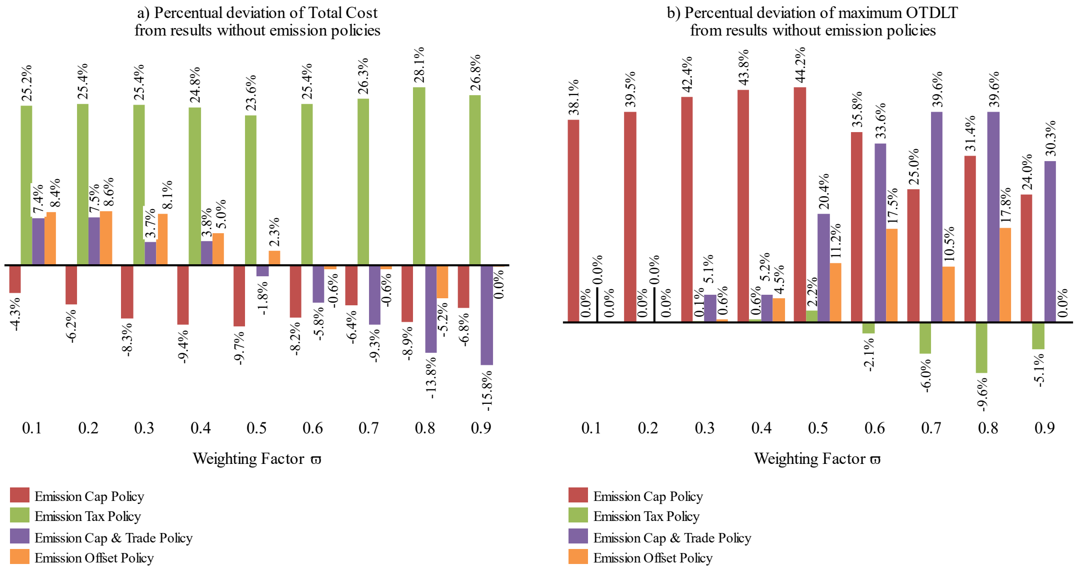

Figure 5.24: Percentual deviation in total cost and maximum OTDLT results compared to results without emission policy (varying ϖ)

Emission tax policy always increases total cost but can also lower OTDLT and total emission (see Fig. 5.25) with a high weight on total cost. This is explainable by companies selecting more suppliers and the use of Lp-metrics calculations. Regarding the trade-off between total cost and OTDLT, emission cap policy always negatively affects OTDLT but lowers total cost. With a high preference for OTDLT, an emission cap policy seems to regulate total emissions most effectively. Nevertheless, it strongly limits the decisions of a company.

Under the emission cap policy, the optimal OTDLT value cannot be achieved due to harsh regulation. Therefore, this policy seems the most inflexible because companies cannot necessarily achieve their lead time targets. With an emphasis on total cost, a well-designed emission cap and trade system can enhance the reduction efforts by companies as they can gain additional revenue by selling their excess emission credits. However, these reductions are accompanied by increases in OTDLT. Therefore, it is questionable whether a company could lower its OTDLT in such a manner without losing time-sensitive customers. In addition, a suitable – and in most cases voluntary – emission offset system can lower total emissions with a smaller influence on total cost and OTDLT.

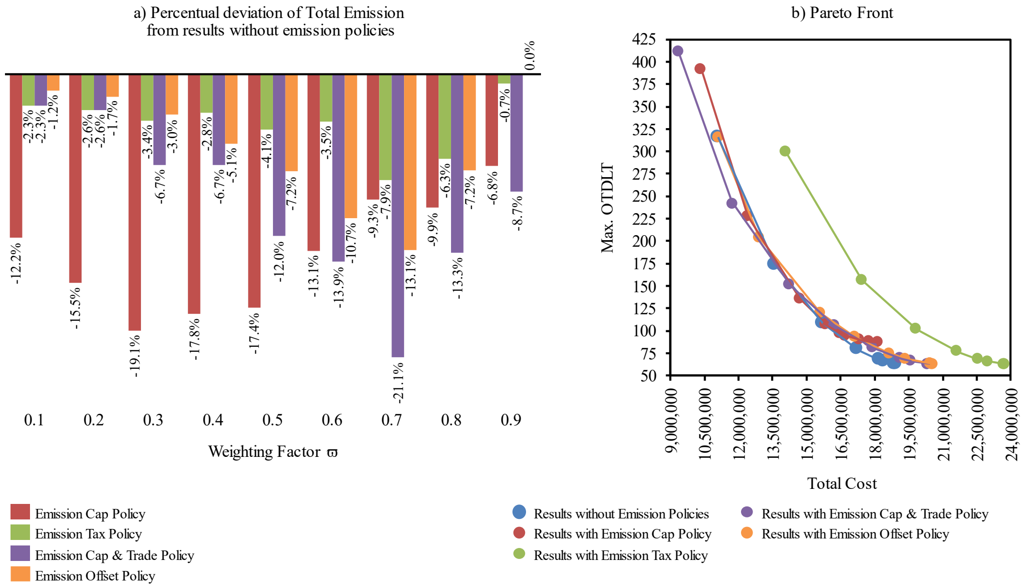

Figure 5.25: Percentual deviation in total emission from results without emission policy and pareto front

The pareto fronts are illustrated in Fig. 5.25 b). Emission tax has the highest impact on total cost, whereas all other policies have much less negative impact on the cost side. In some cases, improvements in total cost are also achieved. Emission cap is the harshest form of regulation and offers no flexibility to achieve the lowest OTDLT.

Different heights of the imposed emission cap significantly influence total cost and OTDTL, as shown in Fig. 5.26. Under a strict emission cap policy setting, a low cap can cut total costs by up to 45%, leading to a large increase in OTDLT. Therefore, it can be threatening for companies that compete on OTDLT-sensitive markets in the short run.

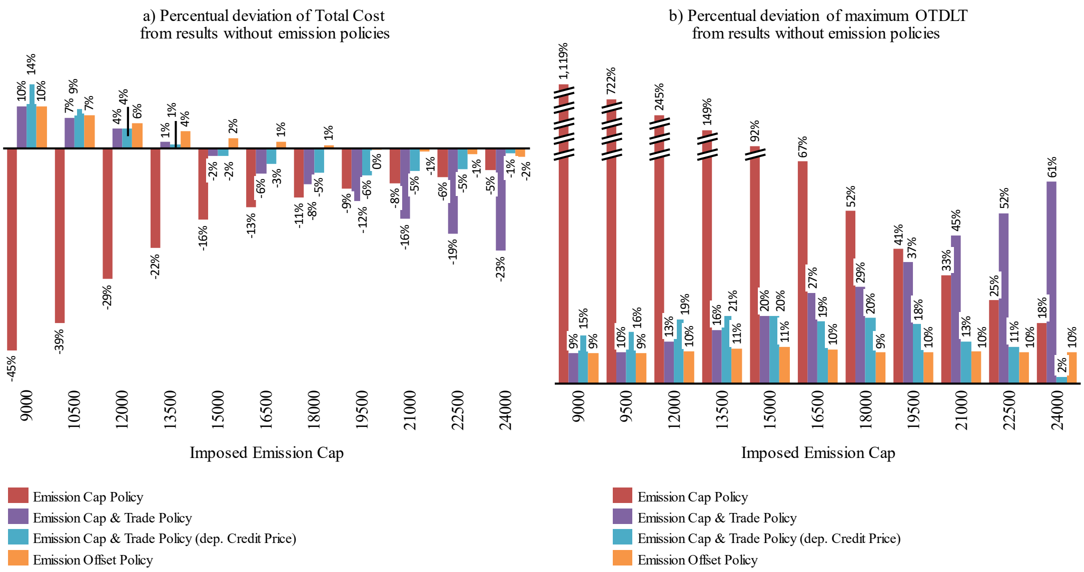

Figure 5.26: Percentual deviations in total cost and maximum OTDLT results compared to results without emission policy (varying imposed emission cap per period)

With an increase in the cap, these effects relax, and the results then approach the solution without an emission policy. A contrary effect occurred in the case of an emission cap and trade policy. With a low cap, effects on total cost and OTDLT are relatively small, but with an increasing cap, the total cost is reduced due to additional revenues from selling excess credits; however, OTDLT increases significantly. As already mentioned, it is questionable in lead-time-sensitive markets whether such a decision would be suitable. A more realistic view of the emission cap and trade policy offers emission-cap-dependent credit price results. A low cap would increase the price of emission credits, and therefore, a more substantial effect on total cost is possible. Credit prices would decrease with a high cap and would thus affect total cost and OTDLT. The voluntary offset policy has a relatively small impact on the regarded dimensions but can be helpful to lower the total emission (see Fig. 5.28). The results indicated that the emission cap's height can strongly impact relevant performance measures such as total cost and OTDLT. Especially with strict emission cap regulation, companies can face onerous difficulties to fulfill this regulation and stay competitive. Under cap and trade regulation, too high a cap can turn into a subsidy system for some companies or can remove incentives to lower the total emission.

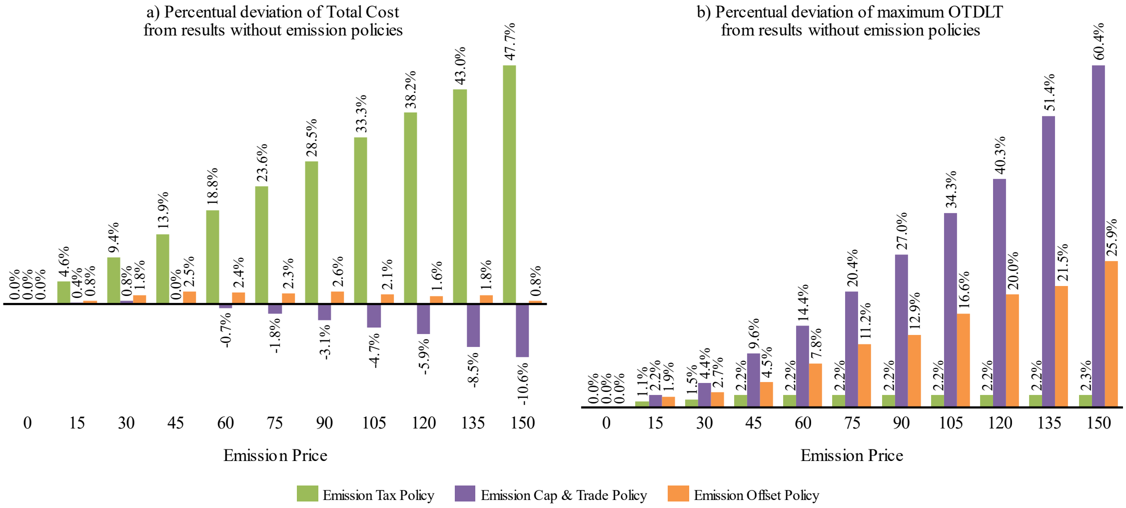

Figure 5.27: Percentual deviation in total cost and maximum OTDLT results compared to results without emission policy (with varying emission prices)

With higher prices on emissions, companies may face different problems. A high emission tax rate can greatly increase the total cost; however, in the trade-off solution, it has a low impact on OTDLT. In the case of price-sensitive markets, this point can be problematic for some companies. In contrast, in time-sensitive markets where customers are probably willing to pay higher prices for products, emission tax can be a positive policy to deal with. Offset policy, in contrast, has a low influence on total cost, but in the trade-off context, it seems beneficial to increase OTDLT. The most decisive influence on OTDLT occurs under the emission cap and trade policy. Due to revenue from selling excess credits, it seems beneficial to increase OTDLT to gain such additional income.

As shown in Fig. 5.28, all emission policies can set incentives to lower total emissions in the trade-off scenario, as long as they are appropriately designed. Interestingly, the emission cap and trade policy results, under the assumption of an emission-cap-dependent emission credit price, show that such a system's design is crucial. The height of the imposed cap determines the price for emission credits due to the market-based nature. With a cap that does not fit the requirements for adequate emission reduction, this instrument loses its incentive to lower emissions. Furthermore, in the trade-off scenario, emission tax seems to be expensive for companies, but the achieved reduction of total emissions are relatively low because of the stable OTDLT. An emission cap policy with a low imposed cap had the strongest influence on total emission and reduced companies' ability to act in time-sensitive markets. Emission offset can be helpful when no governmental regulation is given or in addition to such regulations. However, due to the voluntary nature of such approaches, adequately designing them can be problematic.

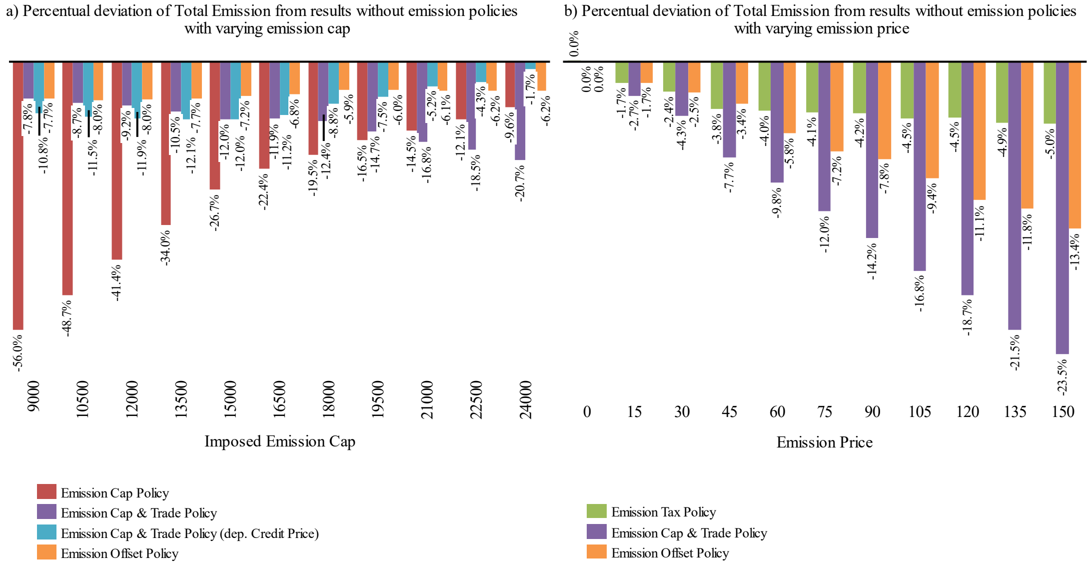

Figure 5.28: Percentual deviations in total emission results compared to results without emission policy

Based on the assumptions made and on the given dataset, the following insights are deduced:

- Shortening the OTDLT has a significant influence on both total cost and total emission. A lower OTDLT is associated with significant increases in total costs and total emissions.
- The weighting factor mainly influences supply chain network design. Therefore, the trade-off between OTDLT and total cost has the strongest impact on supplier selection and facility location.
- Selecting more suppliers can help to reduce OTDLT due to the possibility of multiple sourcing. Furthermore, tighter emission policies may lead to selecting additional suppliers who are less emission intensive. When orders are placed at these suppliers, the emissions generated by purchasing activities can be reduced. Under a strict emission cap policy, emission-intensive suppliers are not contracted.
- All of the examined emission policies can reduce the total emission. Moreover, the reduction efforts are highly connected to policy design. Therefore, a poorly designed emission policy will not achieve adequate emission reduction or provide flexibility to react to specific market needs.
- Except for emission cap policy, the examined emission policies have only a slight influence on location decisions. The market-based policies offer more flexibility to react to regulations. Due to the strict political requirements, an emission cap policy can prohibit some location decisions.

- The use of different logistic modes is strongly affected by emission policies. Furthermore, logistic modes are highly relevant to achieve a particular OTDLT value. With lower OTDLT, greater use of fast logistic modes can be observed.
- It may be beneficial to quote longer OTDLT to customers to lower the total emission and total cost. Furthermore, quoting for a longer OTDLT might be a strategy to cope with environmental regulations.

5.5 Order-to-Delivery Lead Time as Constraint

5.5.1 Model Reformulation

Another form of multi-objective optimization is applied to provide deeper insights into the outcomes, namely the ε-constraint method.[296] In contrast to compromise programming, the ε-constraint method can also produce unsupported efficient solutions in multi-objective MILP problems.[297] Furthermore, the scaling of objective values has a strong influence on the generated solutions. For applying the ε-constraint method, no scaling is needed. Additionally, by using the ε-constraint method, the number of generated efficient solutions can easily be controlled, in contrast to the weighting method.[298]

Moreover, it is common for firms to propose a certain OTDLT to their customers. With ε-constraint acting as an implicit bound, the reformulation can cover this fact. As noted earlier, some results in the trade-off case may not be suitable for companies if they do not meet the company’s strategic targets regarding OTDLT.

Objective (5.3) has to be reformulated as a constraint to apply this method:

$$MaxLT \leq \varepsilon \tag{5.32}$$

The value of parameter ε is increased to obtain different solutions - starting from a minimum possible OTDLT. Therefore, it can be investigated how supply chain design is altered with different quoted OTDLT and how different emission policy designs influence the network design. The following analysis is based on the combinations of objectives and constraints shown in Table 5.1:

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[296] Cf. HAIMES, Y. Y.; LASDON, L. S.; WISMER, D. A., 1971, p. 296f.
[297] Cf. STEUER, R. E., 1986, p. 208.
[298] Cf. MAVROTAS, G., 2009, p. 457.

Model	Objective	Constraints
No Emission Policies	(5.2)	(5.4) – (5.20) & (5.32)
Emission Tax	(5.23)	(5.4) – (5.21) & (5.32)
Emission Cap	(5.2)	(5.4) – (5.22) & (5.32)
Emission Cap and Trade	(5.24)	(5.4) – (5.21) & (5.25) & (5.32)
Emission Offset	(5.27)	(5.4) – (5.21) & (5.27) & (5.32)

Table 5.1: Objective function and constraints for the different models

5.5.2 Results with Varying Quoted Order-to-Delivery Lead Time

To examine the influence of quoted OTDLT on supply chain design, the emission cap per period for the emission cap and trade and emission offset policy is set to 19,000 emission units. For the emission cap policy, an emission cap per period of 15,000 is imposed. Emission prices are set to 75 monetary units.[299]

As shown in Fig. 5.29 a), total cost decrease with higher quoted OTDLT. When no emission policy is applied, total costs are below the result of any applied emission policy under low quoted OTDLT. Due to the strict regulations of the emission cap policy, no OTDLT of 64 or 79 time units is quotable. The emission cap and trade and the emission offset policy lead to increased total costs when quoting a low OTDLT. With increasing OTDLT, the results with these emission policies are approaching. The same applies to the emission cap policy. A high quoted OTDLT can even, in the case of emission cap and trade, lead to a cost decrease compared to the solutions without an emission policy. This is due to the possibility of gaining additional income from selling excess emission credits. Under an emission tax policy, total costs increase significantly. With higher quoted OTDLTs, total costs also decreased but are always significantly higher than under other emission policies.

Total emission generally decreases with higher quoted OTDLT, as illustrated in Fig. 5.29 b). Overall, it seems preferable to accept higher emission levels at specific quoted lead times. After that point, total emissions again decrease.

[299] Detailed results of the examinations in Chapter 5.5 can be found in appendix B.

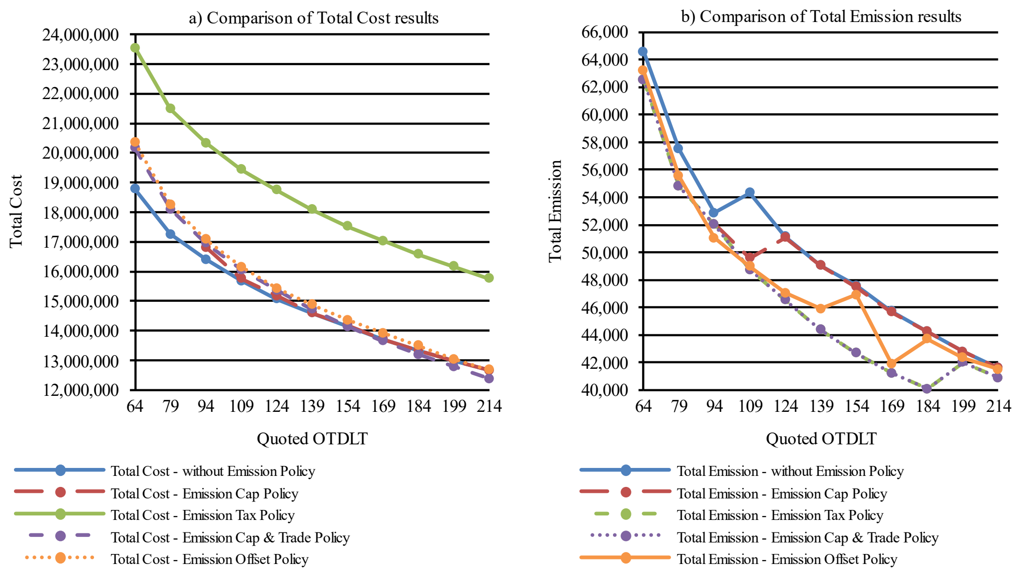

Figure 5.29: Comparison of total cost and total emission with varying OTDLT

Under the emission cap policy, starting with a quoted OTLDT of 124 time units, the same results are generated as the case without emission policies. Hence, the per-period emission cap has no influence when quoted OTDLT is high. Such strict regulations can significantly influence the total emission when emission caps are low. However, it is hard to customize them to be fully effective in every scenario. Emission tax and the emission cap and trade policy lead to the same emission levels for each observed quoted OTDLT. However, this is true only when the cap and trade policy is carefully designed, and prices for emission credits are stable. An emission offset policy leads to results that are generally between those of solutions without an emission policy and those with an emission tax policy. In only one case, at a quoted OTDLT of 94, emission offset policy seems to reach lower emission levels. This may be because of some shifts in between the periods to lower the cost of emission allowances.

The lower emission levels reflect total emission cost, as depicted in Fig. 5.30. With a quoted OTDLT of 94, costs for emissions are the lowest in the case of the emission offset policy. In all other scenarios, total emission costs are lower under emission cap and trade. Furthermore, emission tax causes significantly higher emission costs. This point also explains the large difference in total cost between the cases of emission tax policy and no applied emission policy. Emission cap and trade can, with high quoted OTDLT, be a source of additional income because emissions can be reduced below the emission cap, and excess emission credits can be sold.

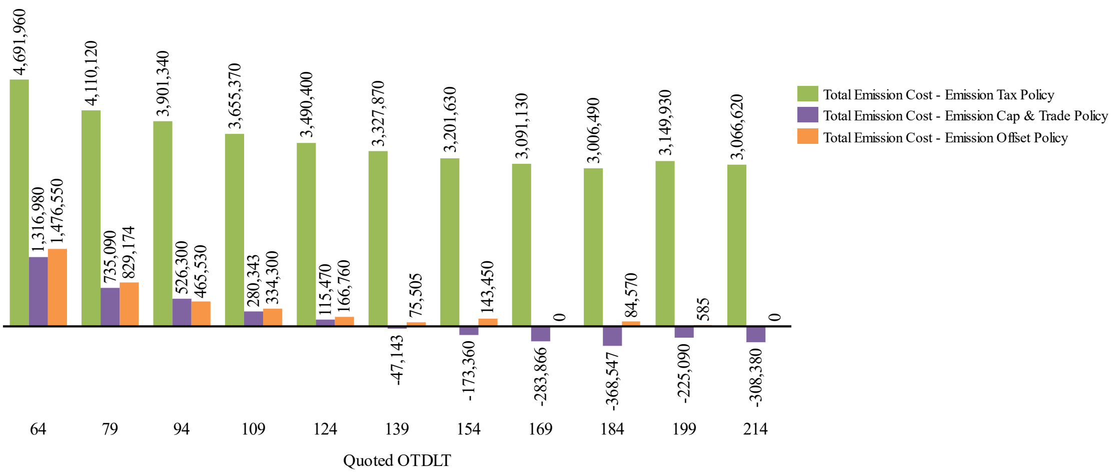

Figure 5.30: Comparison of total emission cost with varying OTDLT

With higher quoted OTDLT, the number of selected suppliers and the available supplier capacity decreases, as shown in Fig. 5.31. When no emission policy is applied, the number of selected suppliers is reduced with lower quoted OTDLT. When emission policies are in charge, this effect can be observed with higher quoted OTDLT. Interestingly, when only four suppliers are contracted, total emission levels (see Fig. 5.29 b) increase. Thereafter, the emission levels continue to decrease. Furthermore, with emission tax and the emission cap and trade policy, the number of contracted suppliers is reduced only with high OTDLT. This fact seems to indicate that, under the given assumptions, the presence of more contracted suppliers can lower the total emission.

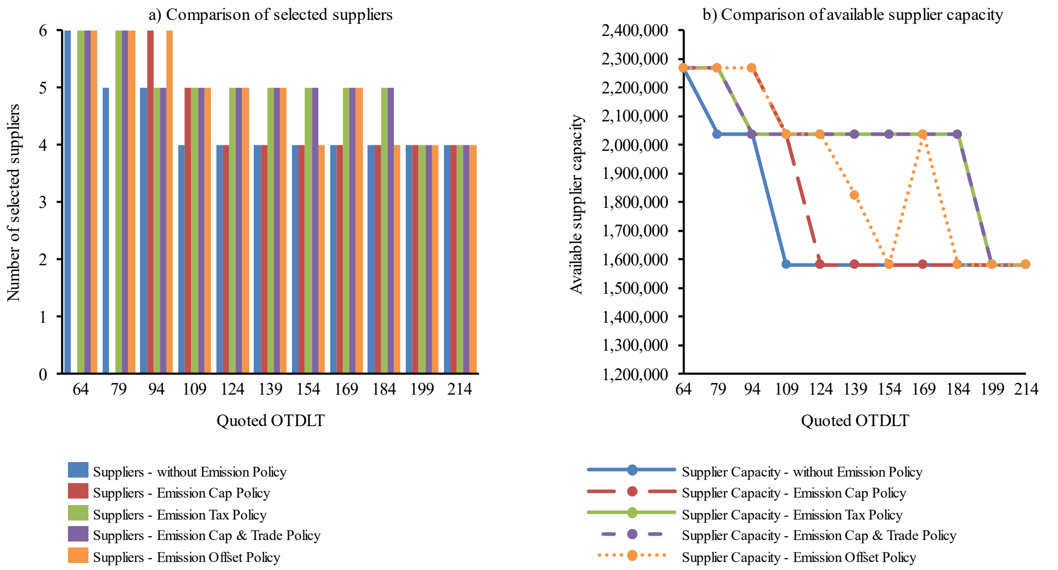

Figure 5.31: Comparison of number of selected suppliers and available supplier capacity with varying OTDLT

The number and capacity option for production facilities and available production capacity are illustrated in Fig 5.32. With higher quoted OTDLT, the number of selected production facilities declines. With higher quoted OTDLT, longer distances between production facilities and warehouses seem to be effective. With a low quoted OTDLT, many small facilities seem preferable to enhance the parallel processing of orders. With higher OTDLT, one large and two small facilities are established. When emission tax and the emission cap and trade policy are applied, this change occurs even with a quoted OTDLT of 139. Under the emission cap and the emission offset policies, the number of opened production facilities is reduced with a higher quoted OTDLT.

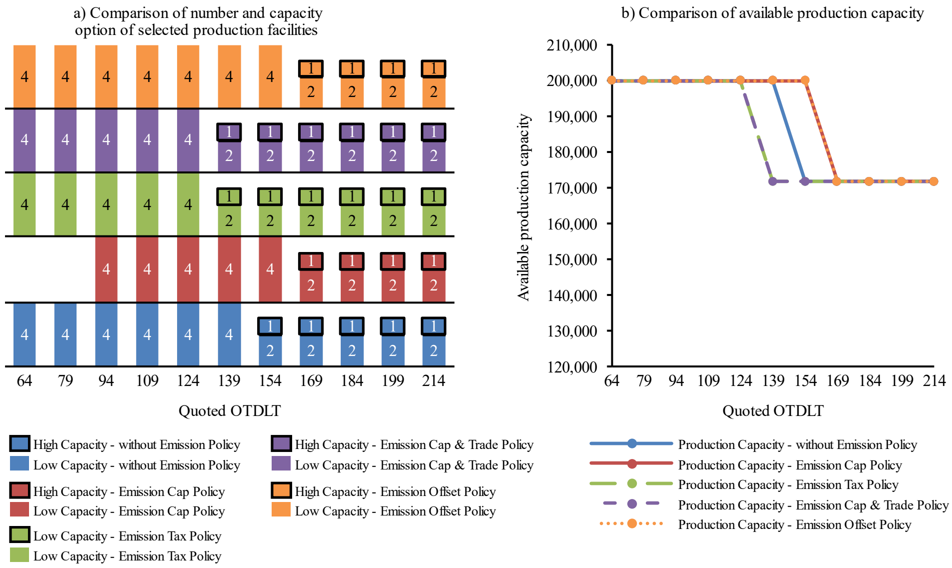

Figure 5.32: Comparison of established production facilities, chosen capacity option, and available production capacity with varying OTDLT

The number of selected warehouses, the chosen capacity option, and the available capacity of warehouses are illustrated in Fig. 5.33. With the lowest examined value of quoted OTDLT, four warehouses are established in every case. When market-based emission policies are applied, more capacity at warehouses is available due to opening two large and two small warehouses. In the case of no applied emission policy, only one large warehouse and three small warehouses are opened. With a higher quoted OTDLT, the number of warehouses and the available capacity decreases. However, with relatively high quoted OTDLTs, it seems favorable to open four warehouses. This effect is evident under each examined policy option. In the case of no applied emission policy, this effect is examined starting from quoted OTDLT of 154; by contrast, for emission tax and the emission cap and trade, with quoted OTDLT started at 199.

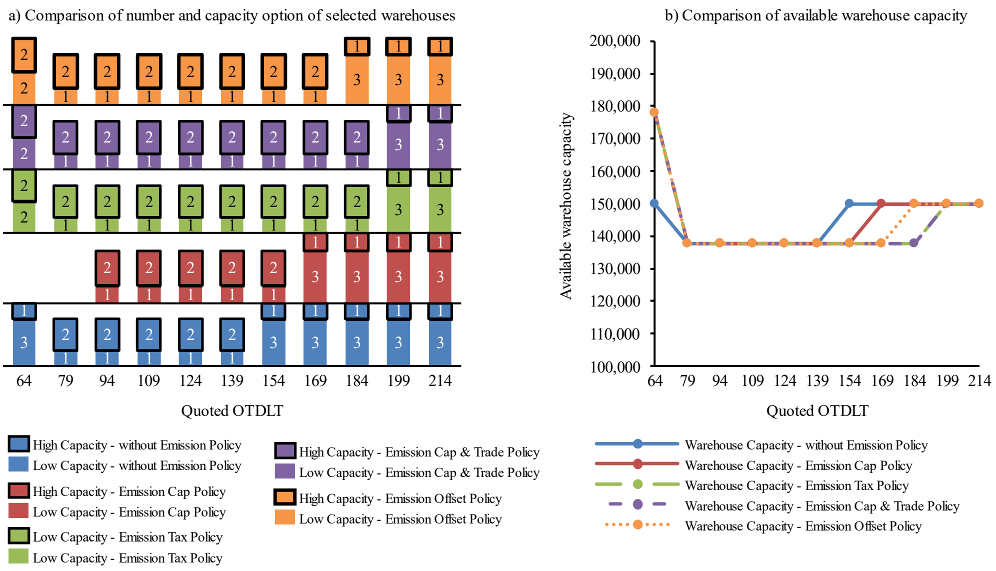

Figure 5.33: Comparison of established warehouses, chosen capacity option, and available warehouse capacity with varying OTDLT

The use of different logistic modes is illustrated in Fig. 5.34. The share of fast but cost-intensive and high-emission logistics mode 3 decreases when higher OTDLT is quoted. However, logistics modes 1 and 2 are subject to significant fluctuations, and their share does not decrease or increase continuously. Only when an emission cap policy is applied a continuous decrease of the shares of logistic modes 2 and 3 can be observed. It appears that the use of logistics mode 2, in particular, is strongly related to location and supplier decisions. If suppliers or locations are reduced, increasing the distances are compensated for by faster logistic modes. Market-based emission policies tend to reduce the use of logistic mode 1. The share of which is lower with all types of marked-based emission policy, especially with low quoted OTDLT than when no emission policy is applied.

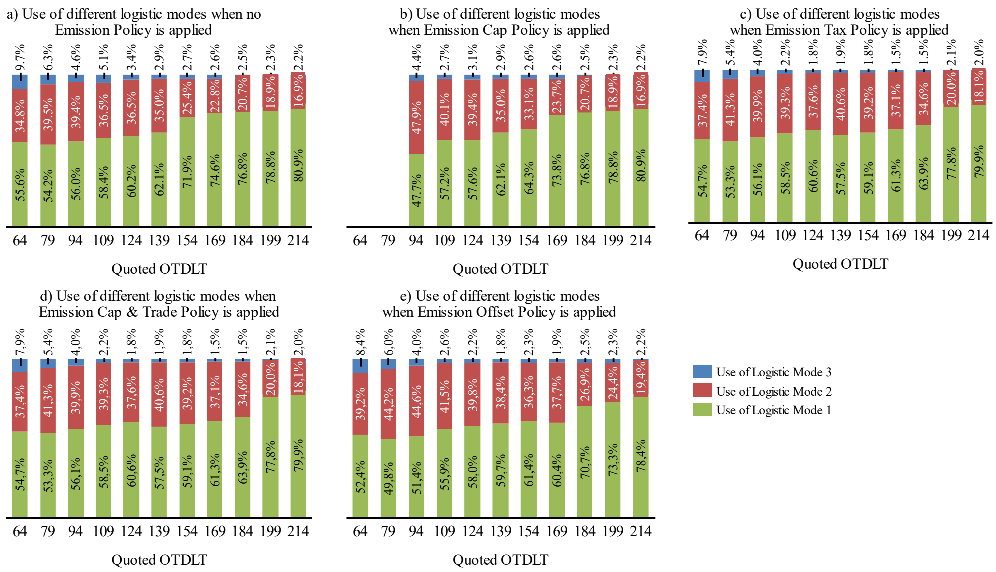

Figure 5.34: Comparison of used logistic modes with varying OTDLT

A similar effect is found by examining the average number of goods in stock, as illustrated in Fig. 5.36. At first, average stock levels decrease, but a substantial increase is noted when the number of suppliers and facilities drops. The emission offset policy tends to reduce stock levels the most. When quoting high OTDLT, stock levels are also strongly influenced by emission tax and the emission cap and trade policy. Both policies lead to the same results. The emission cap policy reduces the stock level strongly with a low quoted OTDLT; with increasing quoted OTDLTs, the results tend to approach those of solutions without an emission policy. Differences between the results without an emission policy and the various policy solutions appear greatest when location decisions differ the most.

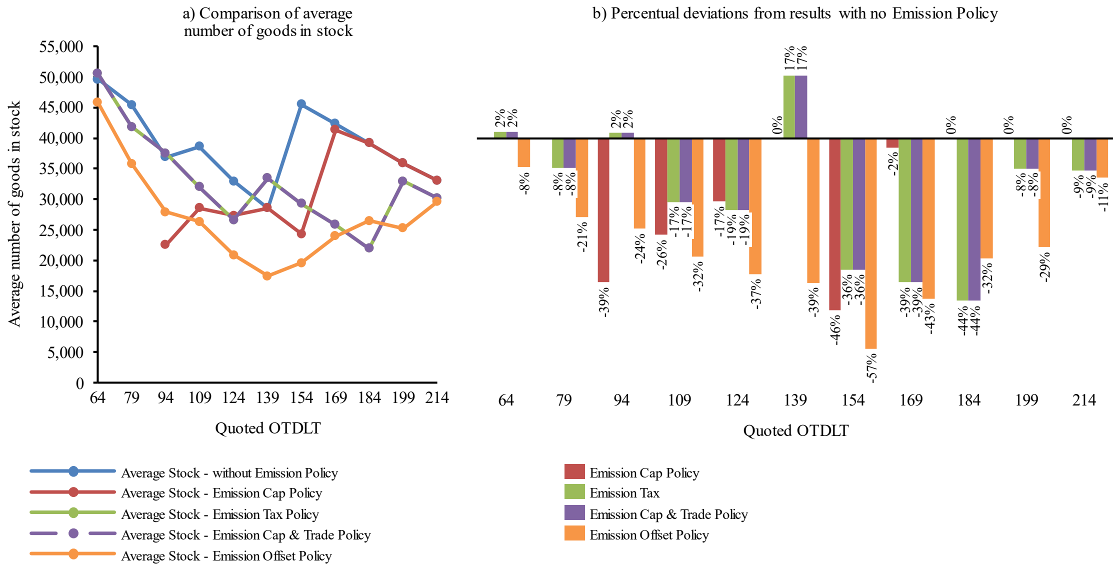

Figure 5.35: Comparison of average goods in stock and deviations from results without emission policy applied with varying OTDLT

5.5.3 Results with Varying Emission Cap

The quoted OTDLT is fixed at a value of 114, and the prices on emission (such as tax rate or emission credit price) are set to 75 monetary units to examine the results from varying emission caps. So that emission credit price fluctuations could be considered according to changes in the imposed emission cap, the emission credit price is calculated in the following form:

$$\Omega^{CAT} = 75 + (15000 - ECap) * 0.0075.$$

As shown in Fig. 5.36 a), the height of the imposed emission cap per period influences the total cost, dependent on the applied emission policy. When an emission cap policy is applied, no solution can be generated below an imposed cap of 16,500 emission units. The subsequent influence on total cost is relatively low, but total costs slightly decrease with a higher cap. With an emission offset policy, a higher imposed emission cap per period can greatly lower the total cost. With a cap of 16,500 emission units, the results approach those of the emission cap policy. Total costs decrease linearly under the emission cap and trade policy with a stable emission credit price. The more realistic view – a cap-dependent emission credit price – results in the highest total cost when the cap is low. This is explainable due to the higher price of emission credits when few credits are available. With an increasing emission cap, total cost first decreases, but this effect weakens with larger caps, and finally, for a cap higher than 21,000 emission units, the total cost increase.

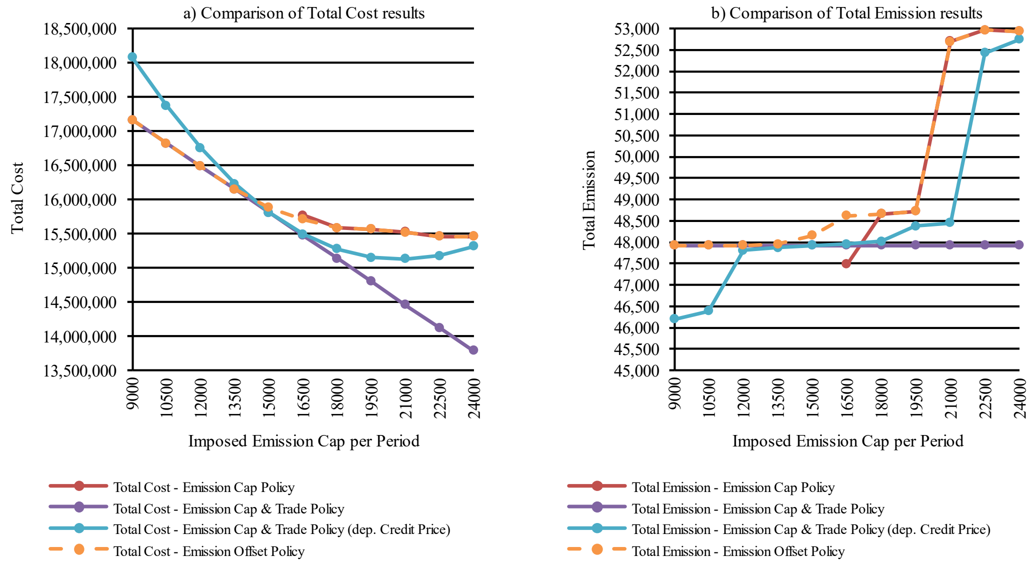

Figure 5.36: Comparison of total cost and total emission with varying emission caps per period

Total emission levels are unaffected in the case of the emission cap and trade policy with stable emission credit prices. When emission credit prices are dependent on the imposed cap, total emissions are initially low and increase with higher caps. Total emissions stabilize between a cap of 12,000 and 18,000 emission units and then increase slightly. Between 21,000 and 22,500 emission units the increase intensifies. When an emission cap policy is applied, the imposed cap of 16,500 emission units lowers the total emissions below the values for the cap and trade policy. Higher emission cap levels seem ineffective due to the increase in total emission. The emission offset policy first generates results comparable to the total emission in the case of emission cap and trade with stable credit prices. With a higher imposed emission cap, total emission increase and approach the results for the emission cap policy.

The development of total emissions with varying imposed caps per period also influences the total emission cost, as illustrated in Fig. 5.37. With higher caps, the spending on emission credits or allowances decreases. The emission cap and trade policy causes the highest cost on emission when prices depend on emission credits. Under an emission offset policy, spending on emission allowances is nil for an emission cap of 18,000. It seems likely that the incentive to further reduce emission amounts is thus weakened. The emission cap and trade policy generates – with or without dependent emission credit prices – additional income starting from a cap of 16,500 emission units. However, this regulation can generate additional income but offers some incentive to further reduce total emission, even with a high cap.

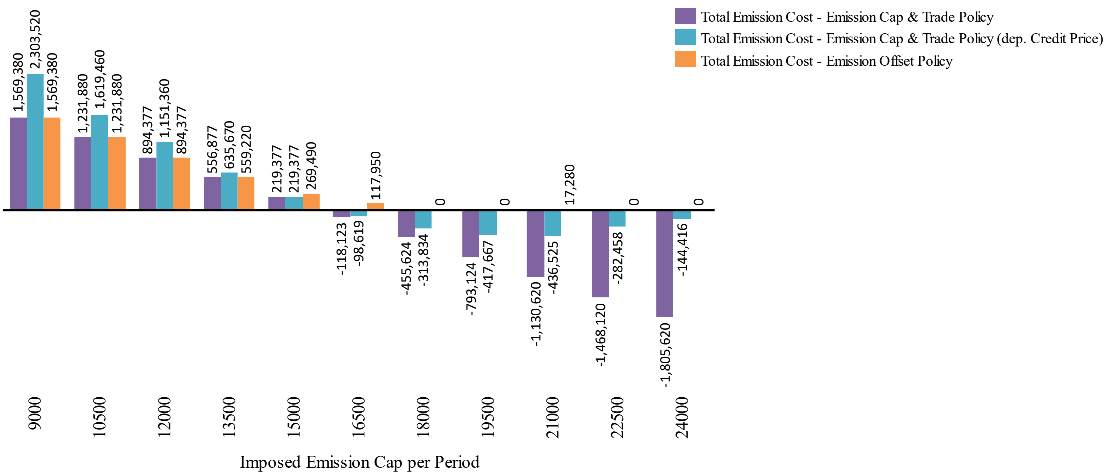

Figure 5.37: Comparison of total emission cost with varying imposed emission caps per period

The available supplier capacity and the number of selected suppliers are influenced by the height of the imposed cap per period, as illustrated in Fig. 5.38. When an emission cap policy is applied, the number of selected suppliers and the available supplier capacity decrease with an increasing cap. With the emission offset policy, five suppliers are contracted under a low emission cap. However, beginning from an imposed emission cap of 21,000 emission units, the number is reduced to four suppliers. Under the emission cap and trade policy with a stable credit price, the height of the cap does not influence the number of selected suppliers and the available capacity. When the price of emission credits depends on the imposed cap, six suppliers are contracted under a low emission cap. This number decreases to five with an imposed cap of 12,000 emission units, and with an imposed cap of 22,500 emission units, it further decreases to four suppliers.

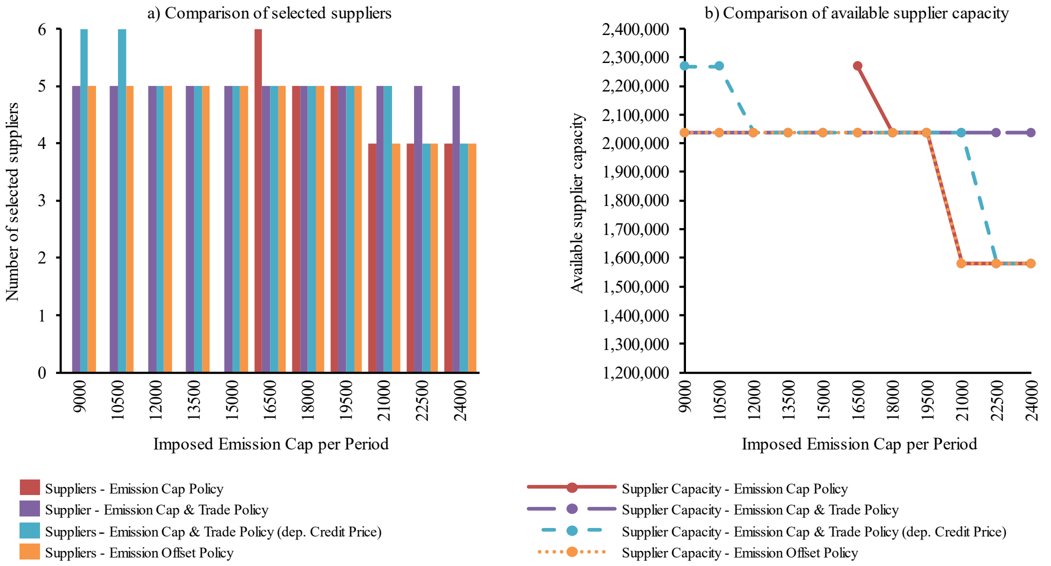

Figure 5.38: Comparison of number of selected suppliers and available supplier capacity with varying imposed emission cap

As shown in Fig. 5.39, varying emission cap values do not influence the selected production facilities, warehouses, or installed capacity options.

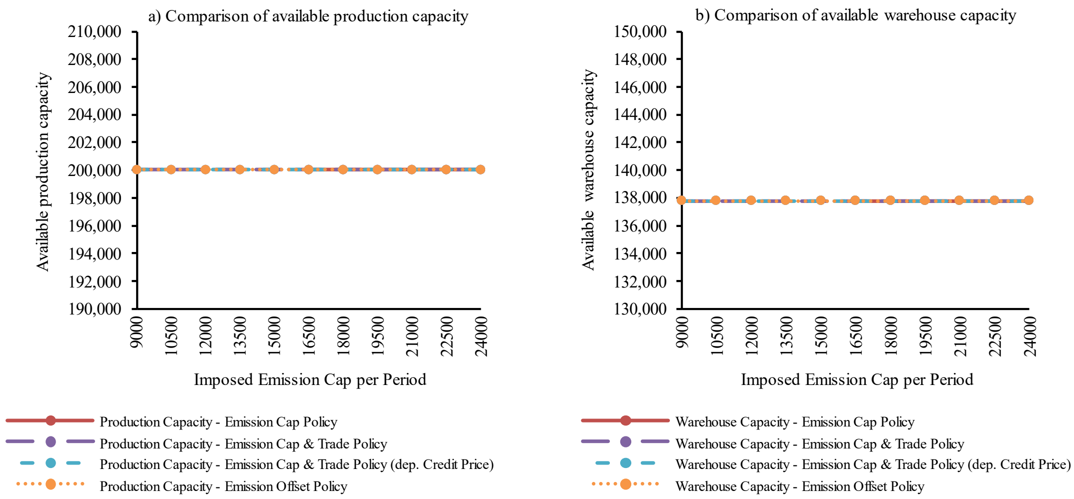

Figure 5.39: Comparison of established production facilities and warehouses with varying imposed emission cap

Changes in the use of logistic modes are observed with varying emission caps, as shown in Fig. 5.40. Under the emission cap and trade policy with stable emission credit price, the cap does not influence the share among different logistic modes.

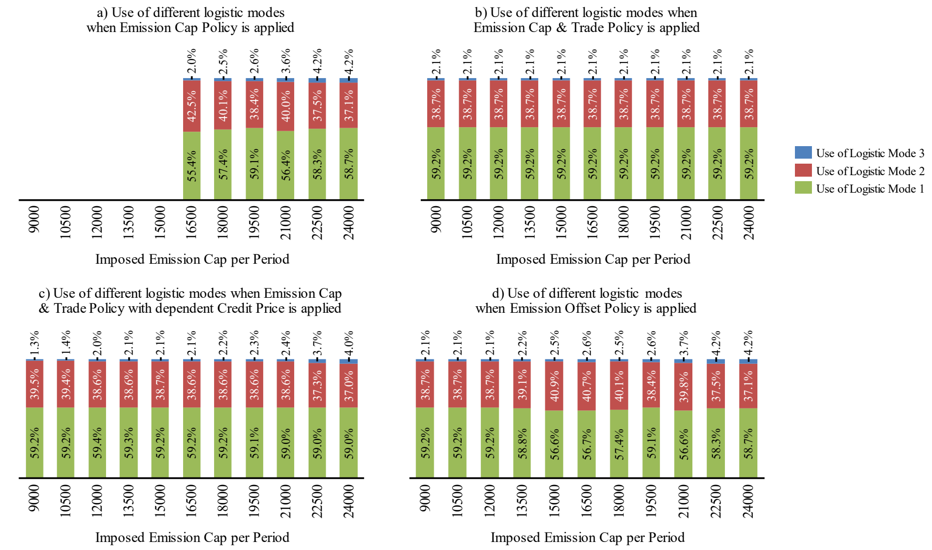

Figure 5.40: Comparison of used logistic modes under varying imposed emission cap per period

When emission credit price depends on the emission cap, the share of logistic mode 3 increases along with increases in the cap. Furthermore, the use of logistic mode 1 is slightly decreasing, and the share of logistic mode 2 is also reduced. For emission cap policy and emission offset policy, the share of logistic mode 3 increases with increasing emission caps. The shares of logistic mode 1 and 2 fluctuated slightly under both policies.

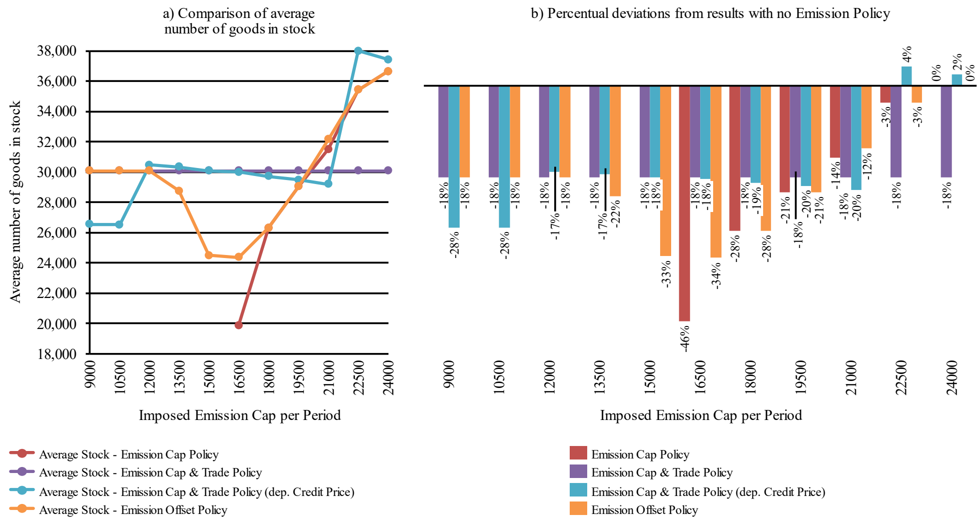

Figure 5.41: Comparison of average goods in stock and deviations from results for no emission policy, with varying imposed emission cap per period

The average number of goods in stock is influenced by the height of the imposed emission cap, as illustrated in Fig. 5.41. For the emission cap policy, the average stock levels increasing with higher caps. The emission cap and trade policy with stable emission credit price seems unaffected by the imposed cap, as no changes in stock levels are evident. When emission credit prices depend on the height of the emission cap, stock levels are stable at low cap values. With an emission cap of 12,000 emission units, average stock levels increase strongly and then decrease slightly. For a cap of 21,000 emission units per period, a significant increase in the average number of goods in stock can be observed, which decreases again as the cap increases. Under the emission offset scheme, stock levels are constant with a low cap; they then decrease starting at a cap of 12,000 emission units per period. From 16,500 emission units per period onwards, stock levels increase, and the results are nearly the same as those under the emission cap policy.

The results are similar to those reported by other researchers, such as BENJAAFAR AND DASKIN. This is especially true for emission cap and trade, both with and without dependent emission credit prices.[300]

5.5.4 Results with Varying Emission Price

The cap for the emission cap and trade policy and the emission offset policy is fixed at 15,000 emission units. Quoted OTDLT is set to 114 time units to examine the influences of emission price variations.

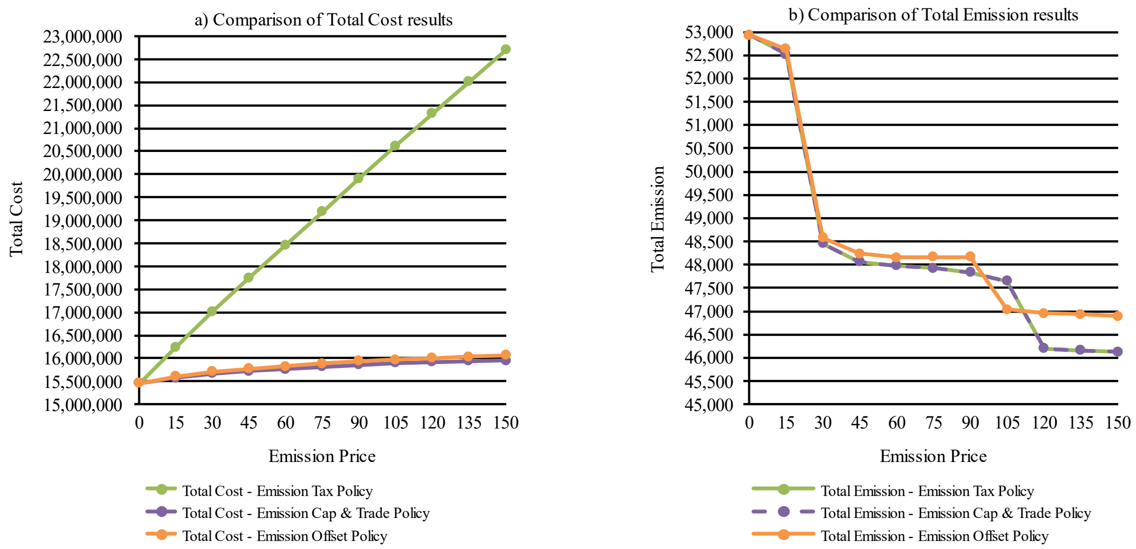

Figure 5.42: Comparison of total cost and total emission with varying emission price

With increasing emission prices, total costs also increase under each policy, as shown in Fig. 5.42. Under the emission tax policy, the increase in total cost is most substantial, with total cost rising steeply with higher tax rates. In comparison, under the emission cap and trade policy, total costs again increase with higher emission credit prices but notably less so. For emission offset policy with a low emission allowance price, total costs are

300 BENJAAFAR, S.; LI, Y.; DASKIN, M., 2013.

rather similar to that under the emission cap and trade policy. With increasing prices, the curves diverge and the emission offset policy causes a slightly higher cost.

For total emissions, under emission tax, and the emission cap and trade policy similar results can be observed. With a high tax rate or emission credit price, total emission constantly decreases. The highest decrease is observed for the price on emissions of 30 and 120 monetary units. Low prices for emission allowances generate only slightly higher results for total emission. With higher emission allowance prices, the gap increased for the total emission under the offset policy and tax versus the emission cap and trade policy. Only with an emission allowance price of 105 monetary units is a lower total emission value obtained.

The differences in total cost are strongly related to the cost of compensating emissions, as Fig. 5.43 shows. With higher tax rates, total emission costs increase significantly under the emission tax policy. At a tax rate of 15 monetary units, the total emission costs are higher than the costs of the other two emission policies for high emission prices. Under the emission cap and trade policy and emission offset policy, total emission costs vary between 100,000 and 300,000 monetary units. In most cases, the emission cap and trade policy seems to be less cost-intensive than the emission offset policy.

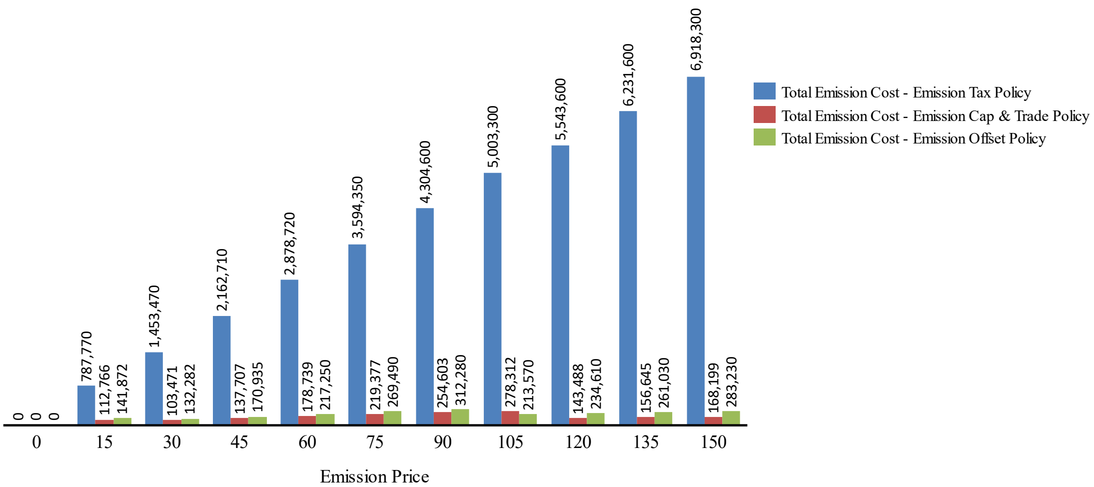

Figure 5.43: Comparison of total emission cost with varying emission price

The influence of emission prices on the number of selected suppliers and the available supplier capacity is illustrated in Fig. 5.44. With increasing emission prices, both the number of selected suppliers and the available supplier capacity increase. The rise in the number of contracted suppliers is associated with a substantial decrease in total emissions. Therefore, the number of suppliers may influence the total emission. Under all examined market-based policies, the results are similar for different applied emission prices. The exception is for a price of 105 emission units. At this point, under emission offset, six suppliers are contracted, whereas under the emission tax policy or the emission cap and trade policy, five suppliers are selected. As illustrated in Fig. 5.42, this is also the only point at which total emissions under the emission offset policy are lower than under the two other policies. This observation indicates that a higher number of suppliers can lead to lower total emissions.

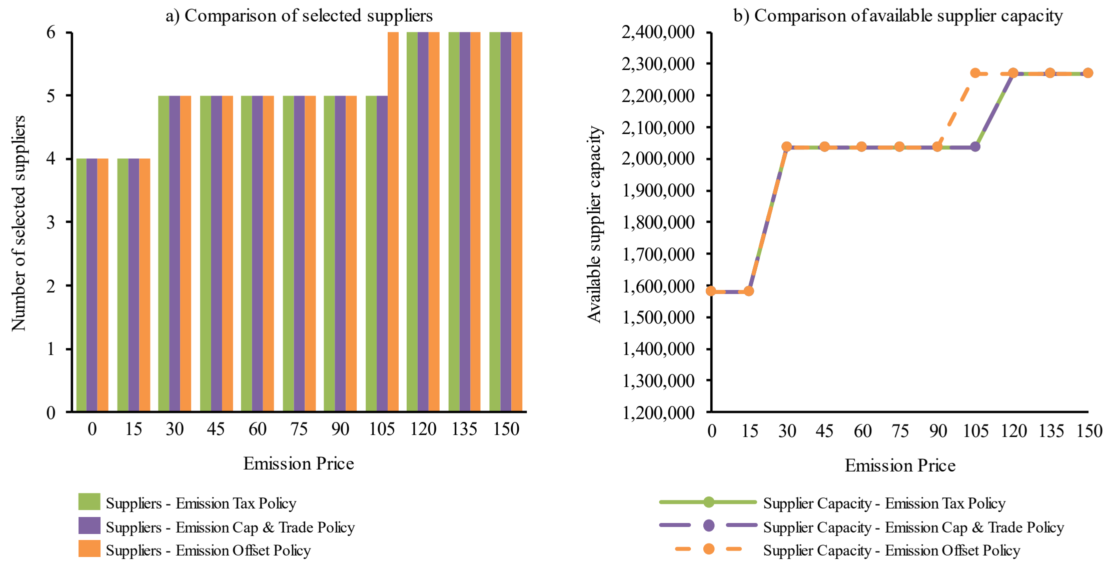

Figure 5.44: Comparison of number of selected suppliers and available supplier capacity with varying emission price

As shown in Fig. 5.45, the emission price does not influence the decision about production and warehouse capacity or the selection of these sites. It seems that quoted OTDLT mainly influences such decisions.

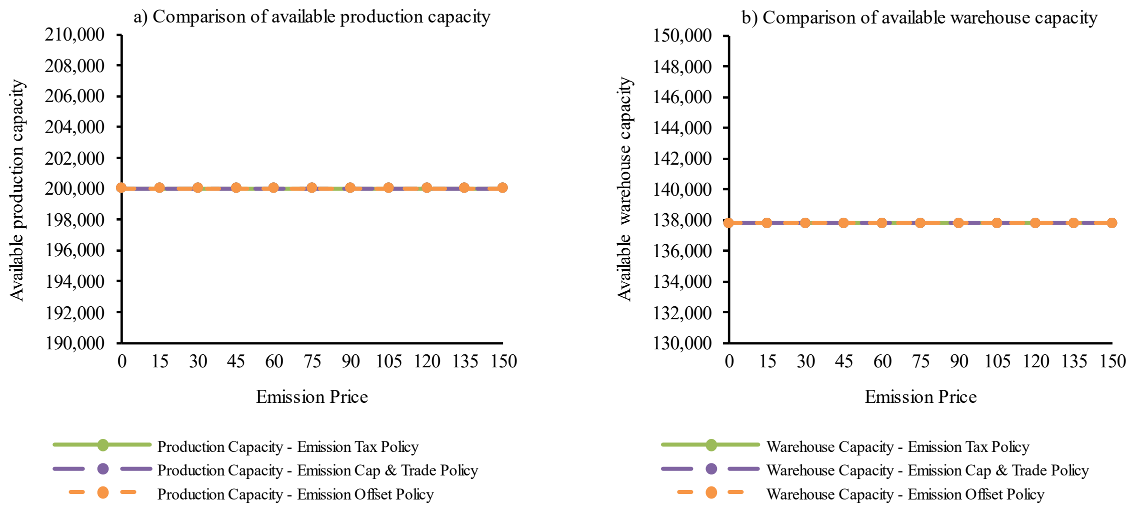

Figure 5.45: Comparison of established production facilities and warehouses with varying emission price

The share of various logistic modes used under the examined policies is illustrated in Fig. 5.46. The emission tax policy and emission cap and trade policy have the same influence on the share of used logistic modes. With higher emission prices, the share of logistic mode 3 decreases, whereas the shares of logistic modes 1 and 2 increase. Under the emission offset policy, the share of logistics mode 3 decreases but not as much as it does under the other policies. Furthermore, the use of logistic mode 1 decreases. Only the share of logistic mode 2 increases with higher prices of emission allowances. Regarding total emission, this finding partly explains the gap between emission offset and the other policies, especially when emission prices are high.

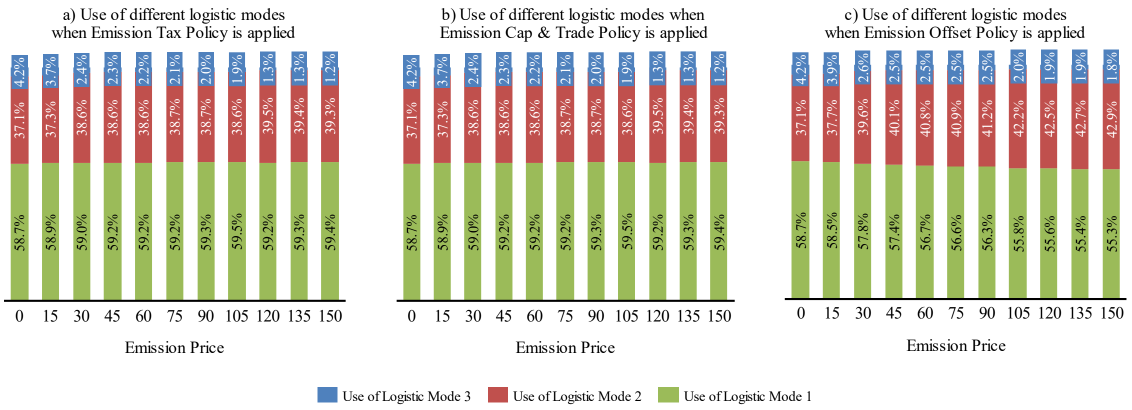

Figure 5.46: Comparison of used logistic modes with varying emission price

The average number of goods in stock under varying emission prices are the same for emission tax and the emission cap and trade policy, as illustrated in Fig. 5.47. Stock levels increase slightly, but substantial decreases are observed at two points, namely emission prices of 30 and 120. The decreases reflect the decrease in total emissions and the increased number of contracted suppliers at these prices. Under emission offset, the decrease in stock levels is more pronounced, and no overall increase is observed. Compared to the results without emission policies, price-based policies tend to reduce stock levels. The highest decreases are observed with the emission offset policy. This decrease seems to be accompanied by an increase in the share of logistic mode 2.

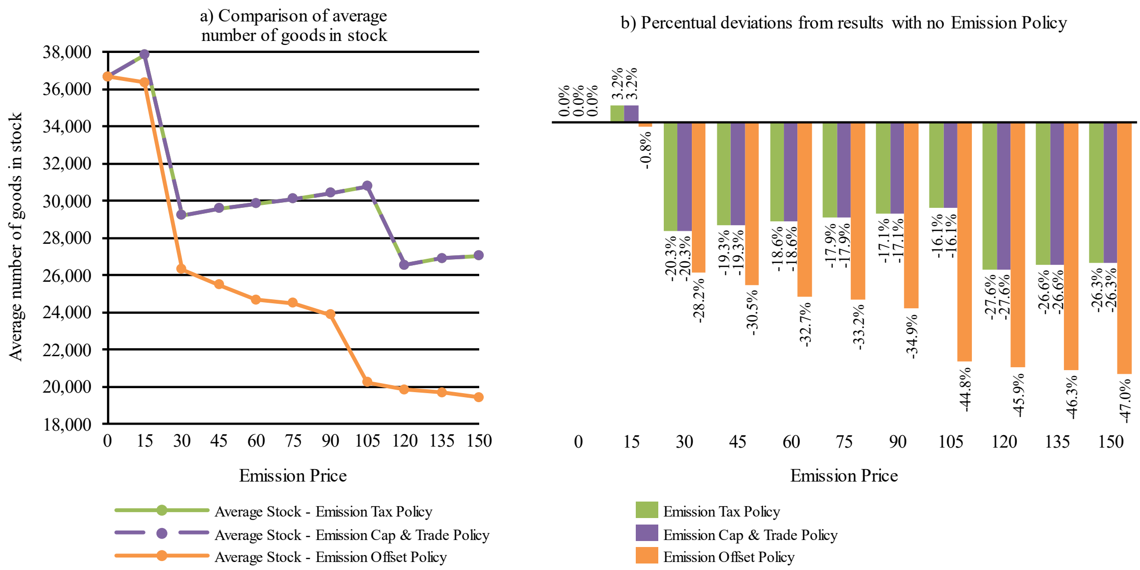

Figure 5.47: Comparison of average goods in stock and deviations from results without emission policy with varying emission price

5.5.5 Conclusion

In conclusion, the analyses showed that quoted OTDLT has a significant influence on total cost and total emission, as illustrated in Fig. 5.48. Total cost and total emission generally decrease with a higher quoted OTDLT.

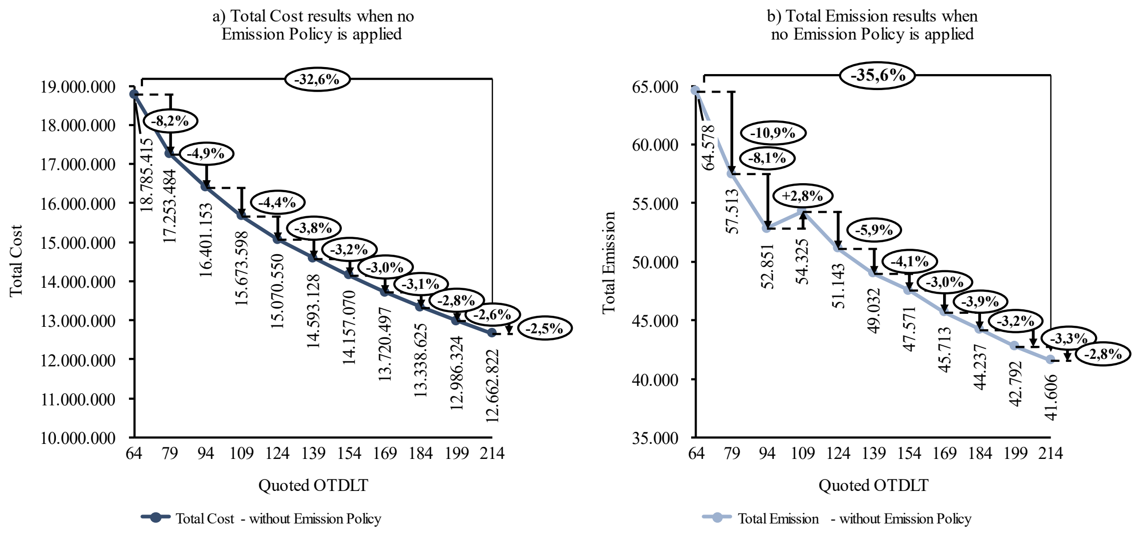

Figure 5.48: Development of total cost and total emission with varying OTDLT

However, this effect becomes smaller the higher the guaranteed OTDLT is. An increased total emission with a quoted OTDLT of 109 time units is associated with a decreased number of contracted suppliers. This finding indicates that having more contracted suppliers may positively impact the total emission because of smaller distances to production facilities and parallel purchasing by different, more environmentally friendly but more costly suppliers.

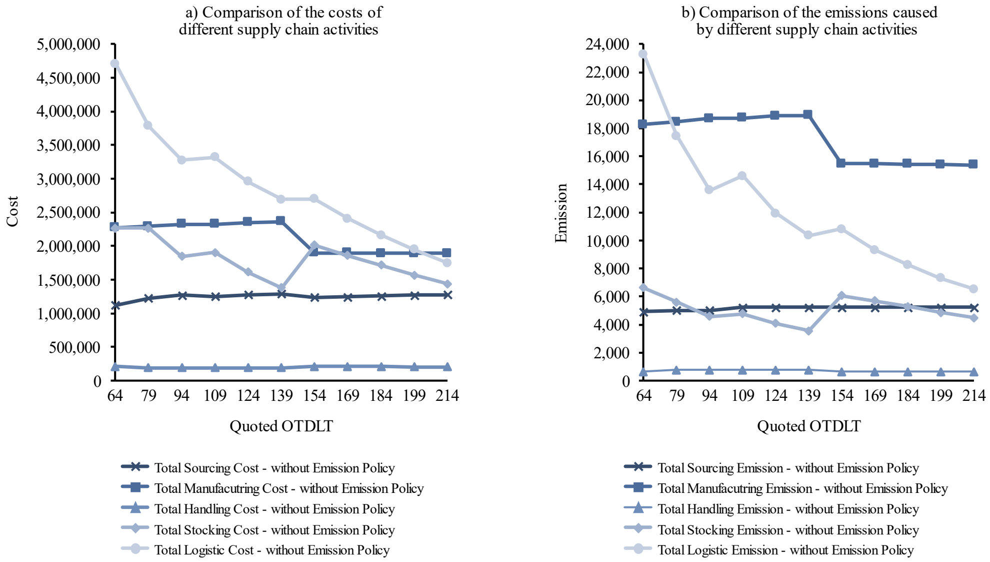

Figure 5.49: Comparison of total cost and total emission of different supply chain activities with varying OTDLT

Fig. 5.49 shows the influence of quoted OTDLT on different activities in the supply chain and the effects on cost and generated emissions. It is evident that handling cost and emissions, and sourcing cost and emissions, are largely unaffected by variations in quoted OTDLT. Manufacturing cost and emissions are reduced when the quoted OTDLT is higher than 139 time units. The most affected activities are stock and transportation. With longer quoted OTDLT, emissions and costs caused by transportation activities are reduced significantly. Emissions and costs of stock-related activities fluctuate vastly. Stock activities seem to be able to compensate for reductions in other activities in order to sustain the quoted OTDLT.

The quoted OTDLT influences the location decisions and the connections between each node of the network; an example appears in Fig. 5.50. With lower quoted OTDLT, additional capacity at the supplier and in production levels help to achieve those requirements. With higher quoted OTDLT, reducing the number of suppliers and production facilities that provide small quantities can reduce the total cost. Interestingly, all four warehouses are selected only with very low quoted OTDLT. With an OTDLT between 79 and 139 time units, only three warehouses are established. With higher quoted OTDLT, it seems beneficial to select all available warehouses to gain additional stocking capacity.

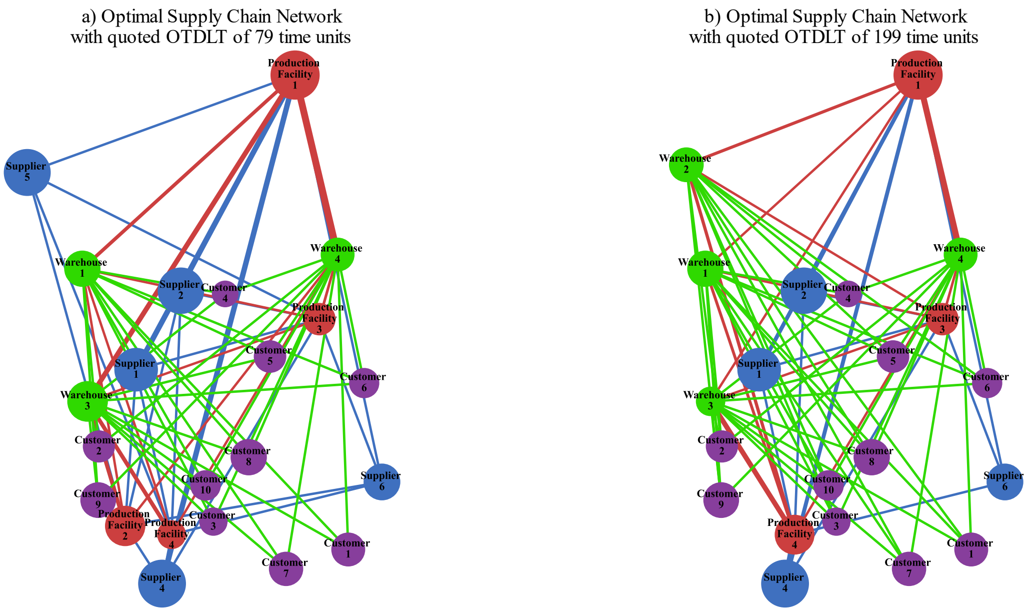

Figure 5.50: Optimal supply chain network configuration

The influence of various emission policies on total costs and total emissions are illustrated in Fig. 5.51. The emission cap policy can be prohibitive to realize a low quoted OTDLT. The rigid regulation has the disadvantage of incurring a significant effect on total emissions only for certain quoted OTDLTs. With higher quoted OTDLT, the effect on total emission vanishes, and effects on total cost are relatively low because no further cost on emission is applied. The emission tax and emission cap and trade policies generally display the most substantial influence on total emission and could achieve reductions of more than 10%. However, the emission tax policy also significantly influences total costs. Under this regulation, total costs increase by more than 23% in every observed case. In contrast, the emission cap and trade policy has a moderate effect on total cost, and under high quoted OTDLT, additional revenues could be made from selling excess credits.

The above observation is only valid if the market mechanism provides stable emission credit prices. The system has to be well defined to guarantee similar emission reduction efforts to those under the emission tax policy. An emission offset policy can also reduce total emissions, but the effect weakens with higher quoted OTDLT. In addition, the influence on total cost is moderate. In the case of no governmental regulation, this scheme can lead to more conscious action by companies if well designed. When poorly designed, it may be an example of “greenwashing”.

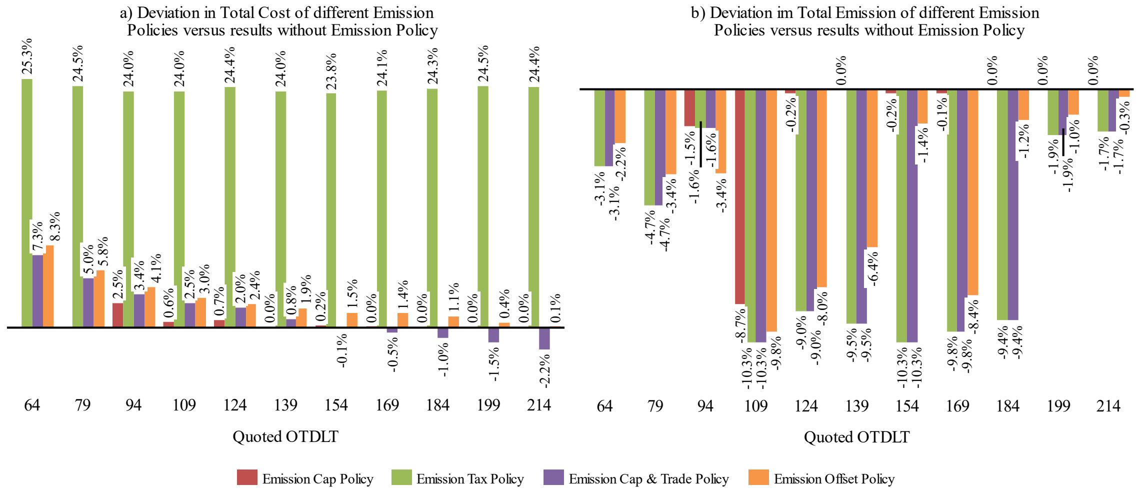

Figure 5.51: Percentual deviations in total cost and total emission results in comparison to results without emission policy (varying OTDLT)

Deviations in total costs and total emissions with varying emission caps, compared with the results for no applied emission policy, are illustrated in Fig. 5.52. With a low emission cap, no results can be produced for the emission cap policy. Therefore, it is evident that the strict command and control policy can be prohibitive for some quoted OTDLTs. With a higher cap, this policy loses its effect, and no further reduction can be achieved. However, when the emission cap is appropriately set, reduction efforts can be realized without a strong influence on total costs. Emission offset works well when the imposed emission cap is low. The generated results are similar to those for emission cap and trade under stable emission credit prices, when the cap is low. With an increasing cap, the offset policy loses its incentive for further emission reduction – similarly to the emission cap policy. Emission cap and trade with stable credit prices have a moderate effect on total cost when the imposed cap is low. With a higher cap, additional income can be generated from selling excess credits. With this policy, total emission can be reduced by about 9.5%, in the given example. With a low emission cap and cap-dependent credit prices, emission reduction efforts can be forced. Nevertheless, with a higher cap, the disadvantage of such systems is evidently the weak incentive to reduce emissions due to the low emission credit price.

No fixed emissions generated by suppliers themselves are considered in the models, but for contracting suppliers, fixed costs arise. Therefore, contracting more suppliers does not influence the emissions summarized under “Facilities,” but it influences the resulting cost. The influences on the cost of other activities are relatively low. Therefore, a large part of the differences in total cost can be deducted from the total emission cost caused by market-based emission policies. As shown in Fig. 5.52 b), an insufficient set cap in the case of an emission cap policy can lower the incentive to reduce emission amounts. Market-based emission policies seem to lead to better results in lowering total emissions and increasing the incentive to lower emission amounts in various supply chain activities.

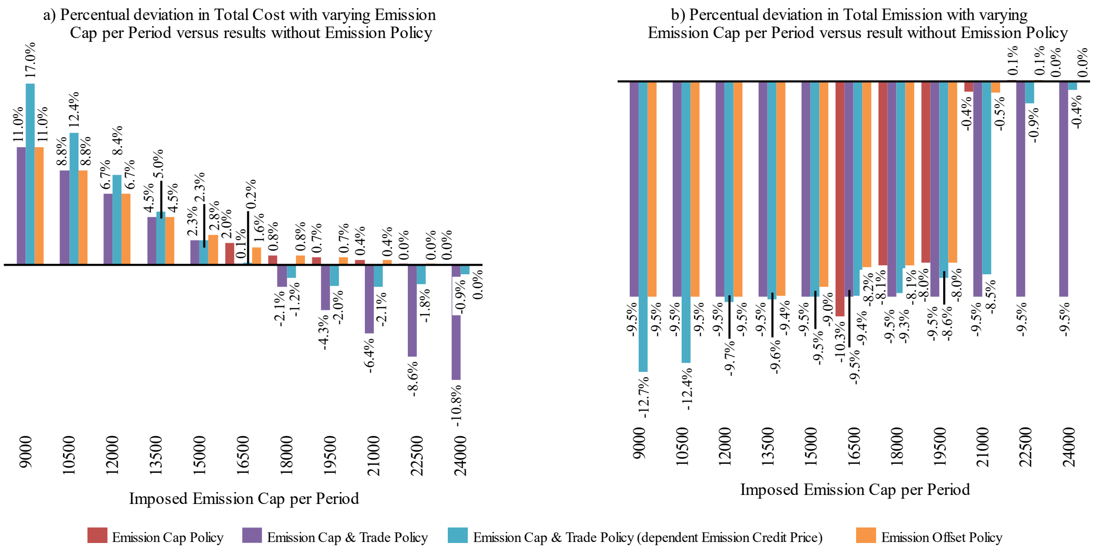

Figure 5.52: Percentual deviations in total cost and total emission results in comparison to results without emission policy (varying imposed emission cap per period)

In the given example, manufacturing is a high-emission activity, but insufficient reductions are achieved because no technology choice for production is considered. Using a low-emission technology, if available, manufacturing could be a source of further emission reduction.

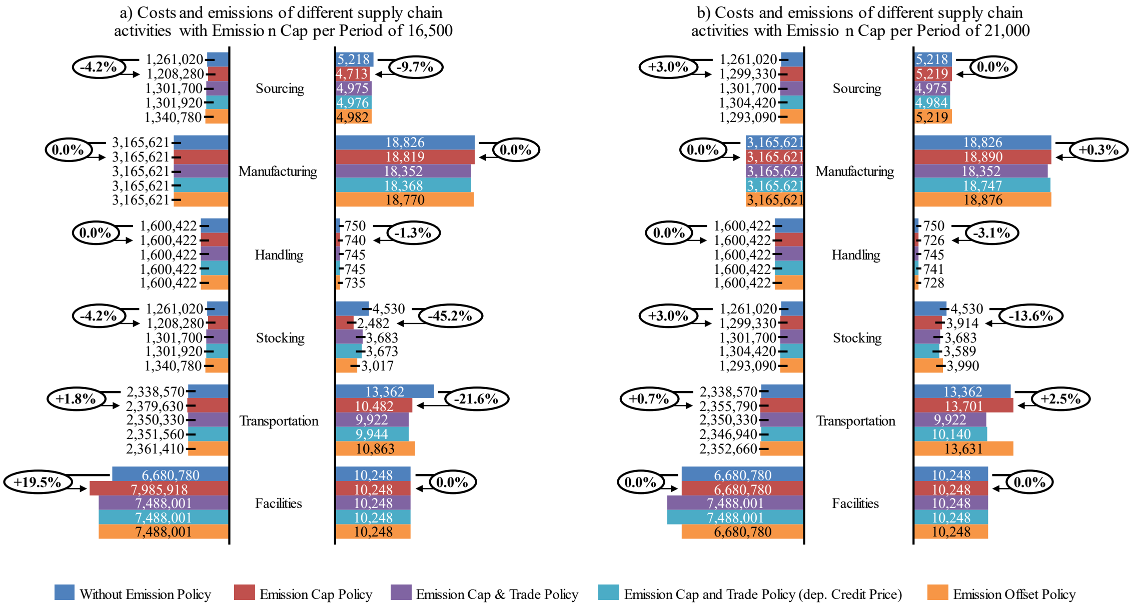

Figure 5.53: Cost and generated emission from different supply chain activities with different imposed emission caps per period

However, sourcing, stocking, and transportation activities are identified as potential areas for reducing emissions. Emission reductions in sourcing activities include contracting more suppliers, probably those who are low-emission.

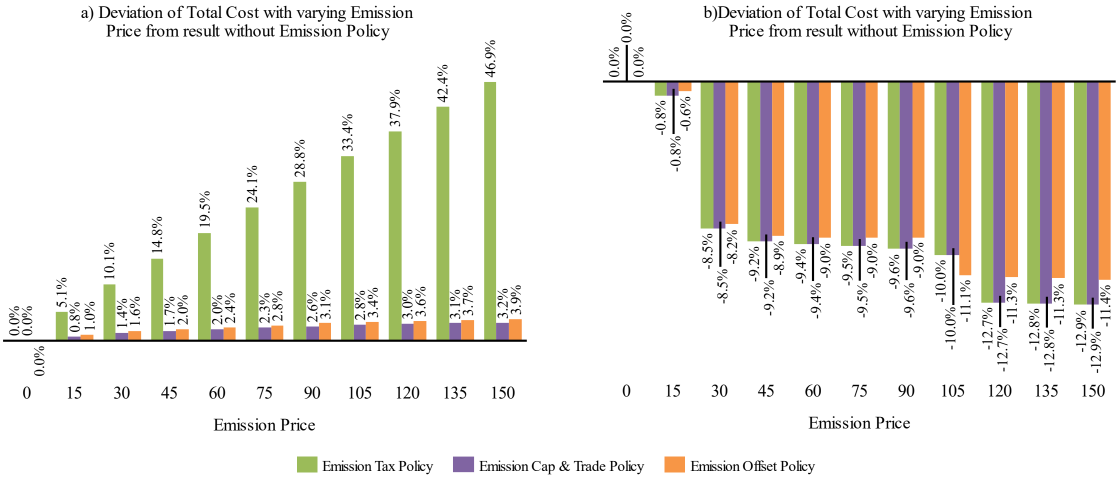

Figure 5.54: Percentual deviations of total cost and total emission results in comparison to results without emission policy (varying emission price)

The importance of the emission price is illustrated in Fig. 5.54. Emission tax and emission cap and trade policies have the strongest influence on total emission and force the reduction of total emission at high emission prices. However, in the case of emission tax policy, the cost increase is significant, whereas emission cap and trade policy has little influence on total costs. As shown before, the effects of emission cap and trade highly depend on the market mechanism's design and the given equipment of emission credits. Emission offset policy leads to slightly worse results regarding total emission but has little influence on total costs. This system also depends strongly on the imposed emission cap. However, if companies use such mechanisms properly to offset their emissions, it can lead to appropriate reduction efforts.

Fig. 5.55 illustrates the effects of emission prices of 30 and 120 monetary units on different supply chain activities. The figure indicates the sources of the differences in total costs and total emissions. Furthermore, the percentual deviations between results without emission policies or an emission tax policy are highlighted. In general, the importance of the emission price is clear because the incentive for emission reduction is increased with higher prices. The drivers of emission reductions, in the given example, are sourcing, stock-related, and transportation activities. Sourcing activities are highly connected to the number of contracted suppliers.

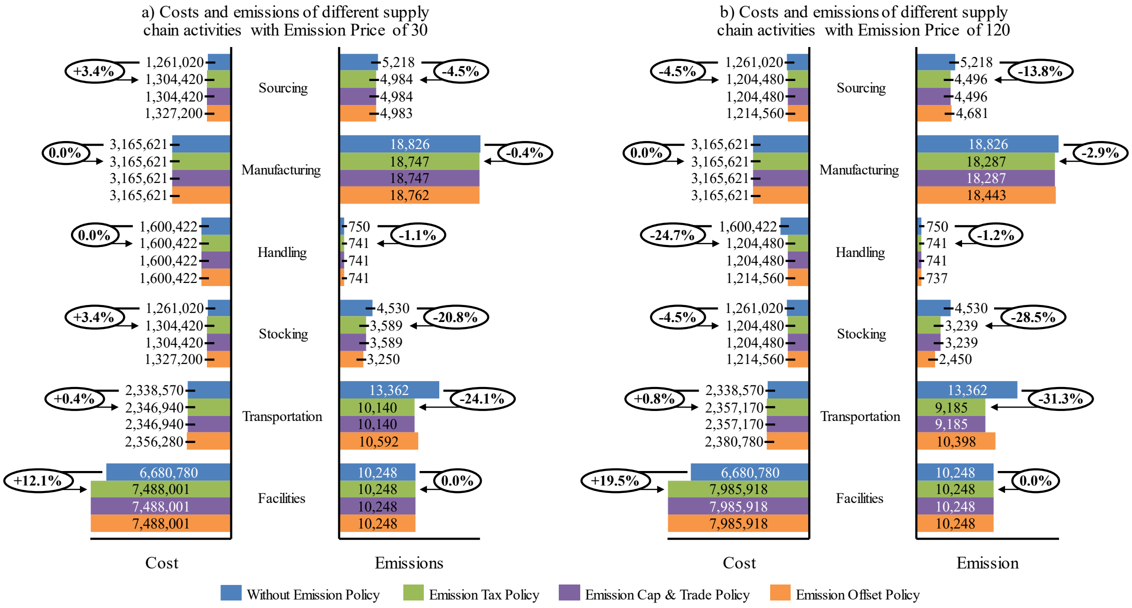

Figure 5.55: Cost and generated emission from different supply chain activities with different emission price

With a decrease in emissions caused by sourcing activities, the cost for contracting suppliers increases. Under the market-based emission policies, slight reductions in emissions from manufacturing are also observed. However, by using other technologies, these effects would probably increase. Handling activities are, in the case of emissions, generally negligible and can be a source of emission reduction. The decrease in cost for handling goods in warehouses is explainable by lower stocks and therefore less handling during certain costly periods. Stock and transportation activities are the most important sources of emission reduction in the given example. However, with lower emissions, the cost increase is relatively low for transportation; regarding stock, the costs may even decrease. Therefore, total costs are influenced mainly by supplier contracting costs and costs caused by the emission policies.

Depending on the assumptions and the exemplary data provided, the following conclusions can be drawn:

- Quoted OTDLT has a significant influence on total cost and total emission. Therefore, including OTDLT into strategic planning can be useful for economic and ecological reasons.
- The number of selected suppliers influences the achievable quoted OTDLT. A multi-sourcing strategy can be beneficial to reduce OTDLT.

- Other location decisions are generally not affected by applied emission policies. However, a higher number of production facilities and warehouses can be necessary in order to quote lower OTDLT.
- Total cost is most affected by costs caused by emission policies and supplier selection. Other activities have a relatively low impact on total costs.
- An emission cap policy may be prohibitive to achieve low lead times. It also has limited influence on emission reduction efforts. It is necessary to find an appropriate emission cap that allows companies to achieve low OTDLT but is not too low so that the regulation has no influence.
- Emission offset may be an effective regulation for companies when no governmental regulation is in place. When such systems are implemented, reduction efforts can be strengthened, and total costs are affected only marginally.
- Best results in case of emission reduction can be attained with either emission tax or the emission cap and trade policy. These policies are also robust to changes in quoted lead time and always lead to emission reduction efforts.
- Emission tax policy can increase total costs significantly, which can be problematic for intense emission industries. This may also be the reason why industry often advocates for market mechanisms like the emission cap and trade policy.
- The emission cap and trade policy gives companies great flexibility to cope with regulations and seems appropriate for intense emission industries. The examined disadvantage of this regulation is the design problem. When such policies are not designed appropriately, the effects on total emission are relatively weak. In contrast, emission tax policy always ensures emission reduction efforts according to the given tax rate.
- Under the given assumptions, fixed production and warehousing technologies as well as sourcing, stocking, and transportation activities can be the most valuable sources for emission reduction.
- Lower emissions from sourcing activities correlate with a higher number of selected suppliers but only slightly affect the cost from sourcing activities. Therefore, multiple sourcing and including green suppliers can be a strategy to reduce emissions from these activities.

6 Supply Chain Design Considering Order-to-Delivery Lead Time Sensitive Customers and Various Emission Policies

6.1 Relevance and Assumptions

Fast cycle capabilities are essential factors in business success today. Such capabilities enable firms to make decisions faster, develop new products faster, and serve customer orders sooner, thereby providing unique value in the markets these firms serve.[301] Customers' concern is primarily how long it takes to receive an ordered product. Their expectation of a suitable time when an order must be delivered is strongly influenced by the service and the OTDLT that competitors offer. These expectations can be termed "customer tolerance levels," which indicate the lower boundaries of what customers see as good service.[302] Furthermore, with the increasing substitutability of products, customer tolerance levels become important.[303] In addition, longer lead times for production or procurement can reduce responsiveness to customer requirements. Customers are (after the price and quality of goods) often sensitive to OTDLT.[304] The expectations of customers have changed over time. In the 1980s, product quality and price were the determining and crucial factors, whereas in the 1990s, customers started to value service – including OTDLT – over price. Furthermore, most customers are willing to pay a reasonable price for products with added value due to better service.[305] To gain a competitive advantage, a company must offer high-quality products and high-quality service. Therefore, by reducing lead time and achieving faster delivery, a company can enhance its competitiveness.[306] In the supply chain context, delivery speed and reliability have become essential requirements for differentiation and are enablers for increased profit.[307]

In many supply chain design models, customer demand is seen as an independent parameter. Therefore, decisions about the structure of the supply chain do not influence customers' demands. Due to the competitive business environment and globalization, this assumption is not always accurate. Sensitive customer demand has been investigated for

[301] BOWER, J. L.; HOUT, T. M., 1988, p. 1.
[302] DAUGHERTY, P. J.; PITTMAN, P. H., 1995, p. 55.
[303] DAUGHERTY, P. J.; PITTMAN, P. H., 1995, p. 56.
[304] YANG, B.; GEUNES, J., 2007, p. 439.
[305] SHYCON, H. N., 1992, p. 13.
[306] ARNHEITER, E. D.; MALEYEFF, J., 2005, p. 14.
[307] CHAN, F. T. S. ET AL., 2002, p. 119.

prices[308] and emissions.[309] When OTDLT-sensitive customers are considered, most researchers use grouping methods to shorten lead times from warehouses to customers.[310] CHRISTOPHER[311] states that with shorter product life-cycles, procurement-to-delivery lead times play an essential role and total lead times have to be considered. Furthermore, the literature suggests that similarly to prices, lower OTDLT can also increase customer demand.[312] In addition, several studies mention that with shorter OTDLT, customers are willing to pay a price premium.[313] Furthermore, OTDLT is widely accepted as a critical measure for service quality due to its significant effects on customers' demand and loyalty and customers' channel choice.[314] BANKER, KOHSLA AND SINHA propose a linear demand function in case of sensitivity to quality.[315] According to the literature, customer demand can depend on lead time and service quality, which OTDLT partly reflects. Therefore, in this section, customer demand is assumed to be OTDLT-sensitive, which means shorter OTDLT results in higher demand and vice versa. To cover this assumption, a piecewise linear function to describe customers' demand is proposed. Furthermore, the model is based on the following assumptions:

- The proposed model is a discrete deterministic model with a finite number of potential suppliers, manufacturing sites, warehouses, and planning periods.
- There is a fixed number of customer regions.
- Suppliers have a fixed capacity for every raw material they provide.
- The planning horizon covers several strategic planning periods.
- Three logistic modes are available, and full truck loads are assumed for each transportation process. Logistic modes differ in cost, speed, and generated emissions. Logistic mode 1 offers low cost, emissions, and speed, whereas logistic mode 3 offers high cost, emission, and speed. Logistic mode 2 is characterized by medium cost, emissions, and speed.
- Capacities of suppliers are restricted.

[308] See e.g. KEYVANSHOKOOH, E. ET AL., 2013; FATTAHI, M.; GOVINDAN, K., 2017; FATTAHI, M.; MAHOOTCHI, M.; MOATTAR HUSSEINI, S. M., 2016.
[309] See e.g. NOUIRA, I. ET AL., 2016; ALTMANN, M., 2015.
[310] See CHEONG, M. L. F.; BHATNAGAR, R.; GRAVES, S. C., 2005; FATTAHI, M.; GOVINDAN, K.; KEYVANSHOKOOH, E., 2017; CORREIA, I.; MELO, T., 2016.
[311] Cf. CHRISTOPHER, M., 1986, p. 66.
[312] Cf. SO, K. C.; SONG, J.-S., 1998, p. 40f; SO, K. C., 2000, p. 403.
[313] WENG, Z. K., 1996, p. 263; XIAO, T.; JIN, J., 2011, p. 263; RAY, S.; JEWKES, E. M., 2004, p. 778.
[314] HUA, G.; WANG, S.; CHENG, T. C. E., 2010, p. 114.
[315] BANKER, R. D.; KHOSLA, I.; SINHA, K. K., 1998, p. 1182.

- Capacities of production facilities and warehouses are restricted to the chosen capacity option.
- The same quality of production and handling processes is assumed at all suppliers, production facilities, and warehouses.
- Due to the fact there are no stocks available in the first period, customers' acceptance for longer OTDLT in period one is higher than in the following periods.
- Demand linearly decreases, from the maximum amount of demand for each customer increasing OTDLT. If the least acceptable OTDLT cannot be met, customer demand is nil.
- Customers have different acceptance levels for maximum and minimum OTDLT.
- Emission policy parameters such as the emission cap, tax rate, or emission allowance price do not vary over time.

6.2 Lead Time-sensitive Customer Demand

It is assumed that the total demand of a customer depends on the time it takes to fulfill that demand. OTDLT is calculated in the same way as in Chapter 5, and the demand function of a customer can be described by function (6.1).

$$D(DLT) = \begin{cases} D^{Max}, \ if \ OTD \leq LT^{MIN} \\ \frac{LT^{Max}D^{Max} - LT^{Min}D^{Min}}{LT^{Max} - LT^{Min}} - \frac{D^{Max} - D^{Min}}{LT^{Max} - LT^{Min}} OTD, \ if \ LT^{Min} \leq OTD \leq LT^{Max} \\ D^{Min}, \ if \ OTD \geq LT^{Max} \end{cases}$$

The piecewise linear[316] function is shown in Fig. 6.1 as an example.

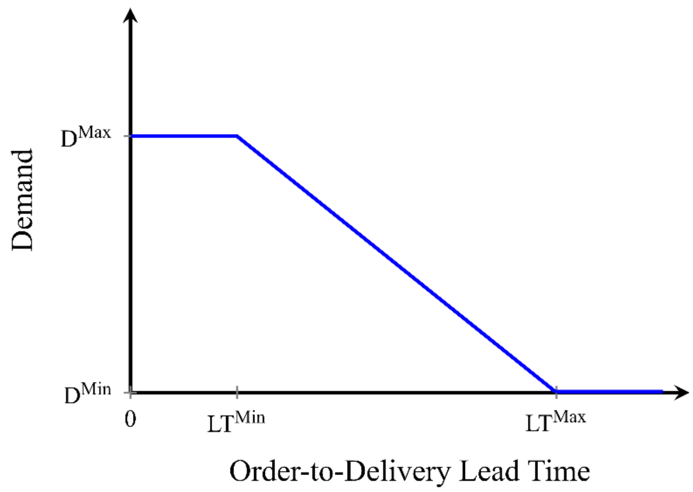

Figure 6.1: Exemplary representation of an OTDLT-sensitive demand function

[316] CHEN, D.-S.; BATSON, R. G.; DANG, Y., 2010, p. 60f.

Piecewise linear functions commonly describe sensitive customer demand, as in (among others) NOUIRA ET AL. and KRASS, NEDOREZOV AND OVCHINNIKOV.[317]

As both the figure and the formula show, the demand function $D(DLT)$ is not linear within its domain $[0, +\infty[$. In order to solve the model to optimality with an exact method, the function must be linearized. For linearization purposes, new binary variables are introduced:

a_{cpt}	1 if $OTD_{cpt} \leq LT_{cpt}^{Min}$, 0 else
b_{cpt}	1 if $LT_{cpt}^{Min} \leq OTD_{cpt} \leq LT_{cpt}^{Max}$, 0 else
c_{cpt}	1 if $OTD_{cpt} \geq LT_{cpt}^{Max}$, 0 else

In order to linearize the demand function, the bounds of these binary variables must be defined. To ensure these bounds are strictly linear, the BigM method[318] is applied, where parameter Φ is defined as a sufficiently large number:

$$\Phi(a_{cpt} - 1) \leq LT_{cpt}^{Min} - OTD_{cpt} \qquad \forall c \in C, p \in P, t \in T$$
$$\Phi\, a_{cpt} > LT_{cpt}^{Min} - OTD_{cpt} \qquad \forall c \in C, p \in P, t \in T$$
$$\Phi(c_{cpt} - 1) \leq OTD_{cpt} - LT_{cpt}^{Max} \qquad \forall c \in C, p \in P, t \in T$$
$$\Phi\, c_{cpt} > OTD_{cpt} - LT_{cpt}^{Max} \qquad \forall c \in C, p \in P, t \in T$$
$$a_{cpt} + b_{cpt} + c_{cpt} = 1 \qquad \forall c \in C, p \in P, t \in T$$

The first and second constraints ensure that a_{cpt} equals 1 if $OTD_{cpt} \leq LT_{cpt}^{Min}$. Then the third and fourth constraints guarantee that variable $c_{cpt} = 1$ if $OTD_{cpt} \geq LT_{cpt}^{Max}$, and finally, the fifth constraint ensures that b_{cpt} takes the value 1 if $LT_{cpt}^{Min} \leq OTD_{cpt} \leq LT_{cpt}^{Max}$.

With the help of these constraints, the demand function $D_{cpt}(OTD_{cpt})$ can be reformulated to:

$$D_{cpt} = D_{cpt}^{Max} a_{cpt} + \left(\frac{LT_{cpt}^{Max} D_{cpt}^{Max} - LT_{cpt}^{Min} D_{cpt}^{Min}}{LT_{cpt}^{Max} - LT_{cpt}^{Min}} - \frac{D_{cpt}^{Max} - D_{cpt}^{Min}}{LT_{cpt}^{Max} - LT_{cpt}^{Min}} OTD_{cpt} \right) b_{cpt} + D_{cpt}^{Min} c_{cpt}$$

Despite the reformulation, the function is still nonlinear due to the multiplication of variables OTD_{cpt} and b_{cpt}. Nevertheless, this type of nonlinearity can be linearized by adding constraints to the model. For linearization purposes, a new variable is introduced:

$$lt_{cpt} = OTD_{cpt} b_{cpt}$$

[317] NOUIRA, I. ET AL., 2016; KRASS, D.; NEDOREZOV, T.; OVCHINNIKOV, A., 2013.
[318] Cf. GRIVA, I.; NASH, S. G.; SOFER, A., 2009, p. 156f.

To ensure that lt_{cpt} is calculated linearly, the following constraints are needed:

$$lt_{cpt} \leq \Phi b_{cpt} \qquad \forall c \in C, p \in P, t \in T$$

$$lt_{cpt} \geq \Phi(b_{cpt} - 1) + OTD_{cpt} \qquad \forall c \in C, p \in P, t \in T$$

$$lt_{cpt} \leq OTD_{cpt} \qquad \forall c \in C, p \in P, t \in T$$

Then the demand function can be linearized in the following form:

$$D_{cpt} = D_{cpt}^{Max} a_{cpt} + \left(\frac{LT_{cpt}^{Max} D_{cpt}^{Max} - LT_{cpt}^{Min} D_{cpt}^{Min}}{LT_{cpt}^{Max} - LT_{cpt}^{Min}} b_{cpt} - \frac{D_{cpt}^{Max} - D_{cpt}^{Min}}{LT_{cpt}^{Max} - LT_{cpt}^{Min}} lt_{cpt} \right) + D_{cpt}^{Min} c_{cpt}$$

6.3 Model Development

6.3.1 Model with no Emission Policy

Objective (6.1) maximizes the profit over all periods t. Total revenue is calculated in (6.2) and consists of the price for a product multiplied by the amount shipped to each customer.

$$\begin{aligned} Z_1 = \sum_{t}^{T} \Pi_t - \Bigg(& \sum_{s}^{S} SC_s \, y_s^{Su} + \sum_{f}^{F} \sum_{o}^{O} FC_{fo} \, y_{fo}^{Fa} + \sum_{w}^{W} \sum_{o}^{O} WC_{wo} \, y_{wo}^{Wa} \\ & + \sum_{s}^{S} \sum_{f}^{F} \sum_{m}^{M} \sum_{p}^{P} \sum_{l}^{L} \sum_{t}^{T} PC_{smt} \, x_{sfmplt} \\ & + \sum_{f}^{F} \sum_{w}^{W} \sum_{p}^{P} \sum_{l}^{L} \sum_{t}^{T} MC_{fpt} \, x_{fwplt} \\ & + \sum_{w}^{W} \sum_{c}^{C} \sum_{p}^{P} \sum_{l}^{L} \sum_{t}^{T} HC_{wpt} \, x_{wcplt} \\ & + \sum_{w}^{W} \sum_{p}^{P} \sum_{t}^{T} \sum_{c}^{C} SC_{wpt} \frac{\left(h_{wp(t-1)c} + h_{wptc}\right)}{2} \\ & + \sum_{s}^{S} \sum_{f}^{F} \sum_{m}^{M} \sum_{p}^{P} \sum_{l}^{L} \sum_{t}^{T} TC_{sfmlt} \, x_{sfmplt} \\ & + \sum_{f}^{F} \sum_{w}^{W} \sum_{p}^{P} \sum_{l}^{L} \sum_{t}^{T} TC_{fwplt} \, x_{fwplt} \\ & + \sum_{w}^{W} \sum_{c}^{C} \sum_{p}^{P} \sum_{l}^{L} \sum_{t}^{T} TC_{wcplt} \, x_{wcplt} \Bigg) \end{aligned} \qquad (6.1)$$

Total profit is the total revenue minus fixed costs for selecting suppliers, setup costs for production facilities and warehouses, procurement costs, manufacturing costs, handling and stocking costs, and transportation costs.

Constraint (6.3) ensures that demand, which is dependent on the realized OTDLT for each customer, is fulfilled. In (6.4), the flows between facilities and warehouses and the number of products in stock are calculated. In (6.5), the flows between supplier and production facilities are calculated according to the given bill of materials.

$$\Pi_t = \sum_w^W \sum_c^C \sum_p^P \sum_l^L \pi_p \, x_{wcplt} \qquad \forall t \in T \qquad (6.2)$$

$$D_{cpt}\left(OTD_{cpt}\right) = \sum_w^W \sum_l^L x_{wcplt} \qquad \forall c \in C, p \in P, t \in T \qquad (6.3)$$

$$\sum_c^C \sum_l^L x_{wcplt} + \sum_c^C h_{wptc} = \sum_f^F \sum_l^L x_{fwplt} + \sum_c^C h_{wp(t-1)c} \qquad \forall w \in W, p \in P, t \in T \qquad (6.4)$$

$$\sum_w^W \sum_p^P \sum_l^L x_{fwplt} \, BOM_{mp} = \sum_s^S \sum_p^P \sum_l^L x_{sfmplt} \qquad \forall f \in F, m \in M, t \in T \qquad (6.5)$$

$$\sum_f^F \sum_p^P \sum_l^L x_{sfmplt} \leq Cap_{sm}^{Su} y_s^{Su} \qquad \forall s \in S, m \in M, t \in T \qquad (6.6)$$

$$\sum_w^W \sum_p^P \sum_l^L x_{fwplt} \leq \sum_o^O Cap_{fo}^{Fa} \, y_{fo}^{Fa} \qquad \forall f \in F, t \in T \qquad (6.7)$$

$$\sum_p^P \sum_c^C h_{wptc} \leq \sum_o^O Cap_{wo}^{Wa} \, y_{wo}^{Wa} \qquad \forall w \in W, t \in T \qquad (6.8)$$

$$\sum_c^C \sum_p^P \sum_l^L x_{wcplt} \leq \sum_o^O Cap_{wo}^{Wa} \, y_{wo}^{Wa} \qquad \forall w \in W, t \in T \qquad (6.9)$$

$$\sum_o^O y_{fo}^{Fa} \leq 1 \qquad \forall f \in F \qquad (6.10)$$

$$\sum_o^O y_{wo}^{Wa} \leq 1 \qquad \forall w \in W \qquad (6.11)$$

Constraint (6.6) ensures that each supplier can only deliver a specific raw material according to its capacity. Constraints (6.7), (6.8), and (6.9) ensure that the capacities of production facilities and warehouses are not exceeded. In (6.10) and (6.11), it is ensured that only one capacity option is chosen for each production facility and each warehouse.

$$OTD_{cpt} \geq LT_{smt}^{Su}\delta_{sfmpltc}^{SF} + LT_{fpt}^{Fa}\delta_{fwpltc}^{FW} + LT_{wpt}^{Wa}x_{wcplt} + LT_{sfmlt}\delta_{sfmpltc}^{SF} + LT_{fwplt}\delta_{fwpltc}^{FW} + LT_{wcplt}x_{wcplt} \quad \forall s \in S, f \in F, w \in W, c \in C, m \in M, p \in P, l \in L, t \in T \qquad (6.12)$$

$$\sum_{l}^{L} x_{wcplt} - h_{wp(t-1)c} = \sum_{f}^{F}\sum_{l}^{L} \delta_{fwpltc}^{FW} \quad \forall w \in W, p \in P, t \in T, c \in C \qquad (6.13)$$

$$x_{fwplt} \geq \sum_{c}^{C} \delta_{fwpltc}^{FW} \quad \forall, f \in F, w \in W, p \in P, l \in L, t \in T \qquad (6.14)$$

$$\sum_{w}^{W}\sum_{l}^{L} \delta_{fwpltc}^{FW} BOM_{mp} = \sum_{s}^{S}\sum_{l}^{L} \delta_{sfmpltc}^{SF} \quad \forall f \in F,, c \in C, m \in M, p \in P, t \in T \qquad (6.15)$$

$$x_{sfmplt} \geq \sum_{c}^{C} \delta_{sfmpltc}^{SF} \quad \forall s \in S, f \in F, m \in M, p \in P, l \in L, t \in T \qquad (6.16)$$

In constraint (6.12), the OTDLT for each customer, each product, and each period is calculated. It consists of procurement, manufacturing, handling, delivery, and transportation lead times for goods that are not kept in stock. Constraint (6.13) calculates the additional needed products from facilities to serve customers' demand for a specific product in each period. Constraint (6.14) ensures that these additional needed products are within the transportation arc with the specific logistic mode between production facilities and warehouses. Constraint (6.15) calculates the additional need for raw materials to serve a customer order according to the bill of materials multiplied by the additional needed products. In constraint (6.16), it is ensured that these additional needed raw materials are within the established transportation arcs between suppliers and manufacturing facilities.

$$D_{cpt}(OTD_{cpt}) = D_{cpt}^{Max}a_{cpt} + \left(\frac{LT_{cpt}^{Max}D_{cpt}^{Max} - LT_{cpt}^{Min}D_{cpt}^{Min}}{LT_{cpt}^{Max} - LT_{cpt}^{Min}} b_{cpt} - \frac{D_{cpt}^{Max} - D_{cpt}^{Min}}{LT_{cpt}^{Max} - LT_{cpt}^{Min}} lt_{cpt}\right) + D_{cpt}^{Min}c_{cpt} \quad \forall c \in C, p \in P, t \in T \qquad (6.17)$$

$$\Phi(a_{cpt} - 1) \leq LT_{cpt}^{Min} - OTD_{cpt} \quad \forall c \in C, p \in P, t \in T \qquad (6.18)$$

$$\Phi\, a_{cpt} > LT_{cpt}^{Min} - OTD_{cpt} \quad \forall c \in C, p \in P, t \in T \qquad (6.19)$$

$$\Phi(c_{cpt} - 1) \leq OTD_{cpt} - LT_{cpt}^{Max} \quad \forall c \in C, p \in P, t \in T \qquad (6.20)$$

$$\Phi\, c_{cpt} > OTD_{cpt} - LT_{cpt}^{Max} \quad \forall c \in C, p \in P, t \in T \qquad (6.21)$$

$$a_{cpt} + b_{cpt} + c_{cpt} = 1 \quad \forall c \in C, p \in P, t \in T \qquad (6.22)$$

$$lt_{cpt} \leq \Phi b_{cpt} \quad \forall c \in C, p \in P, t \in T \qquad (6.23)$$

$$lt_{cpt} \geq \Phi\left(b_{cpt} - 1\right) + OTD_{cpt} \qquad \forall c \in C, p \in P, t \in T \quad (6.24)$$

$$lt_{cpt} \leq OTD_{cpt} \qquad \forall c \in C, p \in P, t \in T \quad (6.25)$$

The actual demand of each customer for each product in each period depends on the possible OTDLT. Therefore, actual demand is calculated in (6.17). A piecewise linear function, as described in chapter 6.2, depicts customers' OTDLT sensitivity. Furthermore, constraints (6.18) to (6.25) are used to linearize the piecewise linear function. In (6.26), the non-negativity constraints are shown, and in (6.27), the binary variables are defined.

$$x_{sfmplt}, x_{fwplt}, x_{wcplt}, h_{wptc}, \delta^{SF}_{sfmpltc}, \delta^{FW}_{fwpltc}, OTD_{cpt}, E_t, lt_{cpt}, \Pi_t, D_{cpt}\left(OTD_{cpt}\right) \geq 0 \qquad \forall s \in S, f \in F, w \in W, c \in C, m \in M, p \in P, l \in L, t \in T \quad (6.26)$$

$$y^{Su}_s, y^{Fa}_{fo}, y^{Wa}_{wo}, a_{cpt}, b_{cpt}, c_{cpt} \in [0; 1] \qquad \forall s \in S, f \in F, w \in W \quad (6.27)$$

6.3.2 Models with Various Emission Policies

Constraints (6.28) to (6.30) are needed to incorporate an emission cap policy.

$$\begin{aligned} E_t = & \sum_f^F \sum_o^O FE_{fot} y^{Fa}_{fo} + \sum_w^W \sum_o^O WE_{wot}\, y^{Wa}_{wo} \\ & + \sum_s^S \sum_f^F \sum_m^M \sum_p^P \sum_l^L PE_{smt}\, x_{sfmplt} \\ & + \sum_f^F \sum_w^W \sum_p^P \sum_l^L ME_{fpt}\, x_{fwplt} \\ & + \sum_w^W \sum_c^C \sum_p^P \sum_l^l HE_{wpt}\, x_{wcplt} \\ & + \sum_w^W \sum_p^P \sum_c^C SE_{wpt} \frac{\left(h_{wp(t-1)c} + h_{wptc}\right)}{2} \\ & + \sum_s^S \sum_f^F \sum_m^M \sum_p^P \sum_l^L TE_{sfmplt}\, x_{sfmplt} \\ & + \sum_f^F \sum_w^W \sum_p^P \sum_l^L TE_{fwplt}\, x_{fwplt} \\ & + \sum_w^W \sum_c^C \sum_p^P \sum_l^L TE_{wcplt}\, x_{wcplt} \end{aligned} \qquad \forall t \in T \quad (6.28)$$

In (6.28), the emissions generated in each period are calculated. Emissions from operating production facilities and warehouses are considered, as are those from procurement, manufacturing, handling, stock-related, and transportation activities.

For the implementation of an emission cap policy, additional constraints are necessary. Constraint (6.29) ensures that the generated emissions in each period do not exceed the imposed emission cap. Constraint (6.30) makes sure that the amount of generated emissions cannot be negative.

$$E_t \leq ECap \qquad \forall t \in T \qquad (6.29)$$

$$E_t \geq 0 \qquad \forall t \in T \qquad (6.30)$$

The target function must be altered to capture the emission tax policy. In addition to the costs from (6.1), the tax amount for generated emissions must be subtracted from total profit (6.31).

$$\begin{aligned} Z_1 = \sum_t^T \Pi_t - \Bigg(& \sum_s^S SC_s\, y_s^{Su} + \sum_f^F \sum_o^O FC_{fo}\, y_{fo}^{Fa} + \sum_w^W \sum_o^O WC_{wo}\, y_{wo}^{Wa} \\ & + \sum_s^S \sum_f^F \sum_m^M \sum_p^P \sum_l^L \sum_t^T PC_{smt}\, x_{sfmplt} \\ & + \sum_f^F \sum_w^W \sum_p^P \sum_l^L \sum_t^T MC_{fpt}\, x_{fwplt} \\ & + \sum_w^W \sum_c^C \sum_p^P \sum_l^L \sum_t^T HC_{wpt}\, x_{wcplt} \\ & + \sum_w^W \sum_p^P \sum_t^T \sum_c^C SC_{wpt} \frac{\left(h_{wp(t-1)c} + h_{wptc}\right)}{2} \\ & + \sum_s^S \sum_f^F \sum_m^M \sum_p^P \sum_l^L \sum_t^T TC_{sfmlt}\, x_{sfmplt} \\ & + \sum_f^F \sum_w^W \sum_p^P \sum_l^L \sum_t^T TC_{fwplt}\, x_{fwplt} \\ & + \sum_w^W \sum_c^C \sum_p^P \sum_l^L \sum_t^T TC_{wcplt}\, x_{wcplt} + \sum_t^T \Omega^{Tax} E_t \Bigg) \end{aligned} \qquad (6.31)$$

Objective (6.1) has to be altered to include costs and revenues from buying or selling emission credits in a cap and trade system. Therefore, in (6.32), a further term is included that depicts the costs and revenues for emission credits according to the price for these credits, as well as the amount that has to be bought or sold. The amount of emission credits is calculated in (6.33). Constraint (6.34) is a non-negativity constraint.

$$
\begin{aligned}
Z_1 = \sum_{t}^{T} \Pi_t - \Bigg(& \sum_{s}^{S} SC_s \, y_s^{Su} + \sum_{f}^{F} \sum_{o}^{O} FC_{fo} \, y_{fo}^{Fa} + \sum_{w}^{W} \sum_{o}^{O} WC_{wo} \, y_{wo}^{Wa} \\
& + \sum_{s}^{S} \sum_{f}^{F} \sum_{m}^{M} \sum_{p}^{P} \sum_{l}^{L} \sum_{t}^{T} PC_{smt} \, x_{sfmplt} \\
& + \sum_{f}^{F} \sum_{w}^{W} \sum_{p}^{P} \sum_{l}^{L} \sum_{t}^{T} MC_{fpt} \, x_{fwplt} \\
& + \sum_{w}^{W} \sum_{c}^{C} \sum_{p}^{P} \sum_{l}^{L} \sum_{t}^{T} HC_{wpt} \, x_{wcplt} \\
& + \sum_{w}^{W} \sum_{p}^{P} \sum_{t}^{T} \sum_{c}^{C} SC_{wpt} \frac{\left(h_{wp(t-1)c} + h_{wptc}\right)}{2} \\
& + \sum_{s}^{S} \sum_{f}^{F} \sum_{m}^{M} \sum_{p}^{P} \sum_{l}^{L} \sum_{t}^{T} TC_{sfmlt} \, x_{sfmplt} \\
& + \sum_{f}^{F} \sum_{w}^{W} \sum_{p}^{P} \sum_{l}^{L} \sum_{t}^{T} TC_{fwplt} \, x_{fwplt} \\
& + \sum_{w}^{W} \sum_{c}^{C} \sum_{p}^{P} \sum_{l}^{L} \sum_{t}^{T} TC_{wcplt} \, x_{wcplt} + \sum_{t}^{T} \Omega^{CAT} \left(\alpha_t^{+} - \alpha_t^{-}\right) \Bigg)
\end{aligned}
\tag{6.32}
$$

$$E_t + \alpha_t^{-} = ECap + \alpha_t^{+} \qquad \forall t \in T \tag{6.33}$$

$$\alpha_t^{-}, \alpha_t^{+}, E_t \geq 0 \qquad \forall t \in T \tag{6.34}$$

Emission offset policy is integrated into the model by altering the objective to include the costs of additionally needed emission allowances (6.35). Revenue is also reduced by the price of emission allowances multiplied by the number of additionally needed allowances. The additionally needed emission allowances are calculated in constraint (6.36), and in (6.37), it is ensured that the value of β_t cannot be negative.

$$
\begin{aligned}
Z_1 = \sum_t^T \Pi_t - \Bigg(& \sum_s^S SC_s\, y_s^{Su} + \sum_f^F \sum_o^O FC_{fo}\, y_{fo}^{Fa} + \sum_w^W \sum_o^O WC_{wo}\, y_{wo}^{Wa} \\
& + \sum_s^S \sum_f^F \sum_m^M \sum_p^P \sum_l^L \sum_t^T PC_{smt}\, x_{sfmplt} \\
& + \sum_f^F \sum_w^W \sum_p^P \sum_l^L \sum_t^T MC_{fpt}\, x_{fwplt} \\
& + \sum_w^W \sum_c^C \sum_p^P \sum_l^L \sum_t^T HC_{wpt}\, x_{wcplt} \\
& + \sum_w^W \sum_p^P \sum_t^T \sum_c^C SC_{wpt} \frac{\left(h_{wp(t-1)c} + h_{wptc}\right)}{2} \\
& + \sum_s^S \sum_f^F \sum_m^M \sum_p^P \sum_l^L \sum_t^T TC_{sfmlt}\, x_{sfmplt} \\
& + \sum_f^F \sum_w^W \sum_p^P \sum_l^L \sum_t^T TC_{fwplt}\, x_{fwplt} \\
& + \sum_w^W \sum_c^C \sum_p^P \sum_l^L \sum_t^T TC_{wcplt}\, x_{wcplt} + \sum_t^T \Omega^{Off}\, \beta_t \Bigg)
\end{aligned}
\tag{6.35}
$$

$$E_t = ECap + \beta_t \qquad \forall t \in T \tag{6.36}$$

$$\beta_t, E_t \geq 0 \qquad \forall t \in T \tag{6.37}$$

6.4 Data Generation Process

The general data generation follows the process described in chapter 5.3. However, due to customer-specific demand, additional data is needed. In order to use the linearized OTDLT-sensitive demand functions, the parameters D_{cpt}^{Max}, D_{cpt}^{Min}, LT_{cpt}^{Max}, and LT_{cpt}^{Min} have to be specified.

Parameter D_{cpt}^{Max} is generated according to the demand in chapter 5.3. A number from uniform distribution U[5000, 20000] is assigned for each customer, product, and period. In order to show the influence of customer sensitivity towards OTDLT in the model, different classes for D_{cpt}^{Min} are generated. Data is thus provided for the case that 0% of customers are sensitive towards OTDLT, or 10% are, and so on. The last case is that 100% of customers are sensitive towards OTDLT; therefore, with a longer OTDLT than LT_{cpt}^{Max}, the demand of customer cluster c is zero. For example, with D_{cpt}^{Max} = 150000, the demand for the 0% case would be D_{cpt}^{Min} = 15000; for the 50% case, D_{cpt}^{Min} would be 7500; and for the 100% case, D_{cpt}^{Min} would be 0, if the minimum needed OTDLT is not met.

An example is created to examine the model with four potential suppliers, three possible locations for production facilities, three potential locations for warehouses, and six customer regions. Furthermore, three types of logistic modes are considered as well as three different types of raw material. Furthermore, three planning periods and two different capacity options for production facilities and warehouses are possible, and for simplicity, one final product is considered.

The locations of suppliers, production facilities, warehouses, and customer regions are shown in Fig. 6.2. The bubble sizes differ according to maximum capacity or to customers' demand for each location.

The maximum and minimum expected OTDLTs, LT_{cpt}^{Max} and LT_{cpt}^{Min}, are shown in tables 6.1 and 6.2. They are chosen according to the initially generated data and the per-customer calculated shortest possible OTDLT. It is expected that sensitive customers are willing to wait for double the LT_{cpt}^{Min} to receive their ordered goods.

	c=1	c=2	c=3	c=4	c=5	c=6
t=1	96	56	72	64	72	92
t=2	24	14	18	16	18	23
t=3	24	14	18	16	18	23

Table 6.1: Minimum expected OTDLT of each customer cluster

	c=1	c=2	c=3	c=4	c=5	c=6
t=1	192	112	144	128	144	184
t=2	48	28	36	32	36	46
t=3	48	28	36	32	36	46

Table 6.2: Maximum expected OTDLT of each customer cluster

Since all models described in chapter 6.3 are MILP, a standard solver is used to find the optimal solutions. All models are solved using IBM ILOG CPlex on an Intel Core i7-8750H 2,2 GHz machine with 16 GB Ram under Windows 10.

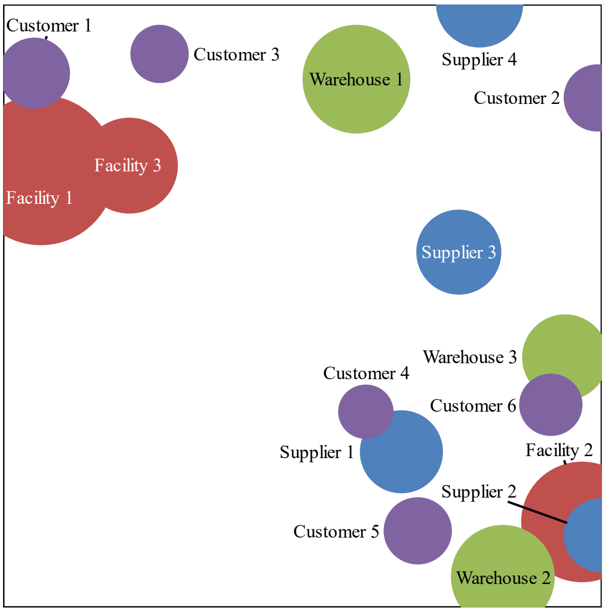

Figure 6.2: Location of potential suppliers, production facilities, and warehouses in the data example for chapter 6

6.5 Numerical Results

6.5.1 Results with Different Shares of Time-sensitive Customers

To enable examination of the influence of the percentual share of OTDLT-sensitive customers, the product price is set to 185 monetary units. The specific value is 75 monetary units for the emission price under the market-based emission policies. A cap of 12,500 emission units per period is imposed under the emission cap policy. For emission offset and the emission cap and trade policy, an emission cap of 9,500 emission units per period is imposed.[319]

Total profit decreases when more customers are sensitive to OTDLT, as shown in Fig. 6.3 a). The development of total profit is highly dependent on fulfilled demand, as illustrated in Fig. 6.3 b). With the rising share of OTDLT-sensitive customers, total profit and fulfilled demand decrease linearly at first. For emission offset, emission cap, and no emission policies applied, this trend is interrupted when more than 20% of customers are OTDLT-sensitive. Under emission tax and the emission cap and trade policy, this effect is observed when more than 30% of customers are OTDLT-sensitive. After these points, the total profit and the quantity of demand met continue to decrease, but rather weakly. These points indicate that it makes sense to strengthen OTDLT reduction efforts and to deliver to time-sensitive consumers at least partially. In addition, increases in fulfilled demand are observed under some circumstances, but due to the costly actions to reduce

[319] Detailed results of the examinations in Chapter 6 can be found in appendix C.

OTDLT, total profit further decreases. Furthermore, an emission tax policy decreases the total profit the most, whereas the emission cap and trade policy increases total profit when only a small percentage of customers is OTDLT-sensitive. With a high share of sensitive customers, total profit and fulfilled demand are below the results under no emission policy. Therefore, emission policies seem to complicate customer need fulfillment.

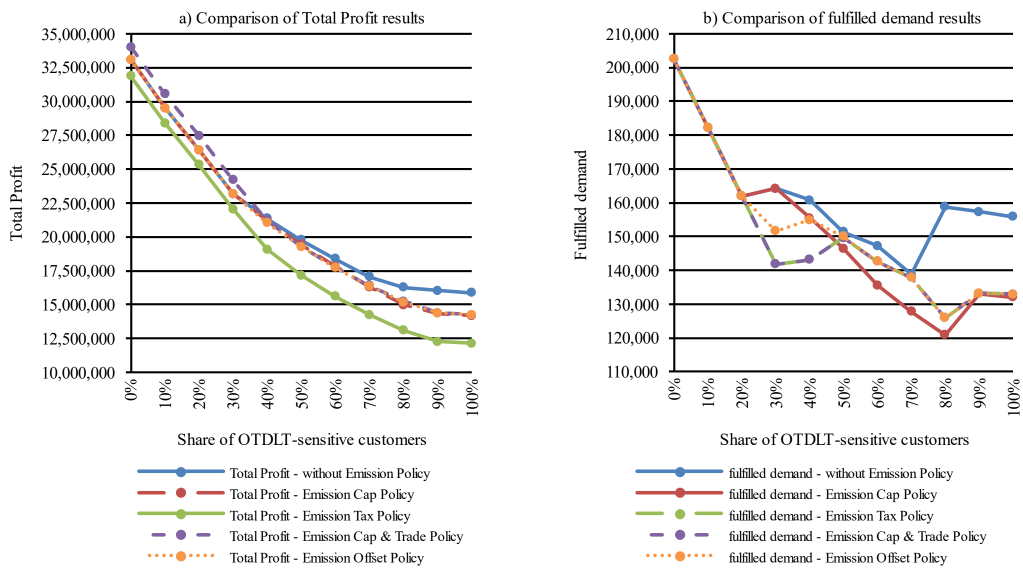

Figure 6.3: Comparison of Total Profit and fulfilled demand with varying share of OTDLT-sensitive customers

To provide deeper insights into the effects on total profit, Fig. 6.4 illustrates total revenues and total cost. Total revenue reflects the development of fulfilled demand, as shown in Fig. 6.4 a). Since no discounts or dynamic pricing strategies are considered, total revenue curves are similar to those for fulfilled demand, scaled by the product price. As illustrated in Fig. 6.4 b), a decrease in total costs is observed with decreasing total revenues. The lower fulfilled demand, with a lower share of OTDLT-sensitive customers, explains these decreases. When fulfilled demand stabilizes, a substantial increase in total cost can be observed due to the costly efforts of reducing OTDLT. Therefore, even if total revenues and fulfilled demand stabilize, total profit is reduced due to increasing total cost. For all emission policies except emission tax, total cost results are never higher than total cost when no emission policy is applied. This point is explainable by the lower fulfilled demand under these policies. In the case of emission tax, cost saving by producing fewer goods is outweighed by the cost of emission through the tax rate. In contrast, emission cap and trade enables cost reductions by selling excess emission credits, especially when a low share of customers is sensitive towards OTDLT, as shown in Fig. 6.5.

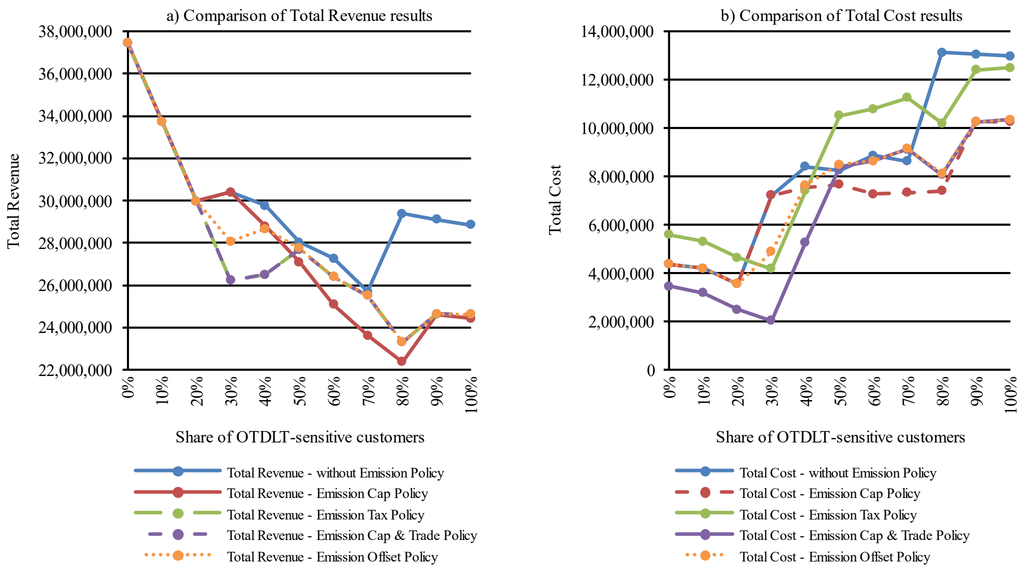

Figure 6.4: Comparison of Total Revenue and Total Cost with varying share of OTDLT-sensitive customers

Total emission initially decreases with an increase in the share of OTDLT-sensitive customers. The total emission results remain consistent if less than 20% of customers are OTDLT-sensitive. With more than 20%, for of the emission cap and trade and the emission tax policy more than 30%, of OTDLT-sensitive customers total emissions are increasing strongly. The increase reflects the efforts to reduce OTDLT to attract additional customers. All examined emission policies reduce the total emission in the case of a high share of OTDLT-sensitive customers. Emission tax and the cap and trade policy seem to create the highest incentive to reduce emission amounts when the share of time-sensitive customers is below 50%. With a higher share, the cap seems particularly effective. Emission offset policy leads to smaller reductions than emission tax when the share of OTDLT-sensitive customers is below 50%; with a higher share, total emissions are identical. The development of fulfilled demand develops contrary to the total emission. Therefore, reducing OTDLT leads to higher total emissions. As Fig. 6.5 b) shows, market-based emission policies have a strong influence on total costs. Whereas the emission cap and trade policy reduces total cost up to a share of OTDLT-sensitive customers of 40%, the emission tax policy increases total cost due to the high emission cost. An emission offset policy apparently affects reduction efforts only when the share of OTDLT-sensitive customers is high.

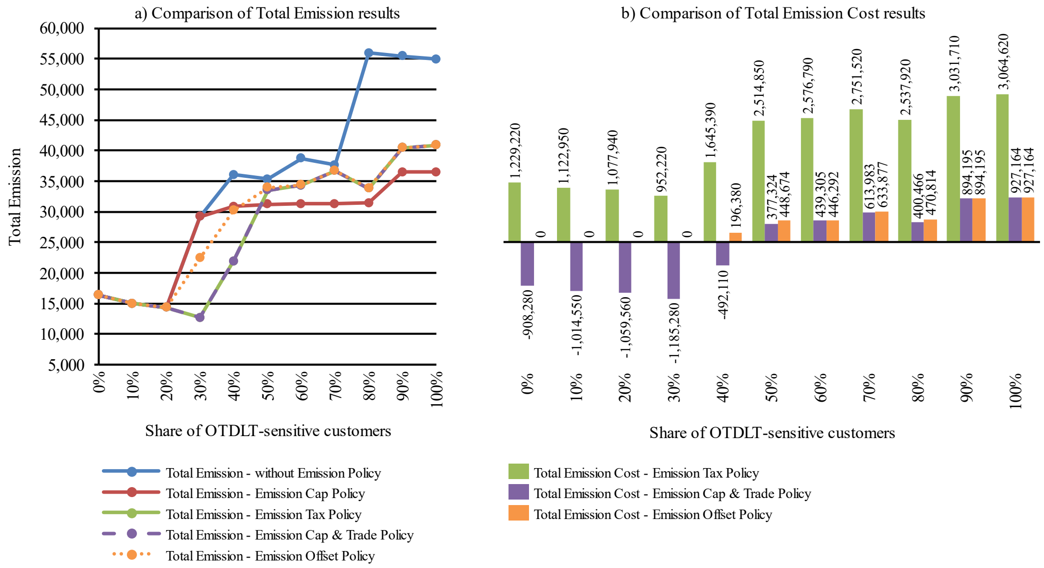

Figure 6.5: Comparison of total emission and total emission cost with varying share of OTDLT-sensitive customers

Regarding the number of selected suppliers, it appears that at least two suppliers are necessary to fulfill the maximum possible demand, as shown in Fig. 6.6. For shares of 0% to 80% of OTDLT-sensitive customers, only two suppliers are selected. When no policies are applied, three suppliers are selected when the share of sensitive customers is 40% and 60%.

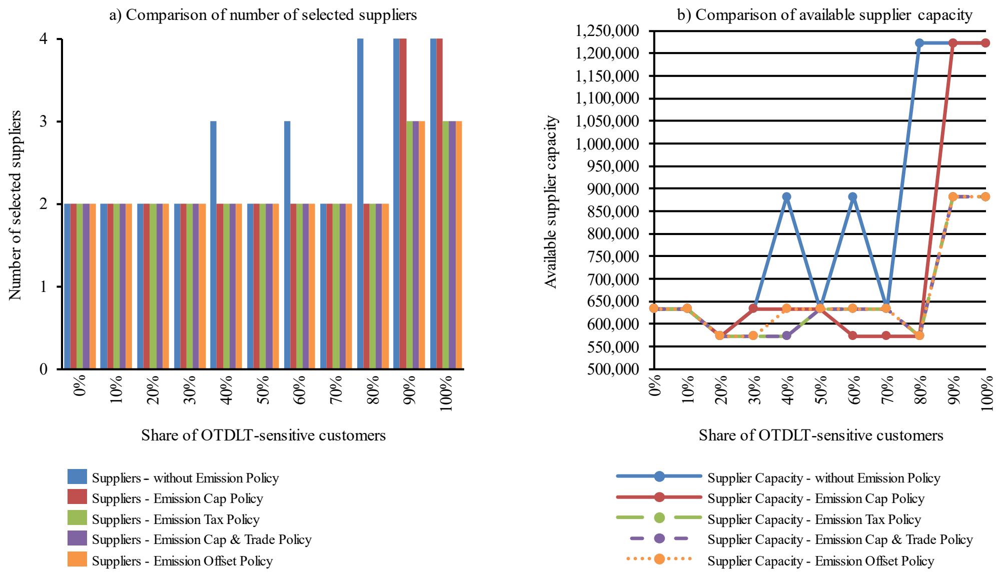

Figure 6.6: Number of suppliers and available supplier capacity with varying share of OTDLT-sensitive customers

The selection of more suppliers may be necessary to access the required raw materials timeously to increase the fulfilled demand. All possible suppliers are contracted with a high share (90% and 100%) under the emission cap policy and without an emission policy. In the case of no applied emission policy, this occurred earlier, at 80%. Under emission tax and the cap and trade policy, at least three suppliers are selected with high shares of sensitive customers. This may be because of the need for more raw materials to deal with the increased demand fulfillment and the possibility of smaller order batches from more suppliers to reduce lead times. In some cases, under emission tax and the emission cap and trade policy, other suppliers are contracted, leading to lower total emission but probably to higher costs.

The number of production facilities established and the chosen capacity option changes when OTDLT-sensitive customers' share is high, as shown in Fig. 6.7. With 80% of OTDLT-sensitive customers and when no emission policy is applied, the number of production facilities increases up to three with the low-capacity option. Under emission policies, an increase of up to two established facilities is observed with a 90% share of sensitive customers. Under market-based emission policies, a low-capacity option is chosen for both established production facilities, leading to a decrease in production capacity. Under emission cap, one facility is established with the low-capacity and one with high-capacity option, leading to capacity increase. It can be assumed that the high-capacity facility is more environmentally friendly. Therefore, more products are manufactured in the high-capacity location under the emission cap policy. In contrast, lead times cannot be reduced as they are under market-based policies, leading to lower fulfilled demand. The increase in the number of established production facilities also comes with a high increase in total costs and total emissions. However, based on the given example, more production facilities seem to allow for further reduction of OTDLT.

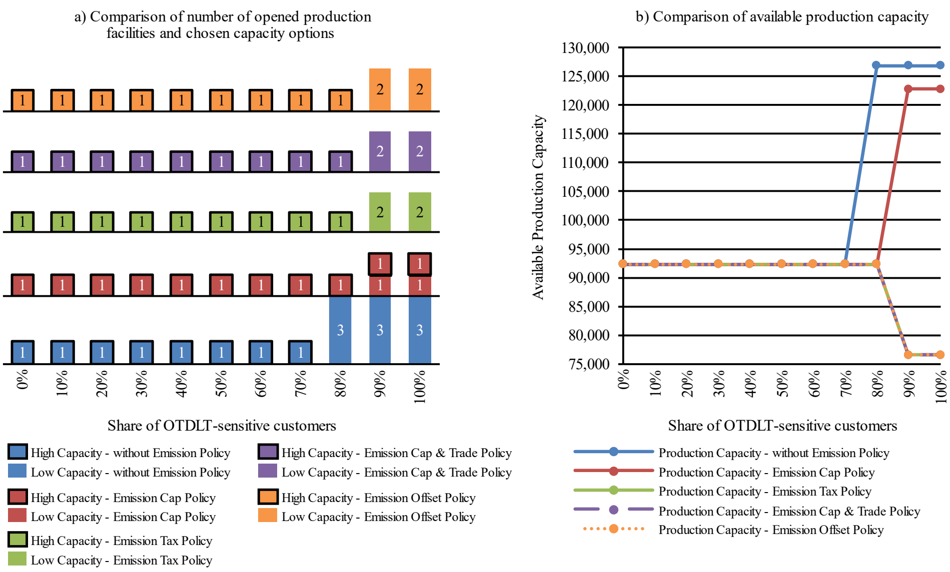

Figure 6.7: Number of selected production facilities and available production capacity

Warehouse capacity is stable with an increasing share of OTDLT-sensitive customers. Beginning from a share of 30% under the emission tax and 40% under the emission cap and trade policy, the number of selected warehouses increases to three with a low-capacity option, as depicted in Fig. 6.8. Under emission tax and the emission cap and trade policy, with a share of 30% of OTDLT-sensitive customers, only one warehouse with low capacity is established. Under an emission offset policy, two small warehouses are established, which leads to capacity reduction. Due to lower demand fulfillment, this amount of capacity seems appropriate to fulfill the demand. The increase of the number of warehouses to three accompanied a slight increase in fulfilled demand. Therefore, it can be assumed that the number of established warehouses strongly influences the achieved OTDLT. Furthermore, the number of warehouses appears more important than the realized capacity because there is only a slight increase in capacity with three small warehouses compared to the situation with one large warehouse.

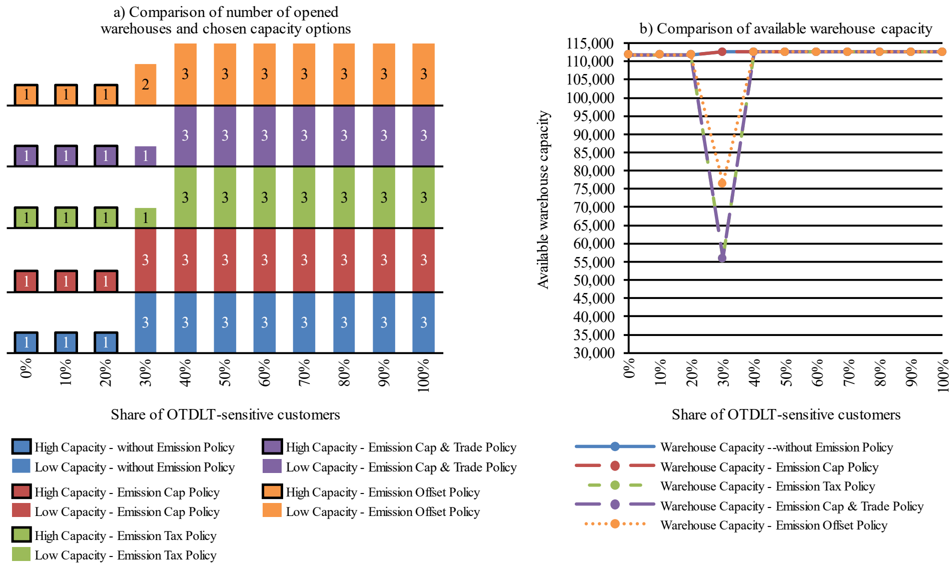

Figure 6.8: Number of selected warehouses and available warehouse capacity

When only a low share of customers is OTDLT-sensitive, under all examined policy options, the share of logistic mode 1 is 100%, as shown in Fig. 6.9. This changes when the share of time-sensitive customers is higher than 30% under the emission cap and trade, and for the emission tax policy, higher than 40%. Thereafter, the share of logistic modes 2 and 3 increases with an increasing percentage of sensitive customers, whereas the share of logistic mode 1 decreases. The increase in modes 2 and 3 is accompanied by stabilizing fulfilled demand and reduced lead time. On the other hand, increased total cost and total emission are observed by using faster logistic modes.

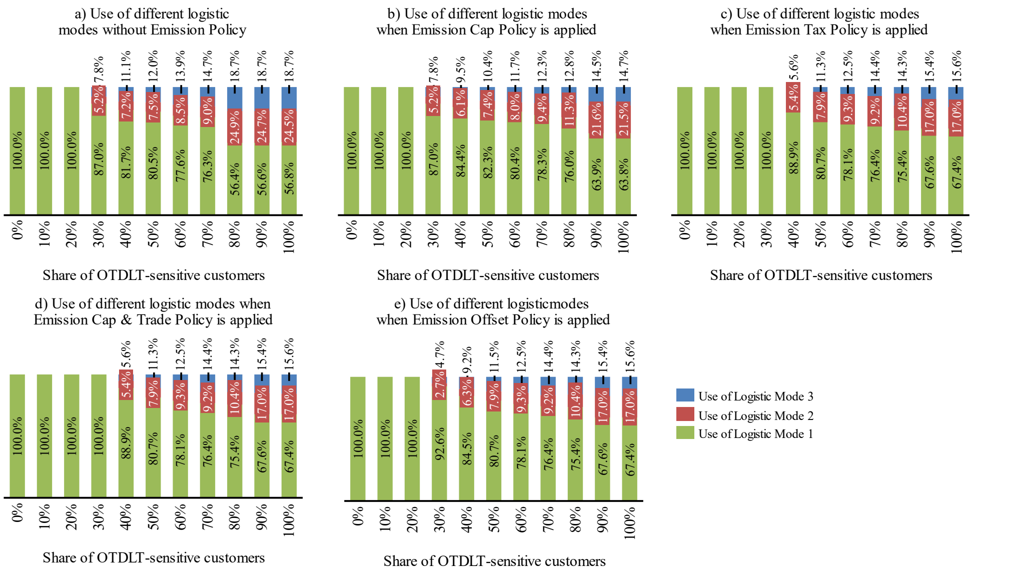

Figure 6.9: Use of different logistic modes under varying share of OTDLT-sensitive customers

Stock levels start to increase with a share of OTDLT-sensitive customers of 30% or 40% in the case of emission tax and the emission cap and trade policy. As illustrated in Fig. 6.10, emission policies reduce the stock levels compared to the results without an emission policy applied. The most decisive influence on stock levels is evident when emission tax and the emission cap and trade policy are applied. This also reflects in a fulfilled demand that is slightly lower when these policies are applied. Furthermore, stock levels can help to reduce lead times; however, under the named assumptions, they negatively impact total cost and total emission.

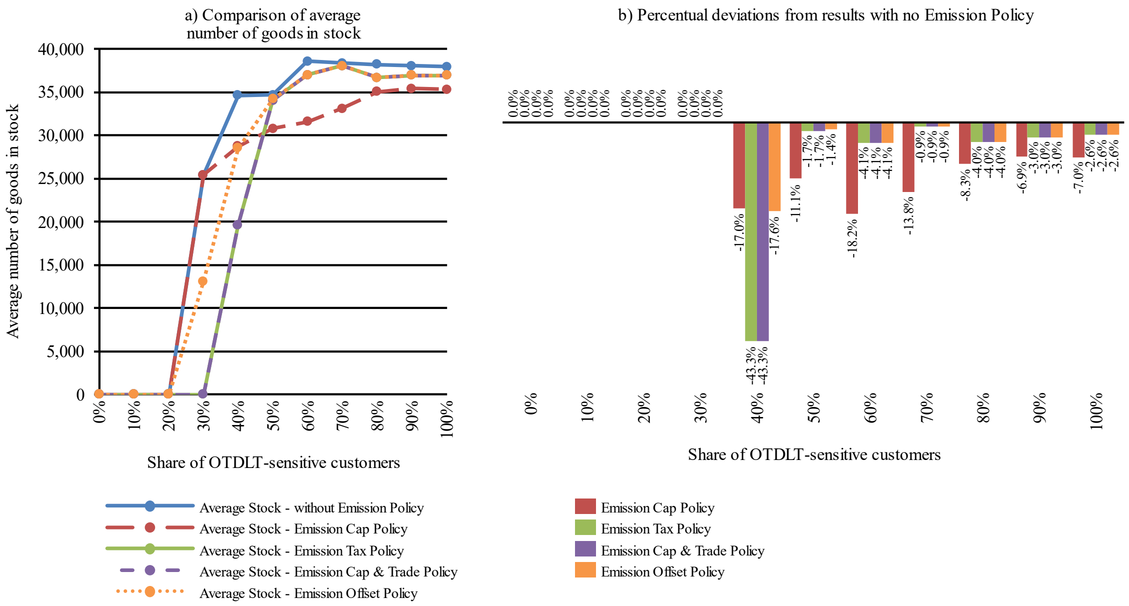

Figure 6.10: Average number of goods in stock and percentual deviation from results without emission policy

The share of OTDLT-sensitive customers influences the design of a supply chain strongly. In combination with different emission policies, an increase in suppliers, production facilities, and warehouses is observed with a higher share than under the situation where no emission policy is applied. Market-based emission policies lead to changes in supply chain structure with a higher share of OTDLT-sensitive customers. Therefore, due to the emission prices, it seems appropriate to take longer OTDLTs into account to achieve a higher total profit.

6.5.2 Results with Varying Product Prices

To examine the influence of different product prices on supply chain design, the share of customers sensitive to lead time is fixed at 100%. The emission cap is set to 9,500 emission units per period for the emission cap and trade and the emission offset policy and to 12,500 for the emission cap policy. For the market-based emission policies, an emission price of 75 monetary units is assumed.

As depicted in Fig. 6.11 a), total profit for all examined policy options increases with rising product prices. However, the increase is not strictly linear. Higher prices lead to increased fulfilled demand, which enhances the total profit, as shown in Fig. 6.11 b).

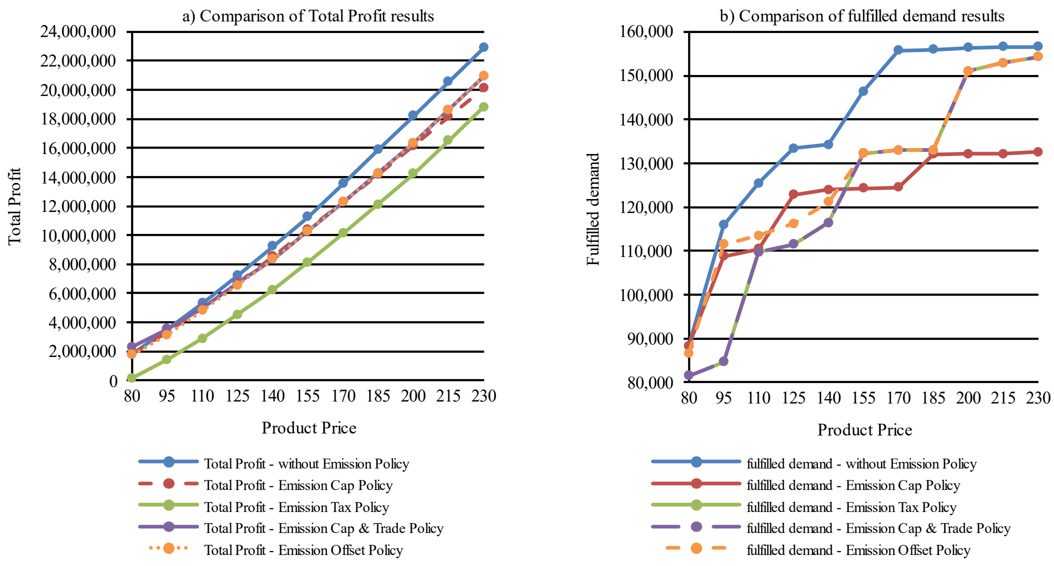

Figure 6.11: Total profit and fulfilled demand with varying product price

As discussed in the previous chapter, the lowest total profit is achieved under the emission tax policy. Under emission tax and the emission cap and trade policy, fulfilled demand is significantly lower than under the other policy options. Only with high product prices are the same results achieved as with an emission offset scheme. Under these circumstances, this might indicate that companies tend to increase their prices under emission tax or cap and trade schemes to fulfill customer needs. Without any emission policy applied, increasing the product price has the strongest effect on fulfilled demand. However, the increase in met demand becomes smaller with product prices above 170 monetary units. The differences in total profit under emission cap, offset, and cap and trade policy are relatively small with increasing product prices. Nevertheless, the strict command and control regulation leads to stagnation of the fulfilled demand when product prices are higher than 230 monetary units.

Total revenue increases with increasing product prices, nearly linearly, as shown in Fig. 6.12 a). The increase can be attributed primarily to rising product prices. This effect is supported by increasing demand. It is evident that, under the emission cap policy, the increase in total revenue is lower, compared to the other emission policies, at high product prices. This can be attributed to the fact that only minimal increases in met demand can be achieved through rigid restrictions. All emission policy options show a significant total cost increase in combination with higher product prices, as shown in Fig. 6.12 b). Only the emission cap and trade policy reduces total costs below the level achieved by no emission policy when product prices are low. This can mainly be attributed to the additional income from the sale of emission credits.

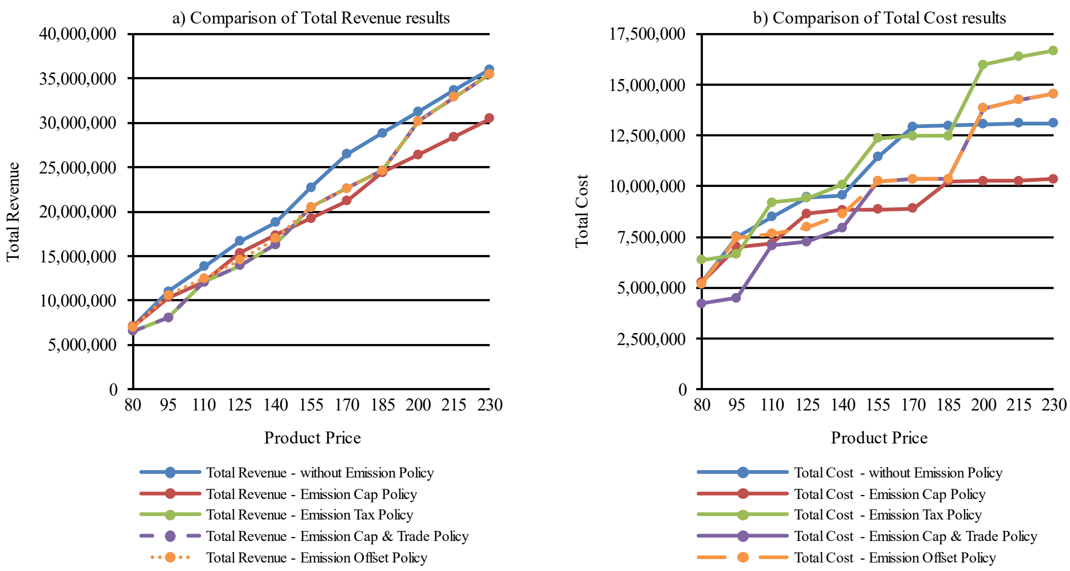

Figure 6.12: Total revenue and total cost with varying product price

With high product prices, both the emission cap and trade and the emission offset policies lead to higher total costs than without an emission policy, even if demand fulfillment is lower. Emission tax results in higher total cost even with low product prices, mainly because of the additional costs caused by this policy. However, total cost under emission cap stagnates at 185 monetary units, whereas market-based emission policies cause a further increase in total cost. Again, this is mainly because no further increases in demand fulfillment are possible under an emission cap policy. The emission offset policy and the emission cap and trade policy lead to equal total costs at high product prices.

Similarly to total cost, total emissions are affected by increasing product prices, as shown in Fig. 6.13 a). With increasing product prices, total emissions increase. Under the emission cap policy, the increase weakens with a product price higher than 125 monetary units. This effect can be attributed to the harsh restriction of the command and control policy. The greatest increases are observed when no emission policy is applied. Emission tax and the emission cap and trade policy have the highest influence on total emission values when product prices are low. With product prices higher than 140 monetary units, total emissions exceed the values under the emission cap policy and continue to approach the values without emission policies as product prices continue to rise. Total emissions under the offset scheme are approximately similar to those obtained under the emission cap policy for low product prices. With a product price of 155 monetary units, the results are equal to those under emission tax and the emission cap and trade policy. Therefore, with high product prices, total emission costs are equal under the emission cap and trade and offset policy. With low product prices, the emission cap and trade policy may result in additional income from the sale of emission credits. Under the emission offset policy, total emission costs are low. The emission tax policy, in contrast, leads under all observed product prices to a high total emission cost.

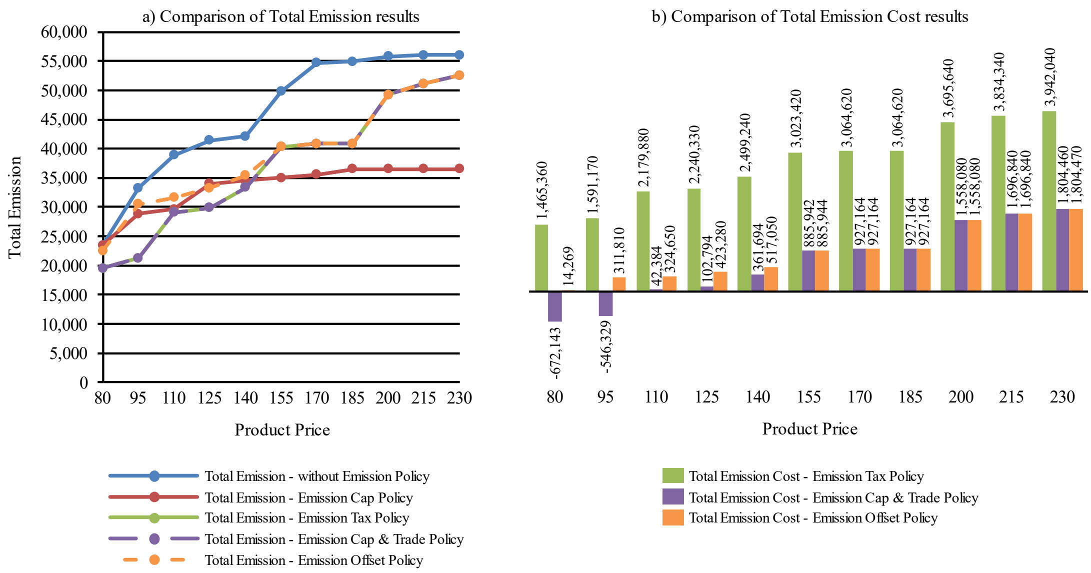

Figure 6.13: Total emission and total emission cost with varying product price

With increasing product price and total revenues, it is possible to contract more suppliers and increase the available supplier capacity, as shown in Fig. 6.14. Without an emission policy or emission cap policy, the number of contracted suppliers increases with lower product prices compared to under the market-based emission policies. This also reflects the development of fulfilled demand with increasing product prices. Furthermore, for high product prices, even under the price-based emission policies, all available suppliers are selected to reduce OTDLT.

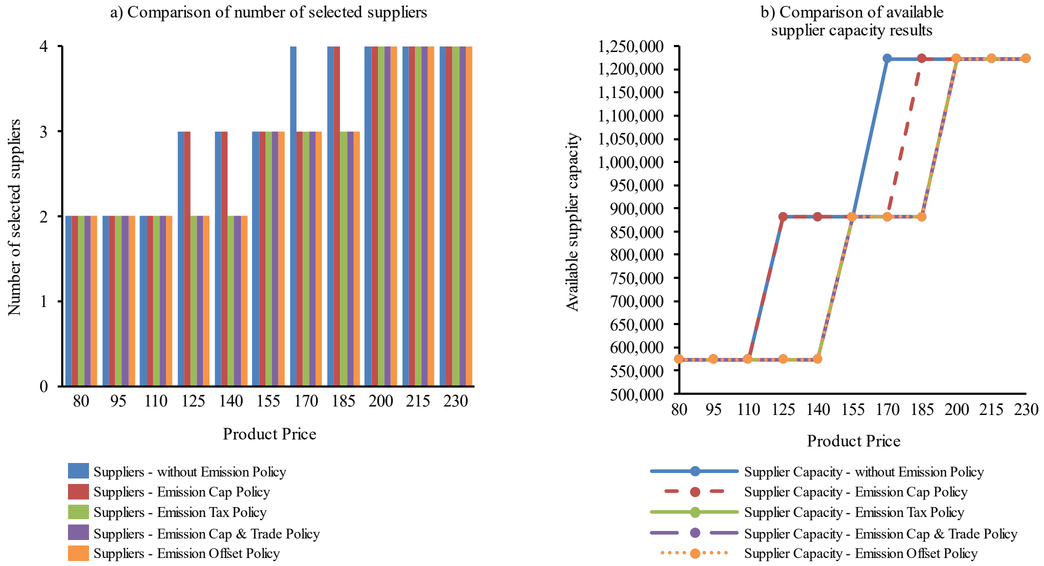

Figure 6.14: Number of suppliers and available supplier capacity with varying product price

Similar observations are made for the selection of production facilities, as shown in Fig. 6.15. When product prices are low, less available production capacity is needed because only low levels of demand can be fulfilled. More production facilities can be established with increasing product prices, leading to lower OTDLT and a greater extent of fulfilled demand. Starting from low product prices, an increase in price leads to choosing a higher capacity option, and two facilities with low capacity are opened. Establishing two small production facilities instead of one with high capacity reduces the available production capacity; however, the greater flexibility of additional facilities helps to reduce lead times and increase the fulfilled demand. With further increasing product prices, three facilities are established, and an increase in production capacity is realized. Under the market-based emission policies, these effects are delayed and are realized for higher product prices. Under the emission cap policy, only two facilities – one with low and one with high capacity – are established. This can be attributed to the harsh regulation of this policy, which does not allow for a higher generation of emissions.

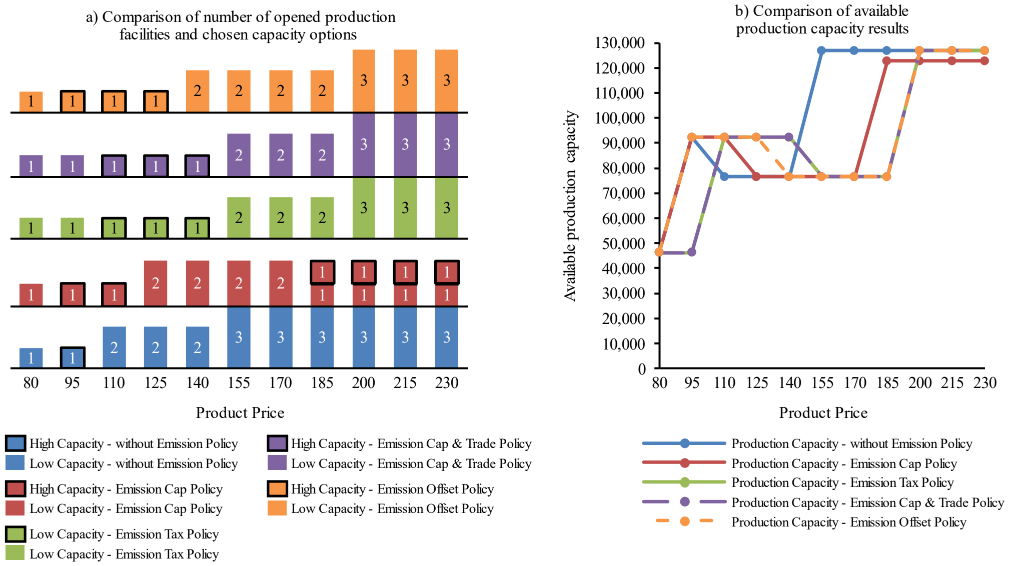

Figure 6.15: Number of production facilities and available production capacity with varying product price

Fig. 6.16 shows the number of opened warehouses and available warehouse capacity with varying product prices. An increase in the number of established warehouses is observed even for low product prices. Three warehouses are established already with a product price of 95, whether there is no emission policy or is an emission cap or an emission offset policy. For emission tax and the emission cap and trade policy, this effect is observed with a product price of 95. In contrast to suppliers and production facilities, more warehouses are established even when product prices are relatively low. Therefore, the number of warehouses seems to strongly influence the realizable OTDLT.

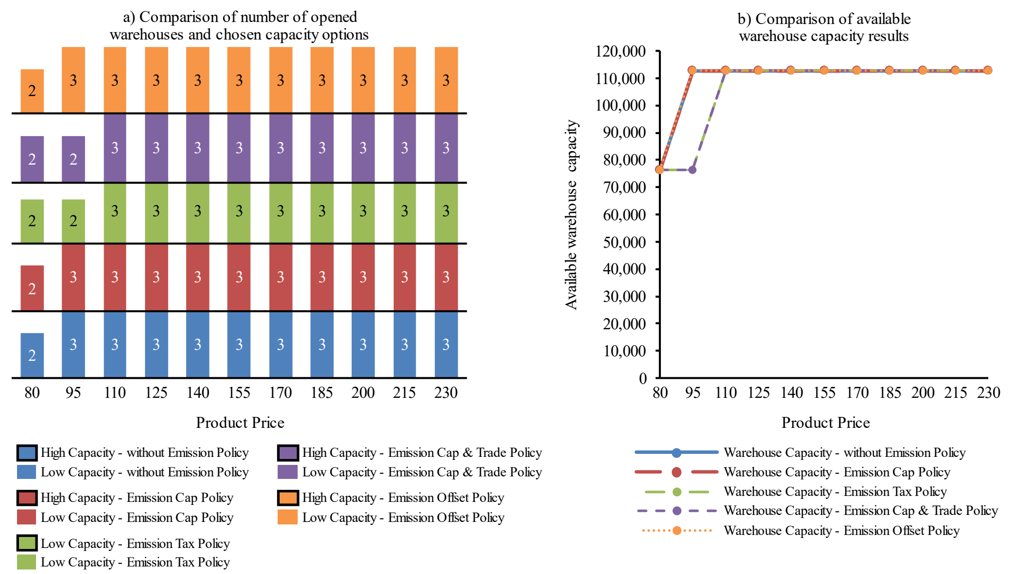

Figure 6.16: Number of warehouses and available warehouse capacity with varying product price

Regarding the used logistic modes, in general, an increase of mode 2 and 3 and a decrease of mode 1 is observed, as shown in Fig. 6.17. The highest increase of mode 2 and 3 is observed in the case no emission policy is applied. The higher revenues caused by higher product prices offer the opportunity to use more expensive logistic modes to decrease OTDLT.

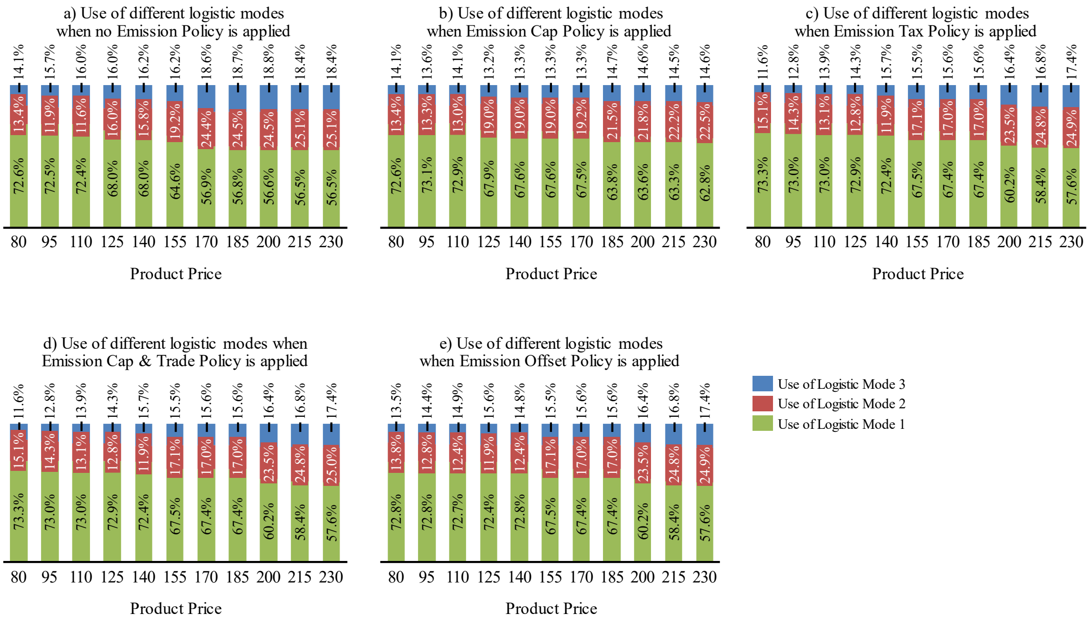

Figure 6.17: Use of different emission policies with varying product prices

The increase of modes 2 and 3 with high product prices is lower compared to the increases with low product prices. These tendencies are also observed with fulfilled demand; with high emission prices, only a slight increase in fulfilled demand is observed. The price-based emission policies reduce the share of emission-intensive modes 2 and 3 compared to those without an emission policy. An emission cap limits the total emission for high product prices the most, and compared to the other results, a lower share of modes 2 and 3 is observed.

The average number of goods in stock increases with increasing product prices, as shown in Fig. 6.18. At first, average stock increases strongly, but less so for higher product prices, until it stagnates at high inventory levels. Under the price-based emission policies, this development is further delayed and stagnation due to the strict emission cap set in earlier with lower product prices and remains below the level under the other policy options. Furthermore, the differences between the results for no emission policy and the market-based emission policies decrease with higher product prices. With high product prices, the stock levels are equal; only under the emission cap are deviations observed.

The stock thus seems to be important, under the given assumptions, to meet customers' requirements regarding OTDLT.

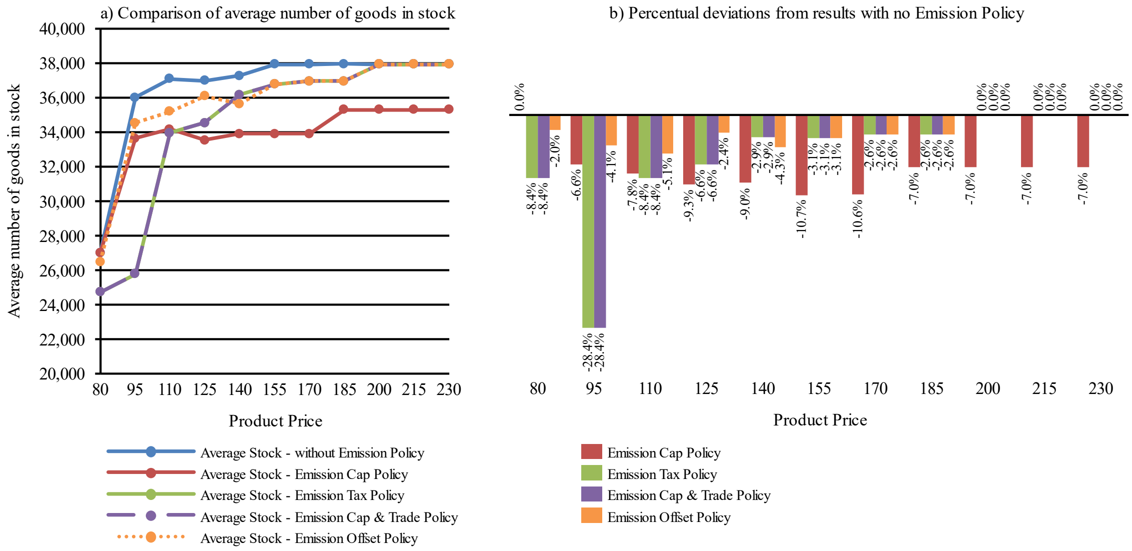

Figure 6.18: Average number of goods in stock and deviations from results without emission policy with varying product price

6.5.3 Results with Varying Emission Cap

To examine the influence of the height of the imposed emission cap per period, the product price is fixed to 185 monetary units. Furthermore, it is assumed that 100% of customers are OTDLT-sensitive, and the emission price is set to 75 monetary units. For the assumption of a cap-dependent emission price, the emission price is calculated as follows:

$$\Omega^{CAT} = 75 + (9500 - ECap) * 0.006.$$

As shown in Fig. 6.19, the level of the emissions cap can have a significant impact on total profit and the met demand. Under the emission cap policy, these results are most affected when the cap is low. Because of the prohibitive nature of a strict emissions cap, fulfilled demand (Fig. 6.19(b)) is much lower than under the other emissions policies when a low cap is imposed per period. With a higher emission cap, both total profit and met demand increase because of the opportunity to generate additional emissions to reduce OTDLT. The emission cap and trade and emission offset policies, on the other hand, provide the flexibility to exceed the imposed limitation. Therefore, even with a low imposed cap per period, both total profit and met demand are higher than under the emissions cap policy.

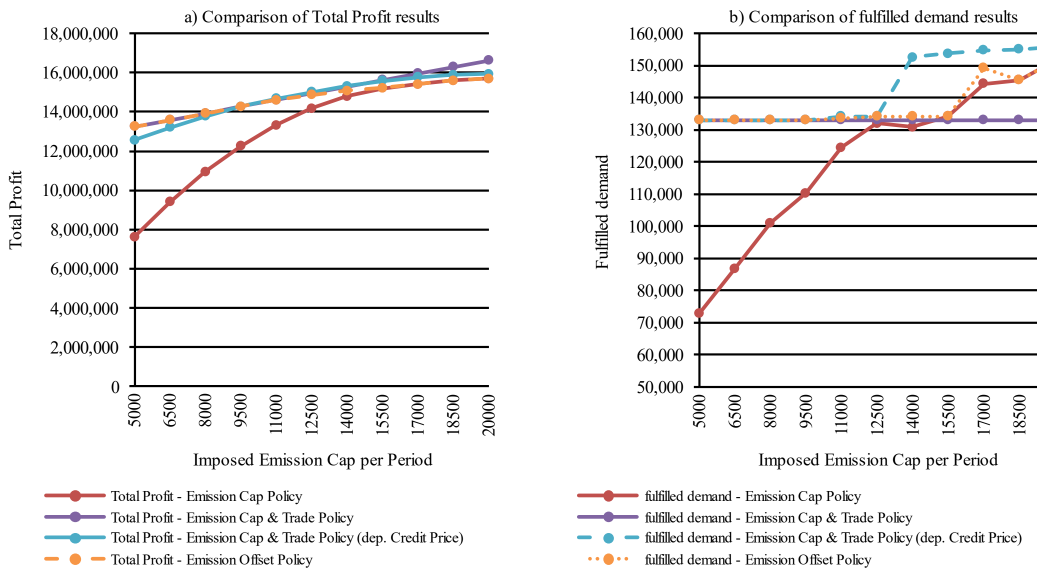

Figure 6.19: Total profit and fulfilled demand with varying emission cap per period

At a higher imposed emissions cap, fulfilled demand increases under all policies, despite of under emission cap and trade policy with fixed emission credit price. This increase is not necessarily reflected as an increase in total profit, as total costs increase to achieve a lower OTDLT. The highest fulfilled demand outcomes are achieved with a high imposed cap under the emission cap and trade with dependent credit price. This effect can be explained by the low incentive to reduce emission levels due to the low price. In contrast, demand fulfillment under the emission cap and trade with a fixed credit price is not affected by the level of the imposed cap, and total profits increase linearly due to the lower demand for additional emission credits.

Due to the linear relationship between product price and fulfilled demand, total revenues reflect the results of fulfilled demand scaled by product price, as shown in Fig. 6.20 a). The imposed cap can strongly impact total revenues under an emissions cap policy. Total costs under the emission cap policy are significantly lower with a low cap compared to the other policies studied. This also reflects the lower levels of fulfilled demand. As the emission cap increases, the too does the total cost. Starting from a low cap, total costs are regressive under market-based emissions policies due to the lower burden of buying credits or allowances. In the case of emissions cap and trade with dependent allowance price, total costs increase sharply at a cap of 12,500 emission units, which is associated with an increase in fulfilled demand. Under the emissions offset regime, there is an increase in total cost at a cap value of 14,000 due to increased fulfilled demand and the associated OTDLT reduction. In contrast, emission trading with fixed emissions prices shows only decreasing total costs, attributable to the stable fulfilled demand and additional revenues for emissions credits.

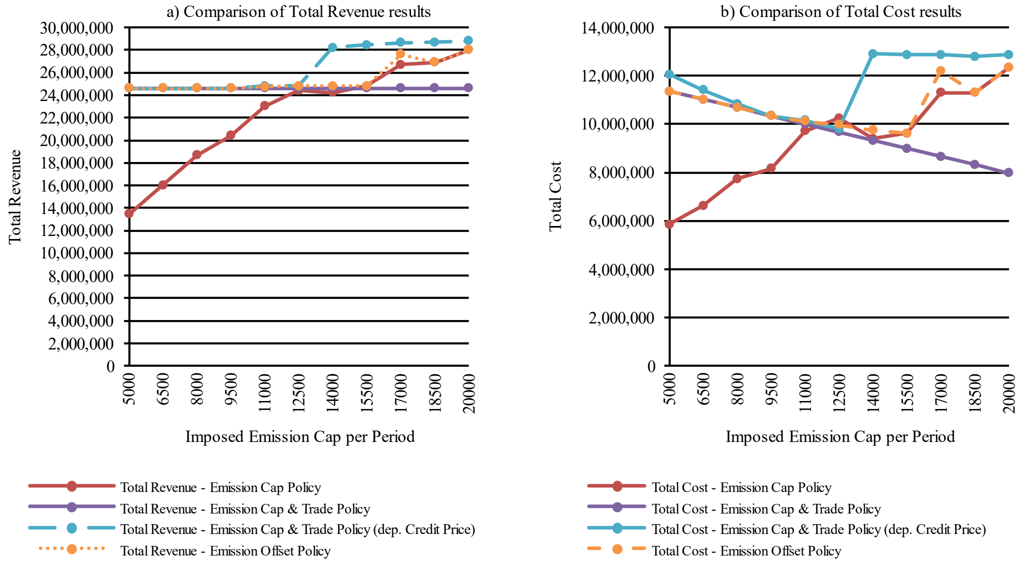

Figure 6.20: Total revenue and total cost with varying emission cap per period

A similar picture emerges for total emissions, as shown in Fig. 6.21 a). As the emissions cap increases, emissions rise sharply and almost linearly under the emission cap policy. Under the emission cap and trade with prices dependent on the emission restriction, the total emission value initially remains constant and rises slightly with an increasing cap.

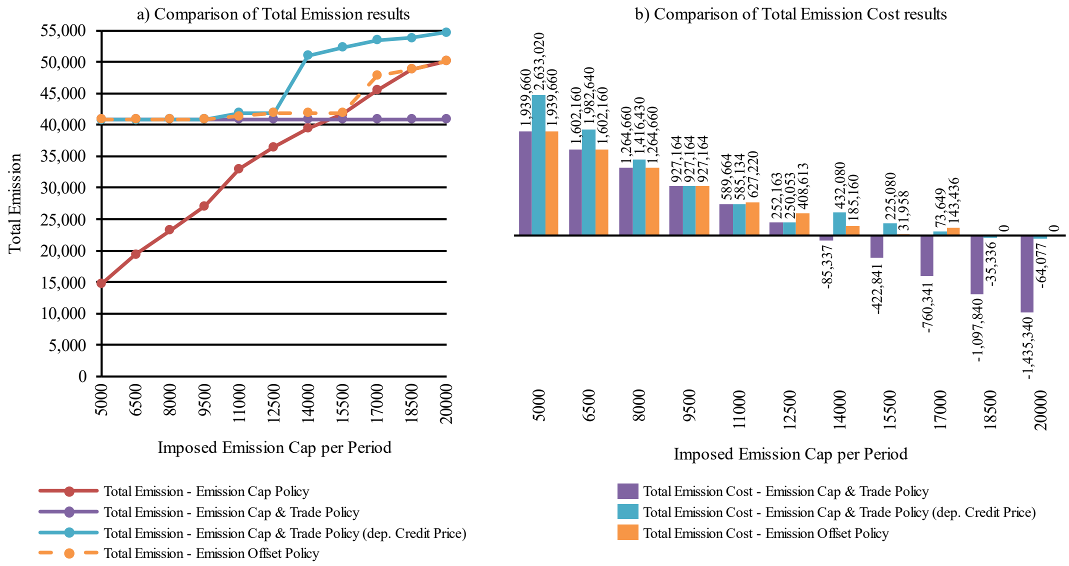

Figure 6.21: Total emissions and total emission cost with varying emission cap per period

A substantial increase is observed at a restriction higher than 12,500 emission units, which then levels off. This can again be attributed to the increase in fulfilled demand and the associated reduction in OTDLT. The total emission value remains constant under emission cap and trade with fixed credit prices, even with increasing emission restrictions.

With higher restrictions, total emission costs decrease, as shown in Fig. 6.21 b). This pattern explains why total costs initially decrease with lower emission restrictions. With high restrictions, additional income can be generated from the sale of emission credits under emission cap and trade.

The number of suppliers chosen, and thus the available supplier capacity, is also influenced by the emission cap, as Fig. 6.22 shows. Under little restriction, only three suppliers are used. Furthermore, under the emission cap policy, other suppliers are chosen than under the other policies. This finding can be attributed to the presence of additional expensive but lower emission suppliers under the emission cap policy.

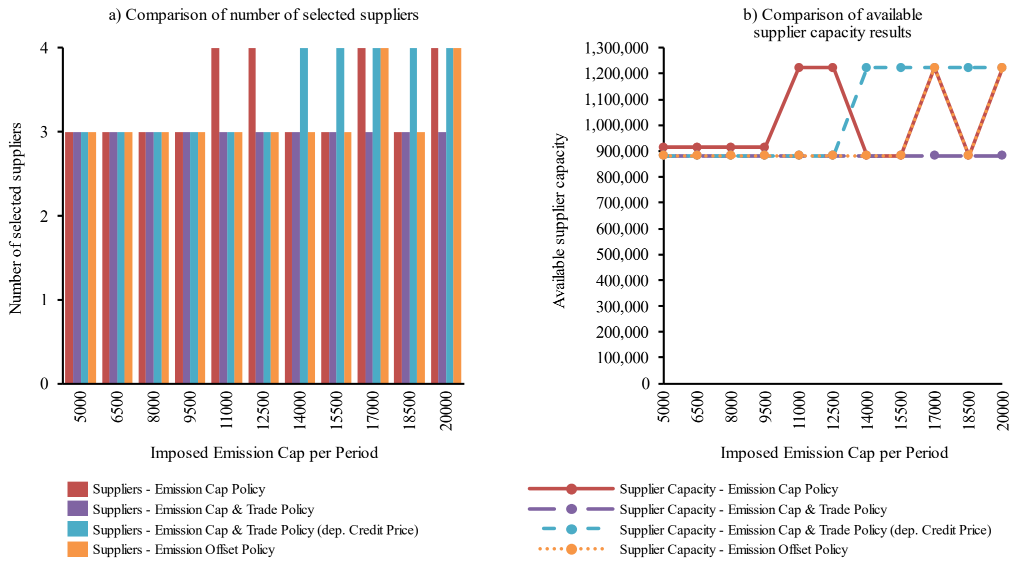

Figure 6.22: Number of selected suppliers and available supplier capacity with varying emission cap per period

With a higher emission cap, the number of suppliers increases to four. However, under the emission cap and emission offset policies, the number of suppliers is reduced to three under certain cap values. This can be attributed to the trade-off between procurement costs, transport costs, and emissions. Under emission cap and trade with fixed credit prices, the number of suppliers does not change as the emission limit increases; with variable credit prices, the number of suppliers increases to four, starting from a limit of 14,000 emission units.

The number and capacity of production sites opened are shown in Fig. 6.23. With higher caps, more sites are opened under the price-based emission policies. Notably, only the lower capacity option is chosen; hence, it appears that the flexibility from having several sites has a stronger influence in reducing OTDLT than does pure capacity increases.

However, with an emission cap and trade policy with fixed credit prices, the number of sites is always two. Under emission cap policy, only one production site is opened under stringent restrictions. With further relaxation of the emission cap, more sites are established. Notably, in three cases, a high site capacity is also selected. This overlaps with the cases in which four suppliers are selected, and the fulfilled demand also increases.

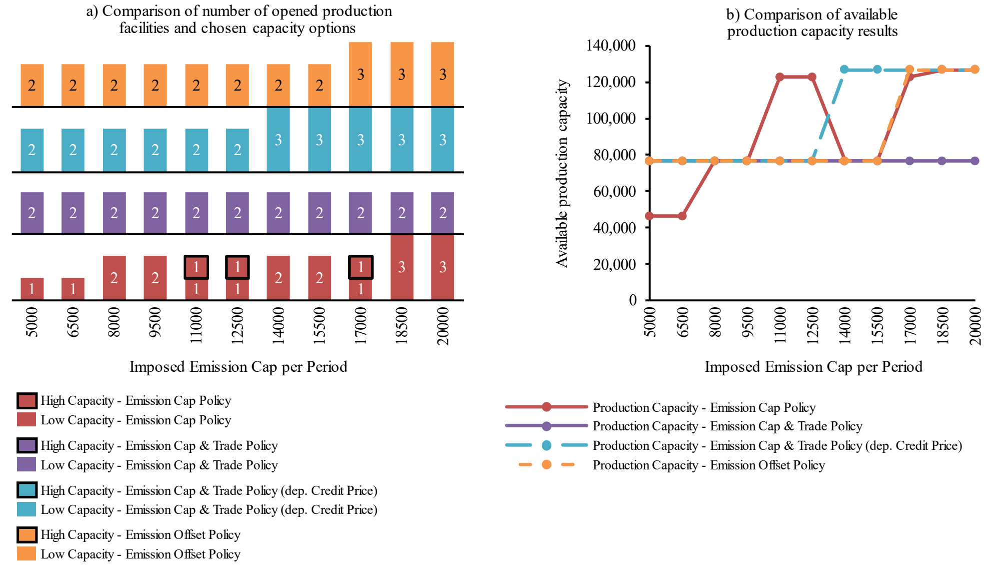

Figure 6.23: Number of selected production facilities and available production capacity with varying emission cap per period

The number of established warehouses is largely unaffected by the level of the imposed emission cap per period, as shown in Fig. 6.24.

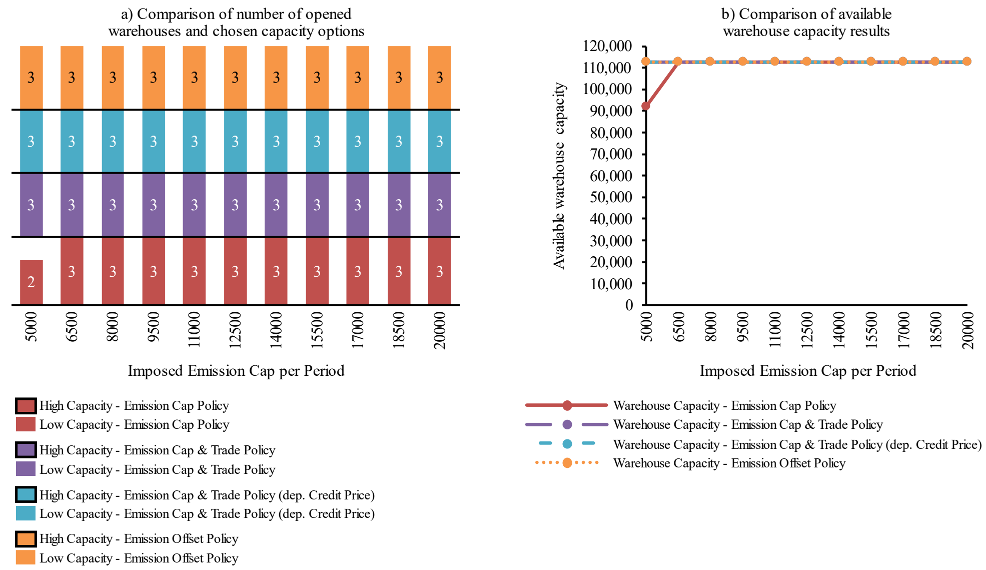

Figure 6.24: Number of established warehouses and available warehouse capacity with varying emission cap per period

In all other examined cases, three warehouses are established. This underpins the assumption of the previous chapters that warehouses are highly relevant to achieve lower OTDLT.

The use of different logistic modes under the examined emission policies is depicted in Fig. 6.25. Under emission cap and trade with stable emission credit prices, no changes in the share of different logistic modes with varying emission caps are observed. Under emission cap and trade with cap-dependent credit prices and under the emission offset policy, the shares of modes 2 and 3 increase with increasing fulfilled demand. The increase is lower for the emission offset policy, which also reflects the total emission under this policy.

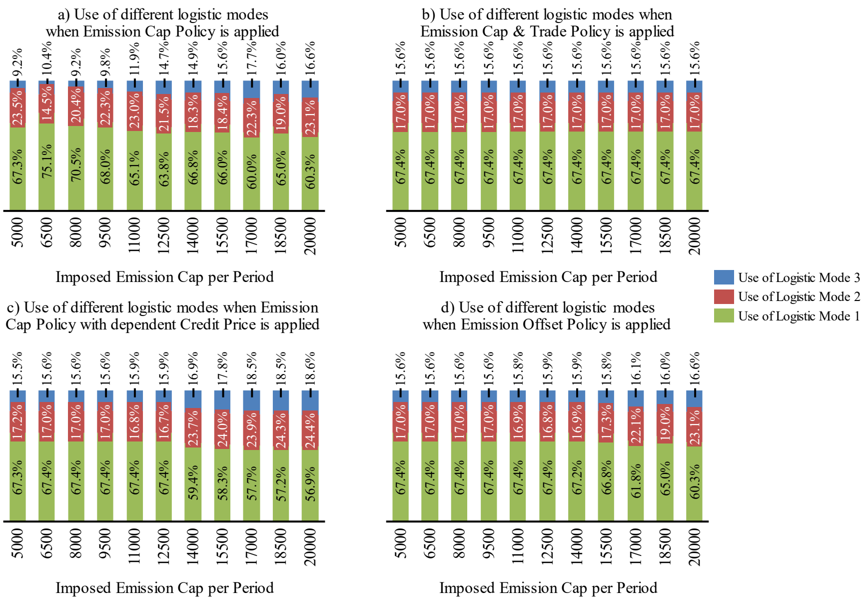

Figure 6.25: Use of different logistic modes with varying emission cap per period

Due to the lower prices for emission credits with a high cap per period, the incentive to reduce emission amounts appears lower than under the emission offset regime. The share of different logistic modes fluctuated substantially more under the emission cap policy. Due to the harsh regulation, the trade-off between the different emission sources seems to be intensified, and the use of logistic modes is adjusted to suit the cap situation. In general, an increase of logistic mode 3 is observed under milder restrictions. However, the increase of logistic mode 3 can lead to the decrease of logistic modes 1 and 2. Interestingly, there is no evident increase of faster logistic modes when fulfilled demand increases strongly. Shorter transportation routes can explain this finding due to an increase in facilities and suppliers.

Lowering the burden of the imposed emission cap per period is associated with increases in the average number of goods in stock, as shown in Fig. 6.26. With a harshly imposed cap, under an emission cap policy, average stocks are comparably low. Compared to the case of no applied emission policy, the average number of goods in stock can be lowered up to 46.1% under emission cap policy. The effect of the imposed cap under the market-based emission policies is weaker than under emission cap policy; nonetheless, an increase of goods in stock is observed for a higher cap. When the emission cap is high, the emission cap and trade with variable credit prices and the offset policy lead to the same stock levels. Mainly due to the substantial increase of goods in stock under emission cap policy and the resulting increase of fulfilled demand, it can be assumed that building up stocks can be an essential factor to achieve low OTDLT.

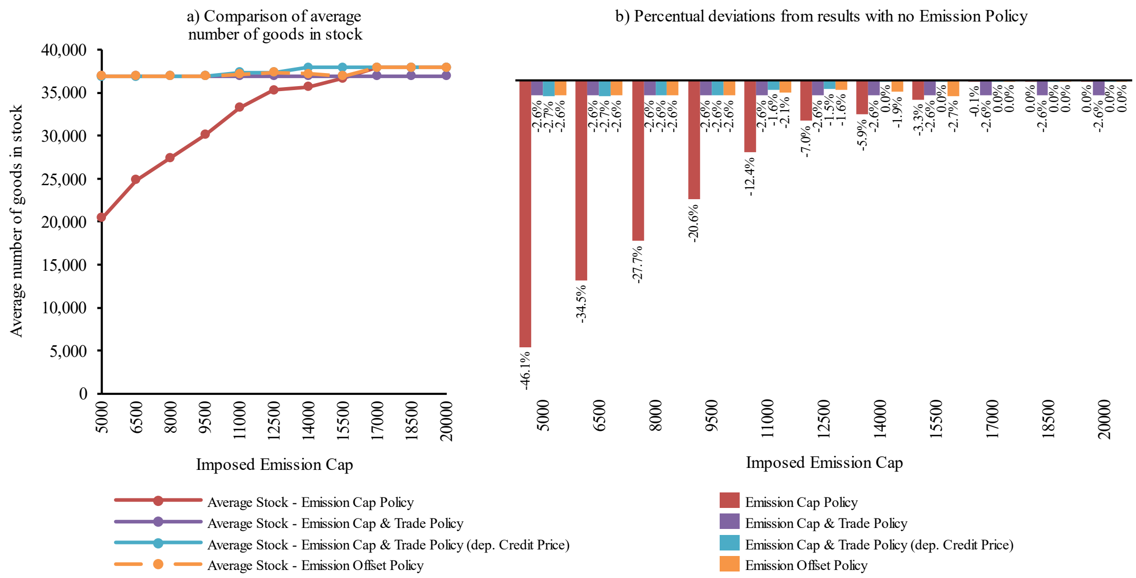

Figure 6.26: Average goods in stock and deviations from results without emission policy with varying emission cap per period

6.5.4 Results with Varying Emission Price

The emission cap per period is fixed at 9,500 emission units to examine the influence of emission prices. Furthermore, a product price of 185 monetary units and a 100% share of OTDLT-sensitive customers is assumed.

With increasing emission price, total profit decreases, as depicted in Fig. 6.27 a). With low emission prices, most of the total profit reduction can be attributed to increasing the total cost through higher emission costs. With an emission price higher than 45 monetary units, a substantial decrease in fulfilled demand is evident under all emission regimes, as shown in Fig. 6.27 b). Because of the linear relationship between total revenues and fulfilled demand, this furthermore lowers the total profit.

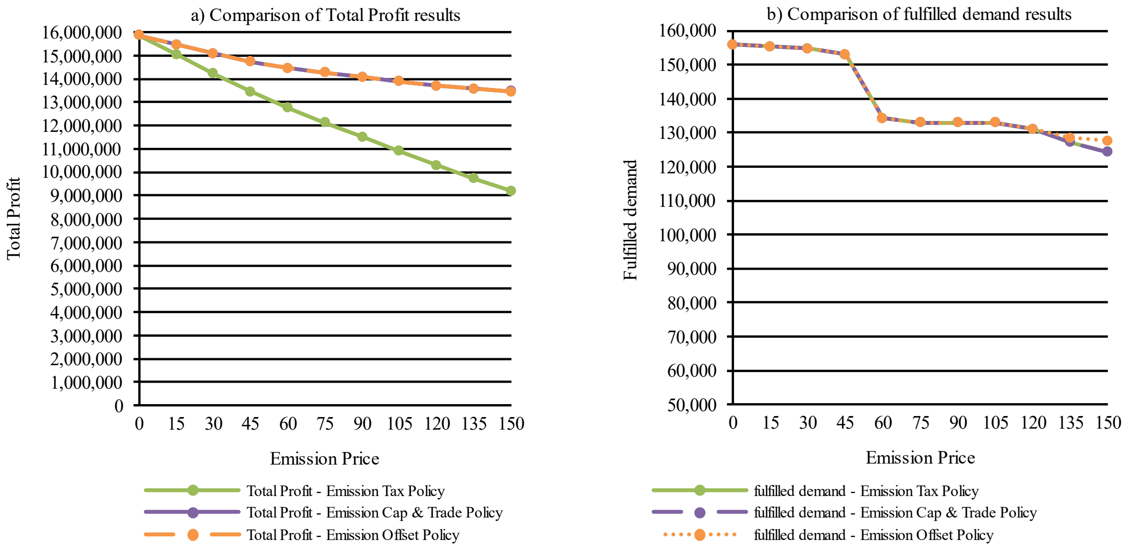

Figure 6.27: Total Profit and fulfilled demand with varying emission price

Under an emission tax policy, total profit is affected the most by increasing emission prices. This effect is weaker with the emission cap and trade and emission offset policies, which lead to identical total profit results. Results of fulfilled demand are the same under emission tax and the emission cap and trade policy. In general, fulfilled demand decreases with increasing emission prices. A marked decrease is evident with emission prices higher than 45 monetary units. With an emission price higher than 60 monetary units, only slight decreases are evident. Under the emission offset policy, fulfilled demand is slightly higher in the case of high emission prices than under the other two examined policies.

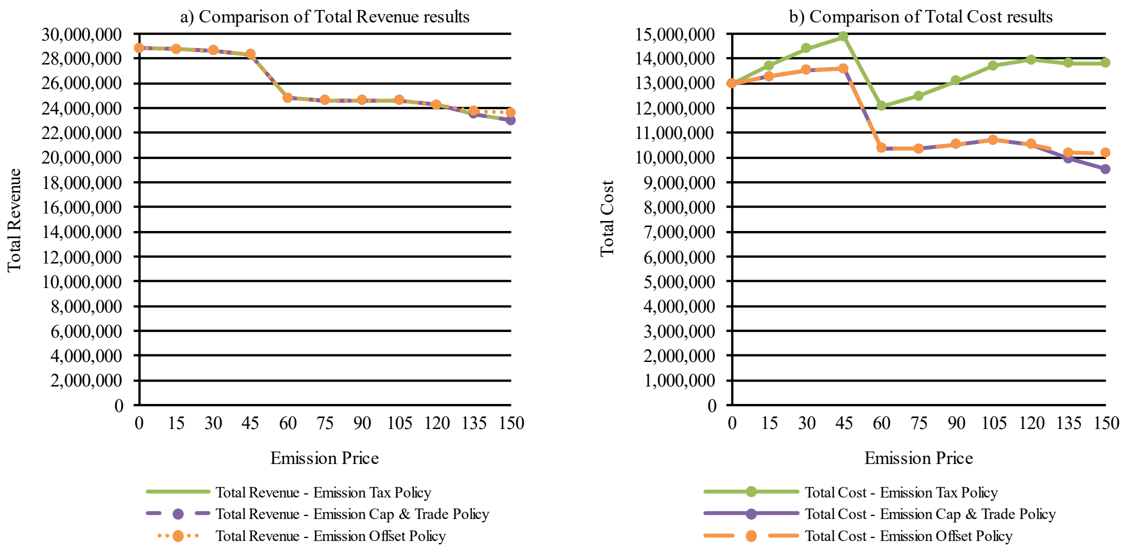

Figure 6.28: Total revenue and total cost with varying emission price

The linear relationship between fulfilled demand and total revenues is illustrated in Fig. 6.28 b). With decreasing demand fulfillment, total revenues also decrease under all emission policies. Total cost, in contrast, initially increase due to the higher emission prices. With an emission price higher than 45, a decrease is evident, which can be attributed to the decrease in fulfilled demand. Afterward, a further increase is evident, starting from emission prices of 60 monetary units due to the additional costs required to achieve lower OTDLTs. Under the emission tax policy, total costs are higher than with an emission cap and trade or an emission offset policy. In addition, the increases in total cost are stronger under an emission tax policy. A slight decrease in total cost is evident with an emission price higher than 120 monetary units. Under high emission prices, emission cap and trade leads to the lowest total cost due to the market-based buying and selling of emission credits. Emission offset generates higher costs than emission cap and trade with high emission prices, but the greatest impact of emission prices on total cost is found with the emission tax policy.

Increasing emission prices lower the total emission strongly, as shown in Fig. 6.29 a). Up to an emission price of 120 monetary units, all policies lead to the same total emission results. With higher emission prices, the incentive to reduce emissions appears weaker under emission offset, and higher total emissions are observed. Under emission tax and emission cap and trade policies, similar results are generated. A marked decrease in total emission is evident for emission prices of 45 to 60 monetary units, which can be attributed to the lower met demand. Total emission costs under emission cap and trade and emission offset policy partly reflect this development.

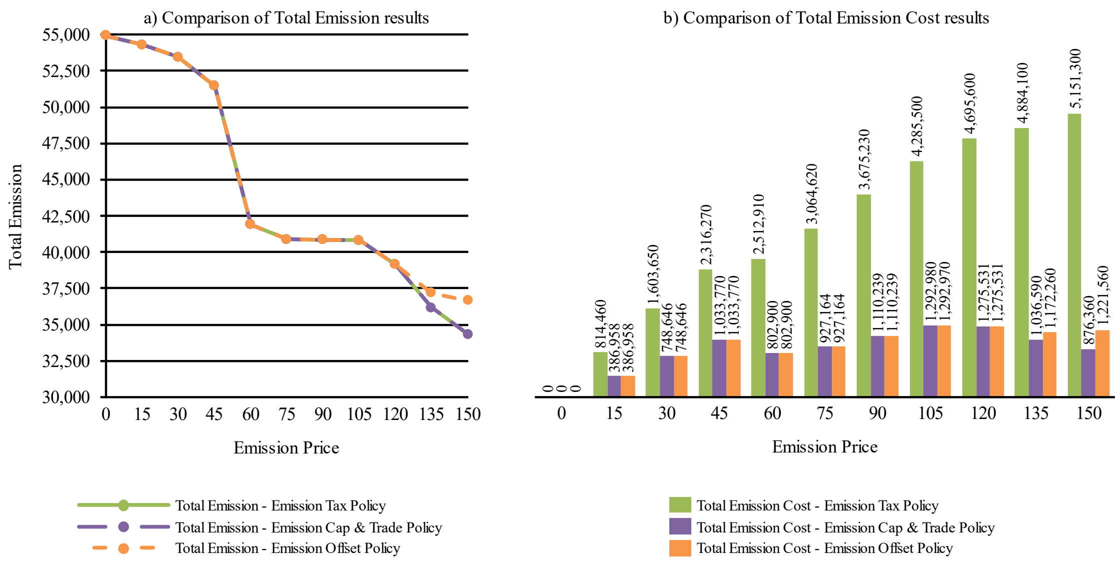

Figure 6.29: Total cost and total emission cost with varying emission price

With low emission prices, an increase in total emission cost can be observed, despite reducing the total emissions. The increase in emission prices seems to outweigh the effects of emission reduction. However, with the strong decrease because of less demand fulfillment, total emission costs are also reduced. An increase is evident with prices between 60 and 105 monetary units. From this point, total emission decreases strongly, leading to lower total emission costs under these policies. By contrast, with increasing emission tax rates, total cost always increased. The increase slows down with higher tax rate, but total emission costs under the emission tax regime are significantly higher than under the emission cap and trade or the emission offset policy.

The number of selected suppliers and the available supplier capacity are illustrated in Fig. 6.30. Under emission offset policy, even with low emission prices the number of selected suppliers is reduced. In the case of emission tax and the emission cap and trade policy, this reduction is evident with an emission price of 45. With further increases in emission price, these policies, the number of suppliers and the supplier capacity do not change.

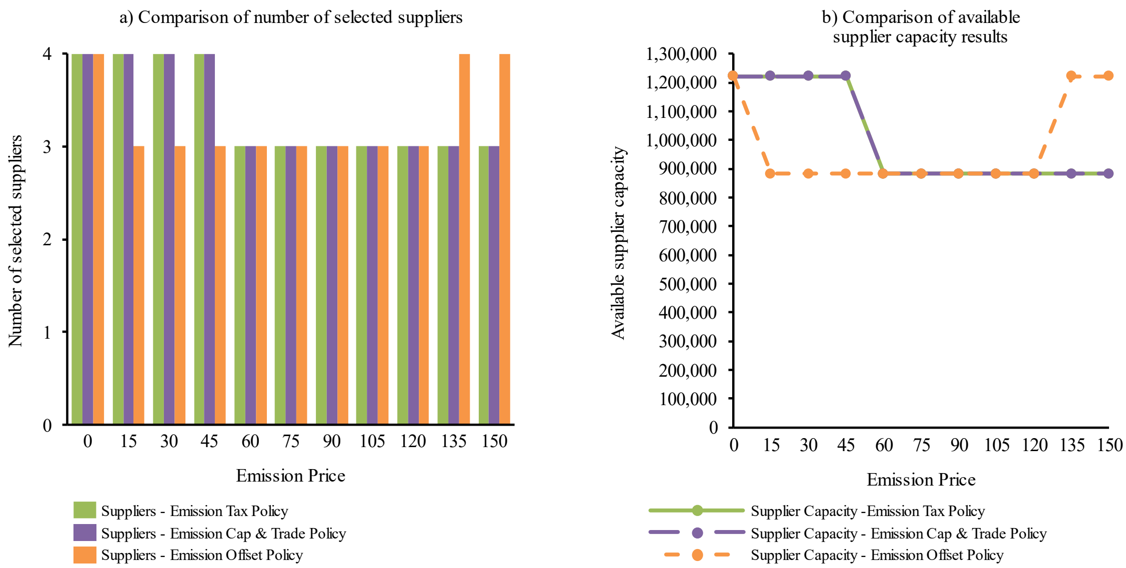

Figure 6.30: Number of selected suppliers and available supplier capacity with varying emission price

By contrast, under the emission offset policy, the number of suppliers increases up to four for high emission prices. Fig. 6.30 b) indicates that the same three suppliers are selected with each emission price.

A similar development is evident for production facilities, as shown in Fig. 6.31. With low emission prices, all facilities are established in low-capacity configurations. This offers flexibility to provide short OTDLT to meet customers' needs. With the observed reduction in fulfilled demand, the number of production facilities is also reduced. However, for lower demand fulfillment, less capacity is needed. The higher facility costs and total emission cost, in particular, seem not to justify using three established facilities to reduce OTDLT.

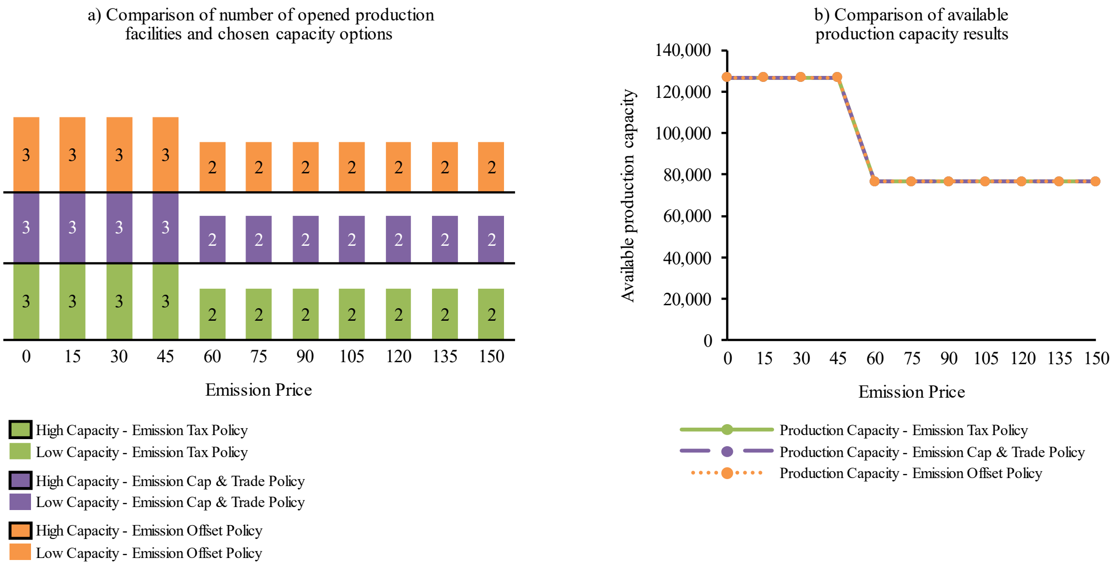

Figure 6.31: Number of established production facilities and available production capacity with varying emission price

In contrast, the number of selected warehouses and available warehouse capacity are not affected by the height of emission prices, as illustrated in Fig. 5.32. Therefore, it can be concluded that warehouses are essential to guarantee a certain degree of OTDTL and are a minor source of either high emission or cost reduction.

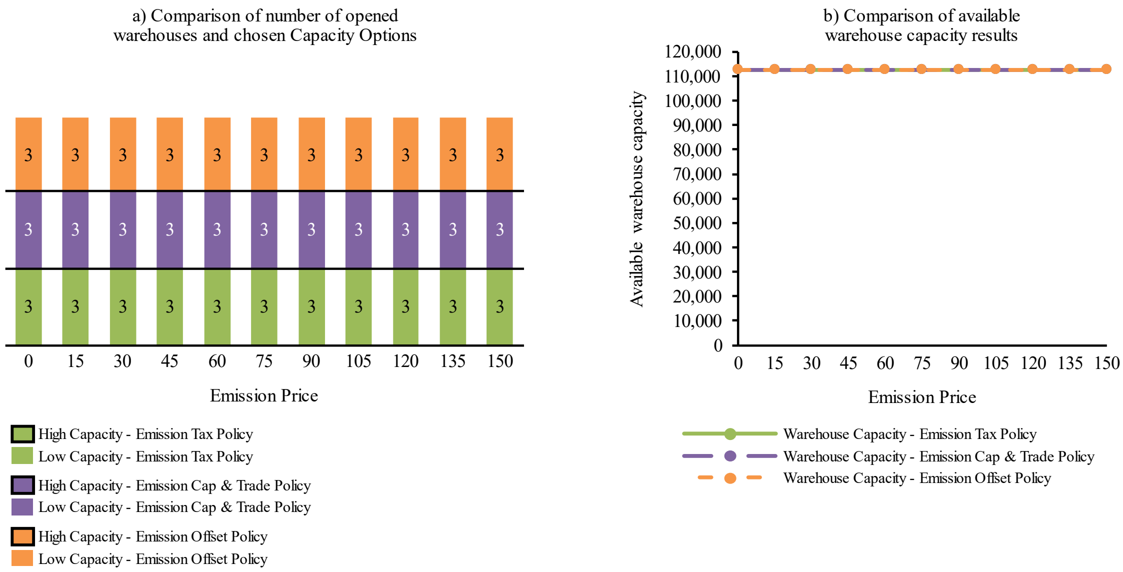

Figure 6.32: Number of opened warehouses and available warehouse capacity with varying emission price

The share of logistic modes is shown in Fig. 6.33. In general, a decrease in logistic modes 2 and 3 is evident with increasing emission prices. Emission tax and emission cap and trade policies lead to similar results. For emission offset, a higher share of logistic mode 3 is evident for high emission prices, whereas the share of logistic mode 2 is reduced compared to under the other two policies. With an emission price of 60 monetary units, a strong reduction of logistic modes 2 and 3 is evident under all emission policies. This reflects the substantial decrease in total costs and total emissions. Furthermore, the reduction in the use of faster logistic modes leads to increasing OTDLT and hence to lower demand fulfillment. Under emission offset policy with high emission prices, a higher share of logistic mode 3 is used, which may explain the higher total cost, total emission, and fulfilled demand.

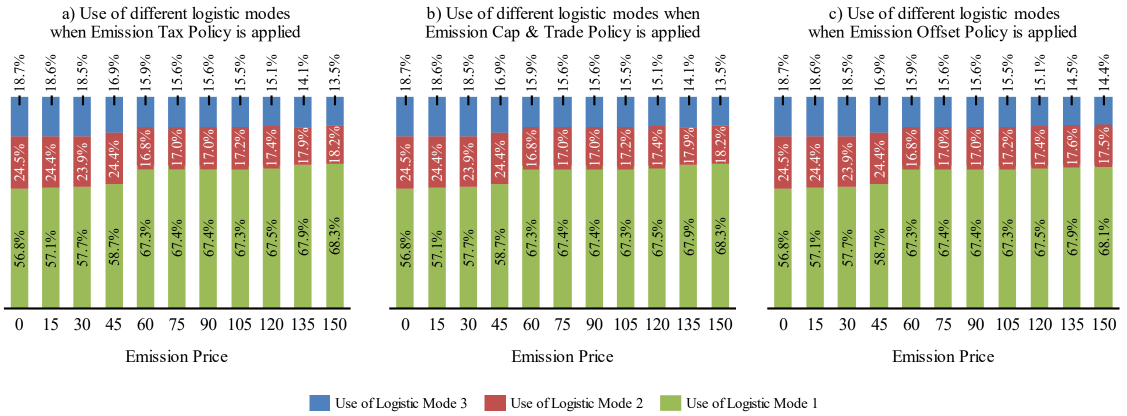

Figure 6.33: Use of different logistic modes with varying emission price

Stock levels are affected by higher emission prices, as Fig. 6.34 a) shows. A decrease in the average number of goods in stock is evident with emission prices higher than 45 monetary units. With high emission prices, the average number of goods in stock is up to 9% lower than without emission policies (Fig. 6.34 b). The lower amount of goods in stock may lead to higher OTDLT and further reduction of fulfilled demand. Compared to the emission tax and emission cap and trade policy, the emission offset policy resulted in less reduction of stocks. This may explain the higher total emissions, total costs, and fulfilled demand, in addition to the higher number of suppliers and the higher share of fast logistic modes.

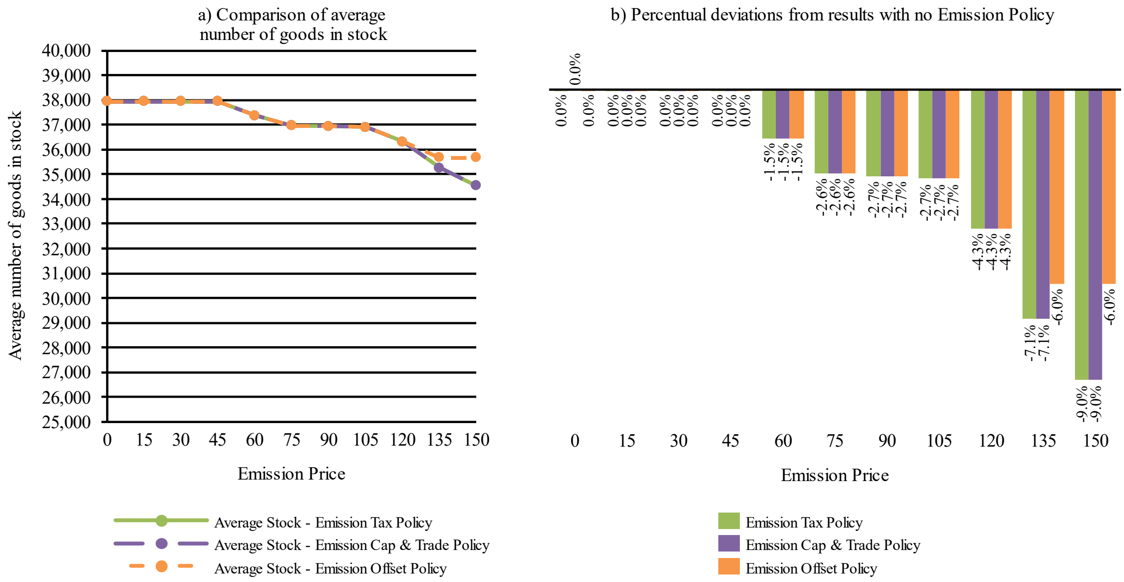

Figure 6.34: Average goods in stock and deviations from results without Emission policy with varying emission price

6.6 Conclusion

As shown in the previous sections, the share of OTDLT-sensitive customers can significantly impact supply chain design. In the examined example, total revenues decrease, whereas total cost increase with a higher share of sensitive customers.

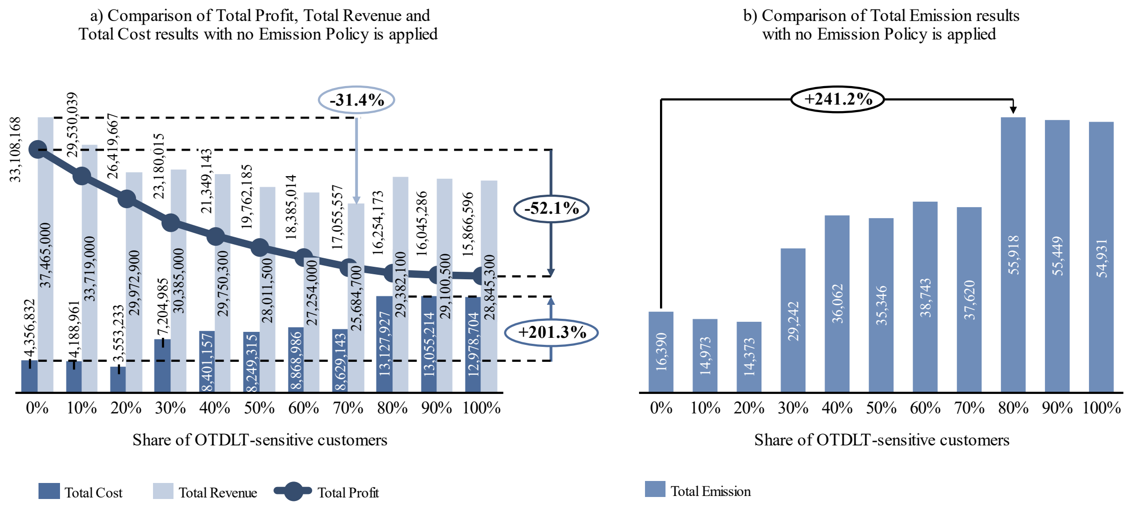

Figure 6.35: Total profit, total revenue, total cost, and total emission results without emission policy

In detail, at maximum, total revenues can be reduced by up to 31.4% in the given example, and total costs can increase by up to 201.3%, as shown in Fig. 6.35 a). Therefore, total profit is strongly affected by customer needs and can be reduced by up to 52.1%. Furthermore, total emission values are highly affected with more OTDLT-sensitive customers, as illustrated in Fig. 6.35 b). With a low percentage of sensitive customers, low levels of total emissions are achievable; however, due to the pressure to lower OTDLT to meet customer needs, total emissions may increase by up to 241.2%.

In general, the share of OTLDT-sensitive customers has a marked impact on the design of supply chain networks. Fig. 6.36 shows the optimal design of the supply chain with 0% (a) and 100% (b) of time-sensitive customers. When no customer is sensitive towards lead time, a lean supply chain seems suitable, and a minimum of suppliers, production facilities, and warehouses is established. As the proportion of OTDLT-sensitive consumers increases, so does the complexity of the network. A significant increase in the number of suppliers, production sites, and warehouses is evident, but as previously explained this is not necessarily due to increased capacity. More important is the additional flexibility provided by having more locations to offer consumers lower OTDLT. Of course, this additional effort also increases total costs and total emissions. Furthermore, the need for faster logistic modes and additional stock-related activities are drivers of cost and emission increases.

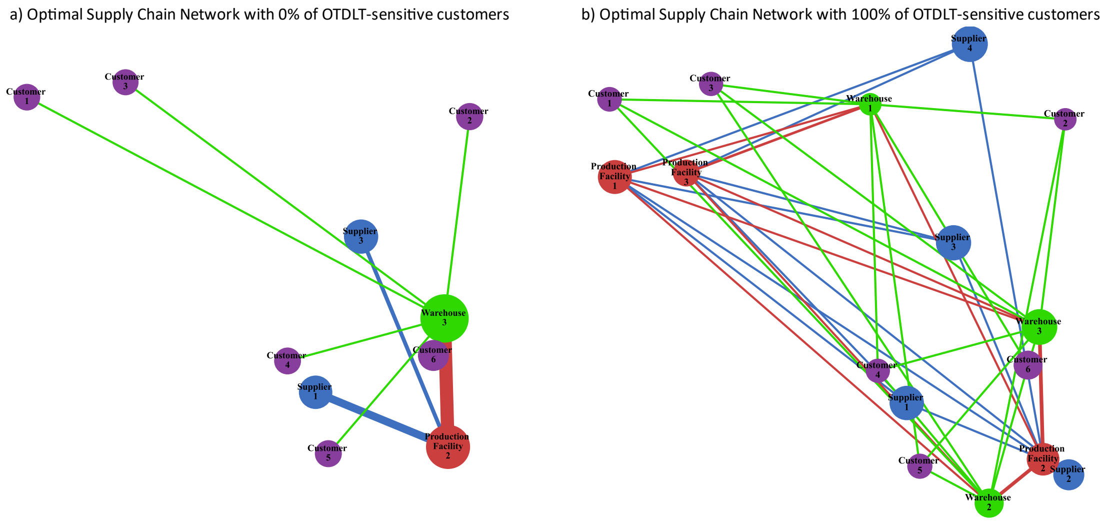

Figure 6.36: Supply Chain Networks with 0% and 100% of OTDLT-sensitive customers

A higher share of OTDLT-sensitive customers leads to a decrease in fulfilled demand, as illustrated in Fig. 6.37 a). The rising share of customers demanding low OTDLT puts pressure on the company to fulfill orders faster. This leads to increased total costs, and the trade-off between demand fulfillment and cost minimization is intensified. In the given example, it seems advantageous to accept only those orders that can be processed economically. Accordingly, the fulfilled demand is always below the maximum possible value with more time-sensitive consumers. As soon as further restrictions arise due to emission policies, the fulfilled demand is reduced further. However, emission policies also lead to a decrease in total emission, as illustrated in Fig. 6.37 b). The impact of emission policies is still low with a small proportion of OTDLT-sensitive customers, as the supply chain in these cases is relatively lean. However, emissions can be reduced significantly as the proportion of sensitive consumers increases. This reduction is also partly due to the reduction in demand fulfillment. However, the reduction in emissions is more significant than the reduction in fulfilled demand, so various supply chain activities are altered to generate lower emissions, leading to reduced total emissions.

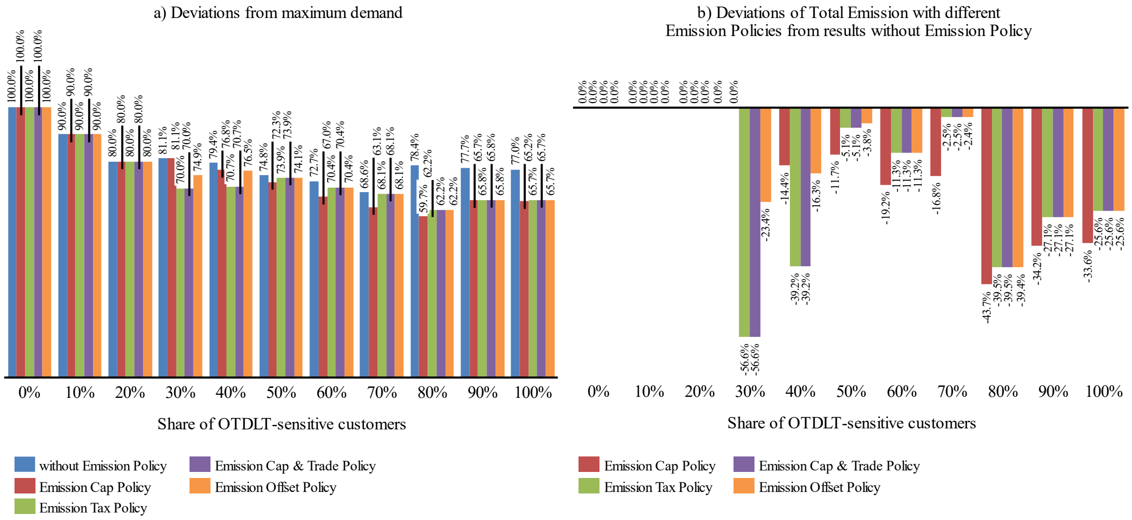

Figure 6.37: Percentage of demand fulfillment and percentual deviations in total emission results in comparison to results without emission policy

Aside from the share of OTDLT-sensitive customers, in the given example it is evident that the product price strongly influences the supply chain design decisions. Total profit and fulfilled demand are highly influenced by the height of the product price, as shown in Fig. 6.38. With a low product price, fulfilled demand and total profit are strongly reduced because it would not be possible to reduce OTDLT economically. With rising product prices, profits and fulfilled demand also increases. Total profit can be enhanced strongly by very high prices, whereas fulfilled demand is only slightly affected. However, these trends are only relevant if customers are only OTDLT-sensitive and are willing to pay a price premium for fast delivery. As soon as customers are also sensitive towards price, the assumptions do not apply. With increasing product prices and the possibility of ensuring faster OTDLT for each customer, total emissions also increase, as illustrated in Fig. 6.38 b). It is evident that strong increases in fulfilled demand lead to high increases in total emission. Therefore, a strong relationship between fulfilled demand – indirectly OTDLT – and total emission is evident.

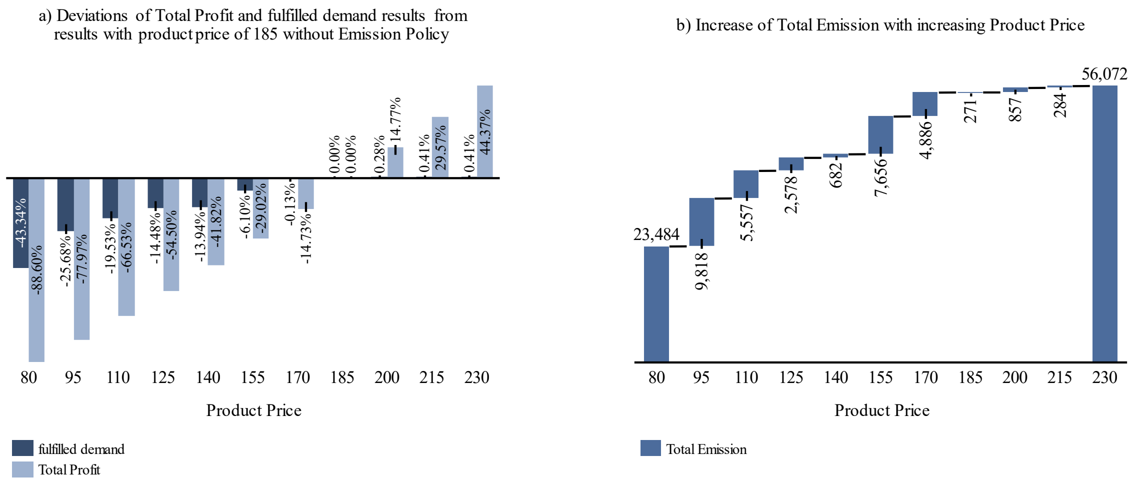

Figure 6.38: Development of total profit, fulfilled demand, and total emissions with varying product price without emission policy

The effects of different emission policies are examined. The total profits and fulfilled demand are further reduced compared to the situation without an emission policy, as illustrated in Fig. 6.39.

Figure 6.39: Percentual deviations in total profit and fulfilled demand results in comparison to result with no emission policy and product price of 185

Even with high product prices, it seems not economically suitable to reach demand fulfillment levels like in the absence of emission policies. However, the same – or higher – total profit levels can be achieved through increased product prices. In the presence of emission regulation schemes, increasing product prices to sustain a certain total profit can be a successful strategy. As long as customers are willing to pay a price premium for fast delivery, costs arising from emission policies can be passed on them. However, reduction efforts can be weakened by higher product prices.

The height of the imposed emission cap significantly impacts demand fulfillment and total emissions. Fig. 6.40 compares the results from chapter 6.5.3 with the results under no emission policy. A low – and therefore harsh – emission cap per period can decrease demand fulfillment significantly. The strongest influence of the cap can be observed under the emission cap policy. The harsh regulation forces companies to reduce their total emissions and offers no flexibility. Therefore, demand fulfillment is strongly reduced. On the other hand, with a high emission cap per period, the total emission is reduced less than it is under the emission offset or emission cap and trade policies. This fact highlights the need for proper adjustment of the emission limit under emission cap policy.

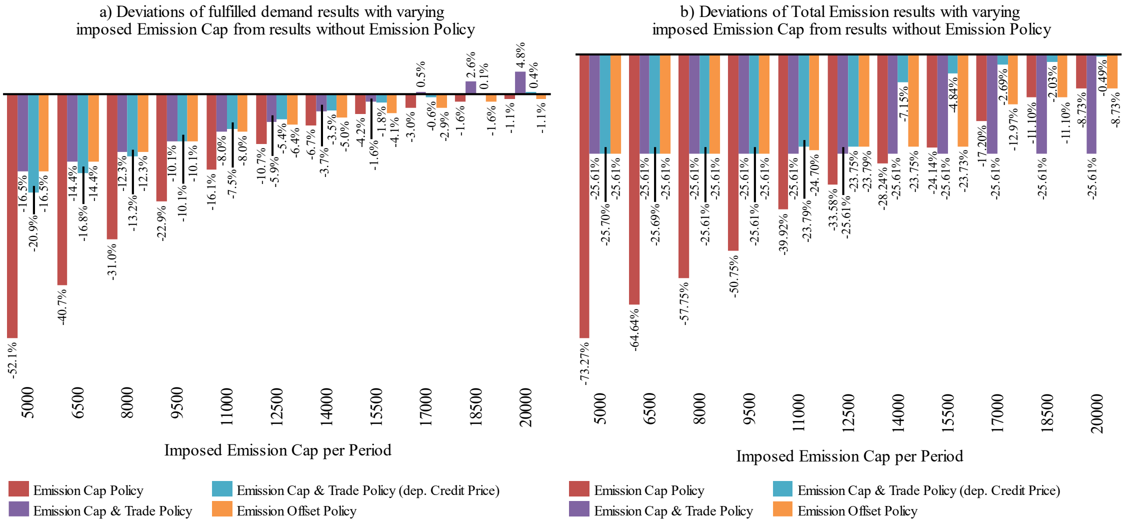

Figure 6.40: Percentual deviations of fulfilled demand and total emission results compared to results without emission policy (varying emission cap per period)

The same need to choose the correct emission cap per period can also be observed for emission cap and trade when emission credit prices are cap-dependent. With too high a cap, the incentive to reduce total emissions is low because of the low credit prices. Emission offset policy also develops strong incentives to reduce emissions when the emissions constraint is set sensibly. In general, too strict a restriction has a substantial impact on the ability of companies to act, whereas too lax a regulation misses its target.

Even if reduced fulfilled demand in turn reduces the total emission, emission policies force a change in various supply chain activities. For a suitable comparison of the different activities, Fig. 6.40 illustrates the average cost and average emission per product under different imposed caps per period. Main sources of emission reduction are sourcing and transportation activities. Furthermore, the average cost per product can be reduced by using slower and less emission-intensive logistic modes (as described in chapter 6.5.3).

In addition, an increase in stock activities is evident under the price-based emission policies. Therefore, a trade-off could occur between faster logistic modes and stock levels. Manufacturing activities offer, in the proposed model, only slight possibilities for emission reduction. This may be due to no consideration of different manufacturing technologies. In contrast, sourcing activities – which the chosen suppliers highly influence – can be vital for lowering emissions, but may increase total costs. Handling activities are negligible in the provided example and offer no possibility to reduce emission amounts.

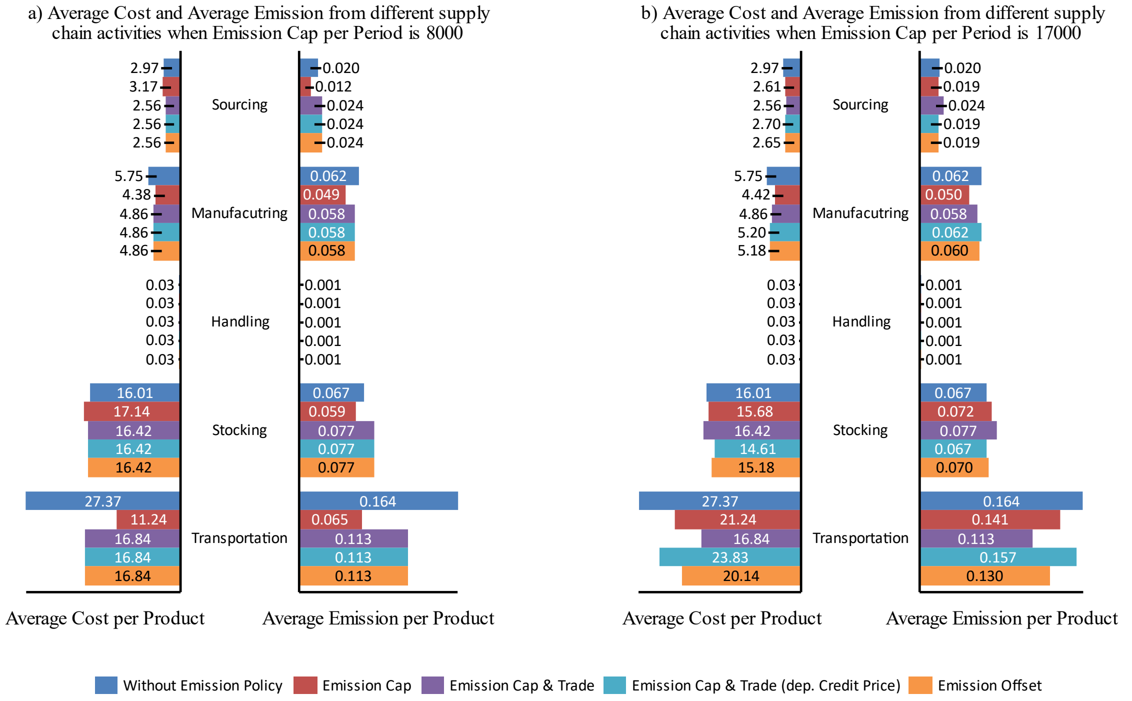

Figure 6.41: Average cost and emissions with different imposed emission caps per period

In the case of the market- or price-based emission policies, the emission price is the determining factor that influences the shape of supply chains. Therefore, emission prices have a high influence on fulfilled demand and total emissions, as shown in Fig. 6.42. With increasing emission price, fulfilled demand deviates significantly and negatively from the results under no emission policy. This deviation results from the pressure to lower emission amounts to reduce emission costs. In the given example, the strongest influence on supply chain design – and thus on fulfilled demand and total emissions – can be attributed to the emission cap and trade and the emission tax policy. Deviations from results under no emission policy are the highest when emission prices are high. In the case of emission cap and trade policy, it is essential to note that the imposed cap must be set properly to achieve these high emission prices. By contrast, the tax rate can be set under the emission tax policy. Emission offset policy can lead to similar results with lower emission allowance prices; however, under this regime, the imposed cap significantly influences the impact. Some reduction in total emission can be attributed to the lower demand fulfillment, but emission policies also force some changes in supply chain activities.

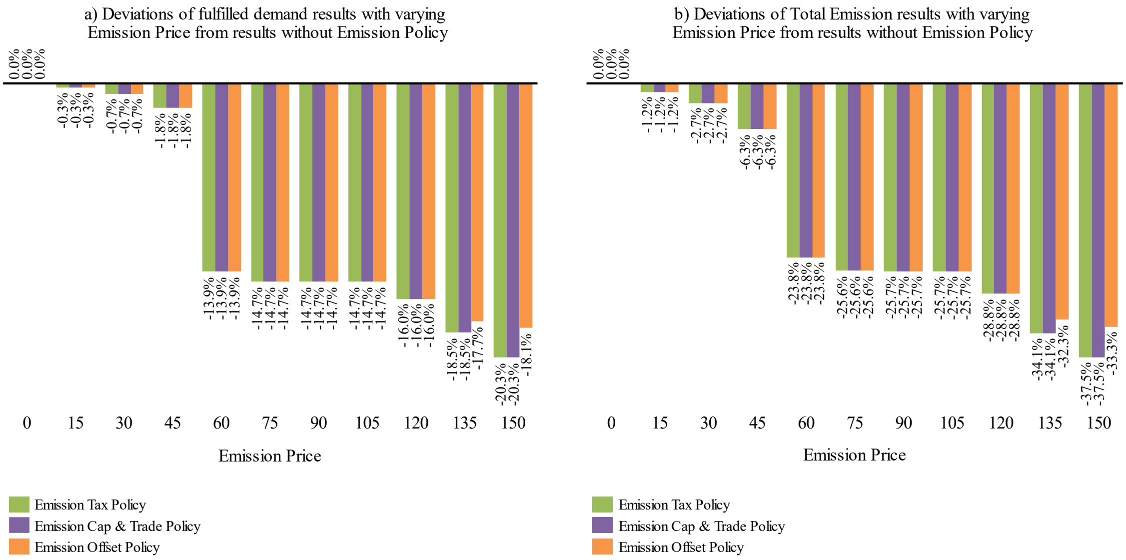

Figure 6.42: Percentual deviations of fulfilled demand and total emission results compared results without emission policy (varying emission price)

To better compare these changes independently from demand fulfillment, Fig. 6.43 shows the average cost and average emission per product for emission prices of 30 and 120 units.

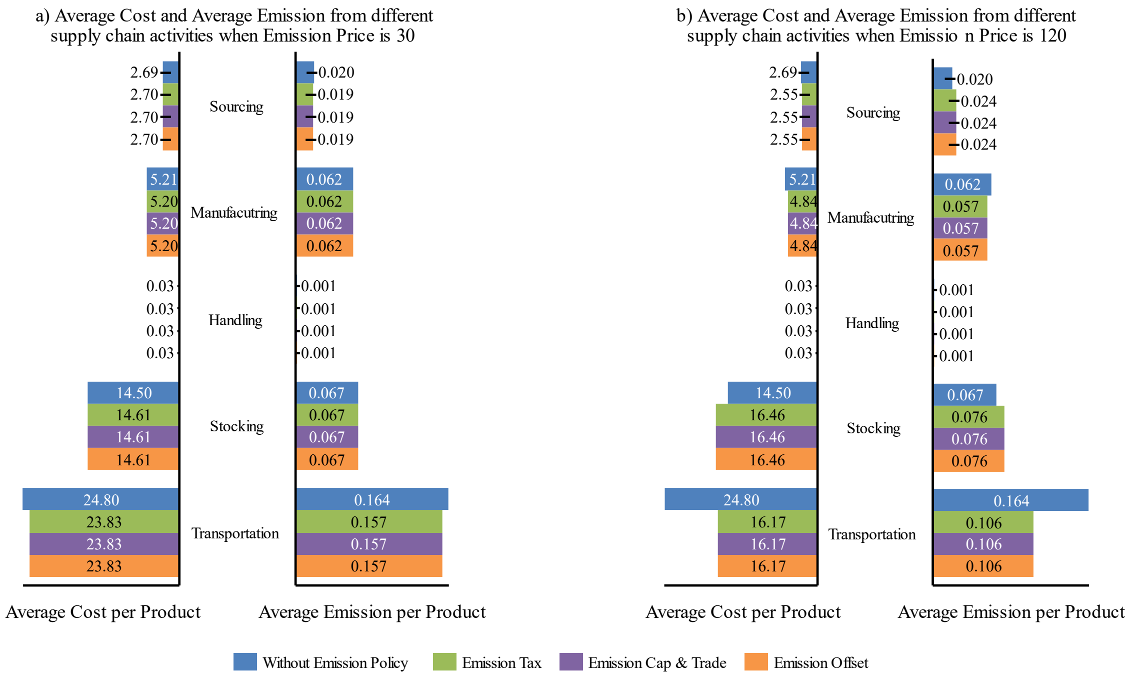

Figure 6.43: Average cost and emission with different emission prices

The primary source of emission reduction can be attributed to transportation activities. By choosing less emission-intense logistic modes, average costs are also reduced. The higher the emission prices, the higher the reduction amounts. To deal with slower logistic modes, stocking activities are intensified. A trade-off between stock-related activities and faster logistic modes is thus identified. Slight reductions in emissions from manufacturing are evident. These reductions are stronger with the possibility of choosing ecofriendly production technologies. In contrast, emissions from sourcing activities seem to increase along with higher emission prices.

Finally, on the basis of the provided model and the data example, the following insights from this chapter are noted:

- The share of OTDLT-sensitive customers has a significant impact on the shape of a supply chain. With demanding customers, the supply chain design must be altered to meet their needs economically.
- A high number of suppliers and facilities can be beneficial to deal with customers' requirements concerning OTDLT. With more suppliers and production facilities, OTDLT can be reduced so that customer needs can be better fulfilled. The number of the facilities seems more important than their capacity. Therefore, more but smaller production facilities seem to be favorable to enable the parallel processing of orders.
- Warehouses are prerequisites for achieving lower OTDLT. In nearly all examined cases, all possible warehouses are established to fulfill demand fast.
- Sufficient product prices are fundamental to achieve customers' OTDLT expectations. With higher prices, higher demand fulfillment can be achieved. Furthermore, under market-based emission policies, increased product prices can cover the total profit losses. Nevertheless, customers must be willing to pay higher prices to attain lower OTDTL.
- Due to its strict command and control nature, an emission cap policy strongly affects the shape of the supply chain and demand fulfillment when the cap is low. With increasing emission caps, these effects decrease, and total emissions are not reduced sufficiently.
- Emission tax has the strongest influence on total cost and therefore on total profits. With a high tax rate, total profits decrease more than under other policies and a company's competitiveness can be harmed. For total emission reduction, an emission tax can lead to significant reduction efforts.

- A well-designed emission cap and trade policy can achieve the same results as an emission tax policy without affecting total cost and profits in as harsh a manner. However, to achieve sufficiently high emission credit prices, the cap must be set correctly. With too low prices, the incentive for emission reduction vanishes. A well-designed cap and trade system may prompt suitable reduction efforts and not lead to dramatic increases in total cost.
- Emission offset policy can lead to similar good results as the other market-based emission policies. The emission price and a properly set cap are essential for the success of such a system. With too high a cap or too low emission prices, this system tends to lose its incentive for emission reduction.
- Transportation activities can be the most crucial source of emission reductions. In addition, considering green suppliers can lower the emissions from sourcing.
- Stocking activities can be used to compensate for slower logistic modes and to reduce total emissions.
- Every emission policy can highly influence fulfilled demand. Therefore, a suitable supply chain design is needed to meet customers' needs and to deal with the restrictions due to such policies.

7 Robust Supply Chain Design Considering Uncertainties and Quoted Order-to-Delivery Lead Time

7.1 Relevance and Assumptions

Agreements such as the KYOTO PROTOCOL and PARIS AGREEMENT have placed governments under pressure to strengthen environmental legislation to reduce emissions. Furthermore, people's concern about climate change is growing.[320] These concerns are visible in the form of protests and movements, such as FRIDAYS FOR FUTURE. Motivated by the Friday school strike of GRETA THUNBERG, the climate movement could reach a global scale among young people. Today, millions are enlisted in different organizations demonstrating for action against climate change.[321] Most of these movements have goals according to the Paris Agreement.[322] Due to such protests and demonstrations, governments are under pressure to reach the goals of climate agreements, and people are regularly

[320] Cf. GROENING, C.; INMAN, J. J.; ROSS JR., W. T., 2015, p. 290.
[321] Cf. HAN, H.; AHN, S. W., 2020, p. 17.
[322] See e.g. FRIDAYS FOR FUTURE, 2019.

confronted with climate change problems. Therefore, legislation is necessary to develop or strengthen environmental policies to reduce emissions.

Recent developments underline the above fact. In 2019, more carbon pricing initiatives were launched than ever before.[323] Furthermore, according to the WORLD BANK, taxes on emissions change regularly in various countries worldwide. For example, recently Ireland increased its carbon tax for liquid transport fuels from 6€/tCO2e to 26€/tCO2e, and Portugal almost doubled its carbon tax from 13€/tCO_2e to 24€/tCO_2e.[324] Around the globe, such tightening of emission policies happens regularly.[325] In addition to emissions taxes, cap and trade systems also underpin such fluctuations. Due to the market-based approach, there are short-term fluctuations in the prices of the traded emission credits. The complexity of emission markets is rising because of the increasing number of instruments regarding carbon marketplaces, such as spot, forwards, and futures.[326] Prices of emission credits are volatile and can therefore be seen as a source of uncertainty.[327] Under EU-ETS, the prices for emission credits fluctuated between nearly 0€/tCO2e and 30€/tCO2e.[328] Furthermore, most emission policies target reducing the total emissions to a level below the amount by a given reference date. Therefore, governments tend to tighten the current emission policies if they prove not to be harsh enough to force industry to lower its emissions according to the goal. Even if most policy changes are announced before being implemented, these changes can be a source of uncertainty due to the long-term nature of supply chain design. The long-term nature of such decisions means they are not alterable or are so only at high cost.[329] Therefore, changes in environmental policies can have a crucial impact on the costs of a supply chain. ARONSSON AND BRODIN[330] and HARRIS ET AL.[331] argue that long-term environmental supply chain design decisions determine the environmental performance of a supply network. Therefore, to deal with influences of environmental policies on supply chain structure, the possibility of changing regulations has to be taken into account even in the design phase. Furthermore, emissions from transportation activities make up a high percentage of emission generated in a supply

[323] Cf. WORLD BANK, 2020, p. 19.
[324] Cf. WORLD BANK, 2020, p. 44.
[325] See e.g. WORLD BANK, 2020, p. 43f; 2019, p. 46; 2018, p. 52f.
[326] Cf. BENZ, E.; TRÜCK, S., 2009, p. 5.
[327] Cf. BENZ, E.; TRÜCK, S., 2009, p. 7ff; FAN, J. H.; TODOROVA, N., 2017, p. 1561f.
[328] Cf. EUROPEAN ENVIRONMENT AGENCY, 2018, p. 25f.
[329] Cf. CHOPRA, S.; MEINDL, P., 2016, p. 19; SANTOSO, T. ET AL., 2005, p. 96.
[330] Cf. ARONSSON, H.; HUGE BRODIN, M., 2006, p. 397.
[331] Cf. HARRIS, I. ET AL., 2011b, p. 313.

chain.[332] The choice of transportation modes highly affects OTDLT.[333] Therefore, uncertainties in the design of an emission policy play a crucial role in strategic supply chain design and can be prohibitive to meet quoted OTDLTs.

In addition, demand uncertainty plays a vital role in the strategic design of supply networks. Although sophisticated methods exist to predict future demand due to constantly changing market conditions, uncertainties in demand are unavoidable.[334] Uncertainties in demand influence capacity planning.[335] Planned capacity that cannot cover requirements to meet the actual demand may lead to congestion effects, which can negatively influence lead time.[336] Therefore, the proposed model covers, in addition to uncertainties in the design of emission policies, the demand uncertainties.

To the author's knowledge, only two publications deal with uncertainties in environmental regulations in the context of closed-loop supply chains. GOA AND RYAN examine a closed-loop supply chain under demand uncertainty, uncertain returns, and uncertainties when considering the design of an emission cap and trade system and an emission tax scheme.[337] HADDAD-SISAKHT AND RYAN examine a closed-loop supply chain design under emission tax rate uncertainty and uncertainty in demand and returns.[338] No study could be identified that deal with uncertainties in emission policies when considering forward supply chains and lead times.

The proposed model is based on the following assumptions:

- There are a finite number of potential suppliers, manufacturing sites, warehouses, and planning periods.
- There is a fixed number of customer regions.
- Suppliers have a fixed capacity for every raw material they provide.
- The planning horizon covers several strategic planning periods.
- Three logistic modes are available, and full truck loads are assumed for each transportation process. Logistic modes differ in cost, speed, and generated emissions.

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332 See e.g. WORLD ECONOMIC FORUM, 2016; UMWELTBUNDESAMT, 2020; UNITED STATES ENVERIONMENTAL PROTECTION AGENCY, 2020.
333 FAN, Y. VAN ET AL., 2018, p. 684f; FACANHA, C.; HORVATH, A., 2007, p. 7140; HORVATH, A., 2006, p. 236.
334 YOU, F.; GROSSMANN, I. E., 2008, p. 3090.
335 PARASKEVOPOULOS, D.; KARAKITSOS, E.; RUSTEM, B., 1991, p. 787.
336 RAJAGOPALAN, S.; YU, H. L., 2001, p. 365; KIM, S.; UZSOY, R., 2009, p. 1923.
337 Cf. GAO, N.; RYAN, S. M., 2014.
338 Cf. HADDAD-SISAKHT, A.; RYAN, S. M., 2018.

Logistic mode 1 offers low cost, emissions, and speed, whereas logistic mode 3 offers high cost, emission, and speed. Logistic mode 2 is characterized by medium cost, emissions, and speed.

- Capacities of suppliers are restricted.
- Capacities of production facilities and warehouses are restricted to the chosen capacity option.
- The same production and handling process quality is assumed for all suppliers, production facilities, and warehouses.
- Several scenarios are designed to cover uncertainties in demand and in the design of emission policies.

7.2 Robust Optimization Formulation

There are different approaches to handle uncertainties in mathematical models. In general, scholars distinguish between stochastic programming[339] and robust optimization approaches.[340] Unlike stochastic programming, robust optimization does not seek to make a solution immune – in a probabilistic sense – to stochastic uncertainty. In these approaches, solutions are constructed that are feasible for any realization of the uncertainty in given sets.[341] A robust optimization approach is applied to guarantee solutions that are feasible for any changes in environmental policies.

The robust optimization approach presented by Mulvey et al.[342] can consider the decision maker's favored risk aversion or service-level function. Furthermore, it can yield different solutions, which are increasingly less sensitive to data realizations of scenario sets.[343] One of the advantages of robust optimization approaches is that the solutions are "nearly" the optimal solution if the input data changes. Mulvey et al. [344] proposed two types of robustness, namely solution robustness and model robustness. Solution robustness describes the state of the model's solution being "nearly" optimal in all scenarios; model robustness means that the model is "nearly" feasible in all scenarios. The shape of "nearly" depends on the decision maker. The objective function includes general penalty functions for both

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339 Cf. BEALE, E. M. L., 1955; DANTZIG, G. B., 1955.
340 Cf. MULVEY, J. M.; VANDERBEI, R. J.; ZENIOS, S. A., 1995; BEN-TAL, A.; NEMIROVSKI, A., 1999.
341 Cf. BERTSIMAS, D.; BROWN, D. B.; CARAMANIS, C., 2011, p. 465.
342 Cf. MULVEY, J. M.; VANDERBEI, R. J.; ZENIOS, S. A., 1995.
343 Cf. LEUNG, S. C. H. ET AL., 2007, p. 226.
344 Cf. MULVEY, J. M.; VANDERBEI, R. J.; ZENIOS, S. A., 1995, p. 265f.

types of robustness, each weighted by an individual parameter. These parameters should capture the decision maker's preference between the two criteria.

The following structure describes a linear programming model:

$$Min \quad f(x,y) = c^T x + d^T y \qquad (7.1)$$
$$s.t. \quad Ax = b \qquad (7.2)$$
$$Bx + Cy = e \qquad (7.3)$$
$$x, y \geq 0 \qquad (7.4)$$

In this structure, x is a vector of the design, and y is a vector of the control variables. Parameter matrices are displayed as A, B and C. Parametric vectors are represented by b and e. While A, b are deterministically known, B, C, and e are uncertain. A finite set of scenarios $\mathrm{T} = \{1,2,\dots,\tau\}$ is used to model the uncertain parameters. Every scenario $\tau \in \mathrm{T}$ is associated to a distinct subset $\{d_\tau, B_\tau, C_\tau, e_\tau\}$ and a scenario probability ρ_τ (with $\sum_\tau^{\mathrm{T}} \rho_\tau = 1$). Furthermore, control variable y is adjusted by scenario realization. Therefore, for scenario τ, it is denoted by y_τ. With parameters being uncertain, the model could be infeasible for specific scenarios. Error vector δ_τ is used to represent the infeasibility of the model under specific scenario τ. When the model is feasible, δ_τ will be 0; otherwise, it will take a positive value according to Eq. (7.7). Based on Eq. (7.1) to (7.4), the robust optimization formulation proposed by Mulvey et al.[345] can be written as follows:

$$Min \quad Z = \sum_{\tau}^{\mathrm{T}} \rho_\tau \psi_\tau + \lambda \sum_{\tau}^{\mathrm{T}} \rho_\tau \left(\psi_\tau - \sum_{\tau'}^{\mathrm{T}} \rho_{\tau'} \psi_{\tau'} \right)^2 \qquad (7.5)$$
$$s.t. \quad Ax = b \qquad (7.6)$$
$$B_\tau x + C_\tau y_\tau + \delta_\tau = e_\tau \qquad \forall \tau \in \mathrm{T} \qquad (7.7)$$
$$x, y_s \geq 0 \qquad \forall \tau \in \mathrm{T} \qquad (7.8)$$

In this formulation, λ expresses the weighting factor of the variability and ψ_τ represents a cost or benefit function $f(x, y_\tau)$, for scenario τ. If there is a high variability for $\psi_\tau = f(x, y_\tau)$, this means that the solution is taken under a high risk descision.

The quadratic formulation implies a high computational effort. Therefore, Yu and Li [346] proposed an alternative formulation for Eq. (7.5). This formulation replaces the quadratic

[345] MULVEY, J. M.; VANDERBEI, R. J.; ZENIOS, S. A., 1995.
[346] YU, C. S.; LI, H. L., 2000.

term in the objective function with an absolute deviation expression. It is represented as follows:

$$Z = \sum_{\tau}^{\mathrm{T}} \rho_\tau \psi_\tau + \lambda \sum_{\tau}^{\mathrm{T}} \rho_\tau \left| \psi_\tau - \sum_{\tau'}^{\mathrm{T}} \rho_{\tau'} \psi_{\tau'} \right| \qquad (7.9)$$

The objective is reformulated according to LI[347] in (7.10) to solve the robust model efficiently:

$$Min \qquad Z = \sum_{\tau}^{\mathrm{T}} \rho_\tau \psi_\tau + \lambda \sum_{\tau}^{\mathrm{T}} \rho_\tau \left[\left(\psi_\tau - \sum_{\tau'}^{\mathrm{T}} \rho_{\tau'} \psi_{\tau'} \right) + 2\Theta_\tau \right] \qquad (7.10)$$

$$s.t. \qquad Ax = b \qquad (7.11)$$

$$B_\tau x + C_\tau y_\tau + \delta_\tau = e_\tau \qquad \forall \tau \in \mathrm{T} \qquad (7.12)$$

$$\psi_\tau - \sum_{\tau}^{\mathrm{T}} \rho_\tau \psi_\tau + \Theta_\tau \geq 0 \qquad \forall \tau \in \mathrm{T} \qquad (7.13)$$

$$x, y_\tau \geq 0 \qquad \forall \tau \in \mathrm{T} \qquad (7.14)$$

When $\psi_\tau - \sum_{\tau}^{\mathrm{T}} \rho_\tau \psi_\tau \geq 0$ then $\Theta_\tau = 0$ and therefore, $Z = \sum_{\tau}^{\mathrm{T}} \rho_\tau \psi_\tau + \lambda \sum_{\tau}^{\mathrm{T}} \rho_\tau \big(\psi_\tau - \sum_{\tau'}^{\mathrm{T}} \rho_{\tau'} \psi_{\tau'}\big)$. On the other hand, if $\psi_\tau - \sum_{\tau}^{\mathrm{T}} \rho_\tau \psi_\tau < 0$, then $\Theta_\tau = \psi_\tau - \sum_{\tau}^{\mathrm{T}} \rho_\tau \psi_\tau$ and $Z = \sum_{\tau}^{\mathrm{T}} \rho_\tau \psi_\tau + \lambda \sum_{\tau}^{\mathrm{T}} \rho_\tau \big(\sum_{\tau'}^{\mathrm{T}} \rho_{\tau'} \psi_{\tau'} - \psi_\tau\big)$. Therefore, it can be stated that solutions of Eq. (7.10) to (7.14) are identical to the solutions of Eq. (7.9).

7.3 Model Development

7.3.1 Model with no Emission Policy

The first objective function Z_1 includes three terms. The first and second terms are mean value and variance of total costs, and the third term in (7.15) measures solution robustness. Total costs include fixed costs for contracting suppliers, opening production facilities and warehouses, and installing production resources at a facility. Furthermore, transportation costs between suppliers, production facilities, warehouses, and customers are included, as are purchasing, production, handling, and stock-related costs. Parameters λ and ω are weighting factors for solution robustness and model robustness. The variable ν_τ is used for formulation convenience and represents the total cost respectively for each scenario. Variable $\varphi_{cpt\tau}$ represents the amount of unmet demand for each customer, each

[347] LI, H. L., 1996, p. 466.

product in each period, and each scenario. Therefore, the model robustness term can also be interpreted as penalty costs for not meeting demand.

$$
\begin{aligned}
Z_1 = \sum_{\tau}^{\mathrm{T}} \rho_\tau \Bigg(& \sum_{s}^{S} SC_s\, y_s^{Su} + \sum_{f}^{F}\sum_{o}^{O} FC_{fo}\, y_{fo}^{Fa} + \sum_{w}^{W}\sum_{o}^{O} WC_{wo}\, y_{wo}^{Wa} \\
& + \sum_{s}^{S}\sum_{f}^{F}\sum_{m}^{M}\sum_{p}^{P}\sum_{l}^{L}\sum_{t}^{T} PC_{smt}\, x_{sfmplt\tau} \\
& + \sum_{f}^{F}\sum_{w}^{W}\sum_{p}^{P}\sum_{l}^{L}\sum_{t}^{T} MC_{fpt}\, x_{fwplt\tau} \\
& + \sum_{w}^{W}\sum_{c}^{C}\sum_{p}^{P}\sum_{l}^{L}\sum_{t}^{T} HC_{wpt}\, x_{wcplt\tau} \\
& + \sum_{w}^{W}\sum_{p}^{P}\sum_{t}^{T}\sum_{c}^{C} SC_{wpt} \frac{\left(h_{wp(t-1)c\tau} + h_{wptc\tau}\right)}{2} \\
& + \sum_{s}^{S}\sum_{f}^{F}\sum_{m}^{M}\sum_{p}^{P}\sum_{l}^{L}\sum_{t}^{T} TC_{sfmlt}\, x_{sfmplt\tau} \\
& + \sum_{f}^{F}\sum_{W}^{W}\sum_{p}^{P}\sum_{l}^{L}\sum_{t}^{T} TC_{fwplt}\, x_{fwplt\tau} \\
& + \sum_{w}^{W}\sum_{c}^{C}\sum_{p}^{P}\sum_{l}^{L}\sum_{t}^{T} TC_{wcplt}\, x_{wcplt\tau} \Bigg) \\
& + \lambda \sum_{\tau}^{\mathrm{T}} \rho_\tau \left[\nu_\tau - \sum_{\tau'}^{\mathrm{T}} \rho_{\tau'} (\nu_{\tau'}) + 2\Theta_\tau \right] \\
& + \omega \sum_{\tau}^{\mathrm{T}} \rho_\tau \sum_{c}^{C}\sum_{p}^{P}\sum_{t}^{T} \varphi_{cpt\tau}
\end{aligned}
\qquad (7.15)
$$

In order to use the approach of Yu and Li,[348] as proposed in (7.10, 7.11, 7.12, 7.13, 7.14), constraint (7.16) is used for linearization purposes.

$$
\upsilon_\tau - \sum_{\tau}^{T} \rho_\tau \upsilon_\tau + \Theta_\tau \geq 0 \qquad \forall \tau \in \mathrm{T} \qquad (7.16)
$$

$$
D_{cpt\tau} \geq \sum_{w}^{W}\sum_{l}^{L} x_{wcplt\tau} + \varphi_{cpt\tau} \qquad \forall c \in C, p \in P, t \in T, \tau \in \mathrm{T} \qquad (7.17)
$$

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[348] Yu, C. S.; Li, H. L., 2000.

$$\sum_{c}^{C}\sum_{l}^{L} x_{wcplt\tau} + \sum_{c}^{C} h_{wptc\tau} = \sum_{f}^{F}\sum_{l}^{L} x_{fwplt\tau} + \sum_{c}^{C} h_{wp(t-1)c\tau} \qquad \forall w \in W, p \in P, t \in T, \tau \in \mathrm{T} \qquad (7.18)$$

$$\sum_{w}^{W}\sum_{p}^{P}\sum_{l}^{L} x_{fwplt\tau}\, BOM_{mp} = \sum_{s}^{S}\sum_{p}^{P}\sum_{l}^{L} x_{sfmplt\tau} \qquad \forall f \in F, m \in M, t \in T, \tau \in \mathrm{T} \qquad (7.19)$$

The product flows, shipped from warehouses to customers, are determined by control constraint (7.17). The product flow must be equal to the demand for product p of costumer c in period t and in scenario τ. If demand cannot be met, $\varphi_{cpt\tau}$ represents the unmet demand. Balance constraint (7.18) ensures that the sum of products shipped from one warehouse to all customers, plus the actual number of products in stock, is equal to the incoming amount of stock plus the number of products in stock during the previous period. Similarly, in (7.19), quantities shipped from all production facilities to a specific warehouse must be equal to the raw materials delivered from suppliers according to the bill of materials for each product.

$$\sum_{f}^{F}\sum_{p}^{P}\sum_{l}^{L} x_{sfmplt\tau} \leq Cap_{sm}^{Su} y_{s}^{Su} \qquad \forall s \in S, m \in M, t \in T, \tau \in \mathrm{T} \qquad (7.20)$$

$$\sum_{w}^{W}\sum_{p}^{P}\sum_{l}^{L} x_{fwplt\tau} \leq \sum_{o}^{O} Cap_{fo}^{Fa}\, y_{fo}^{Fa} \qquad \forall f \in F, t \in T, \tau \in \mathrm{T} \qquad (7.21)$$

$$\sum_{c}^{C}\sum_{p}^{P}\sum_{l}^{L} x_{wcplt\tau} \leq \sum_{o}^{O} Cap_{wo}^{Wa}\, y_{wo}^{Wa} \qquad \forall w \in W, t \in T, \tau \in \mathrm{T} \qquad (7.22)$$

$$\sum_{p}^{P}\sum_{c}^{C} h_{wptc\tau} \leq \sum_{o}^{O} Cap_{wo}^{Wa}\, y_{wo}^{Wa} \qquad \forall w \in W, t \in T, \tau \in \mathrm{T} \qquad (7.23)$$

$$\sum_{o}^{O} y_{fo}^{Fa} \leq 1 \qquad \forall f \in F \qquad (7.24)$$

$$\sum_{o}^{O} y_{wo}^{Wa} \leq 1 \qquad \forall w \in W \qquad (7.25)$$

Constraints (7.20), (7.21), (7.22), and (7.23) are capacity constraints. Constraints (7.24) and (7.25) ensure that only one capacity option can be installed at each production facility and warehouse.

$$MaxLT \geq OTD_{cpt} \qquad \forall c \in C, p \in P, t \in T \qquad (7.26)$$

$$OTD_{cpt} \geq LT^{Su}_{smt}\delta^{SF}_{sfmpltc\tau} + LT^{Fa}_{fpt}\delta^{FW}_{fwpltc\tau} + LT^{Wa}_{wpt}x_{wcplt\tau} + LT_{sfmlt}\delta^{SF}_{sfmpltc\tau} + LT_{fwplt}\delta^{FW}_{fwpltc\tau} + LT_{wcplt}x_{wcplt\tau} \qquad \forall s \in S, f \in F, w \in W, c \in C, m \in M, p \in P, l \in L, t \in T, \tau \in \mathrm{T} \qquad (7.27)$$

$$\sum_{l}^{L} x_{wcplt\tau} - h_{wp(t-1)c\tau} = \sum_{f}^{F}\sum_{l}^{L} \delta^{FW}_{fwpltc\tau} \qquad \forall w \in W, p \in P, t \in T, c \in C, \tau \in \mathrm{T} \qquad (7.28)$$

$$x_{fwplt\tau} \geq \sum_{c}^{C} \delta^{FW}_{fwpltc\tau} \qquad \forall, f \in F, w \in W, p \in P, l \in L, t \in T, \tau \in \mathrm{T} \qquad (7.29)$$

$$\sum_{w}^{W}\sum_{l}^{L} \delta^{FW}_{fwpltc\tau} BOM_{mp} = \sum_{s}^{S}\sum_{l}^{L} \delta^{SF}_{sfmpltc\tau} \qquad \forall f \in F, p \in P, c \in C, m \in M, t \in T, \tau \in \mathrm{T} \qquad (7.30)$$

$$x_{sfmplt\tau} \geq \sum_{c}^{C} \delta^{SF}_{sfmpltc\tau} \qquad \forall s \in S, f \in F, m \in M, p \in P, l \in L, t \in T, \tau \in \mathrm{T} \qquad (7.31)$$

Constraint (7.26) ensures that quoted OTDLT cannot be exceeded. In constraint (7.27), each customer's OTDLT is calculated for each product and period under each scenario. OTDLT consists of procurement, manufacturing, handling, and transportation lead times for goods that are not kept in stock. In (7.28), the additional needed products from facilities to serve customers' demand for a certain product in each period. Constraint (7.29) ensures that these additional needed products are within the transportation arc for the specific logistic mode between production facilities and warehouses. Constraint (7.30) calculates the additional needed raw materials to serve a customer’s order according to the bill of materials, multiplied by the additional needed products. In constraint (7.31) it is ensured that these additional needed raw materials are within the established transportation links between suppliers and manufacturing facilities.

$$x_{sfmplt\tau}, x_{fwplt\tau}, x_{wcplt\tau}, h_{wptc\tau}, \delta^{SF}_{sfmpltc\tau}, \delta^{FW}_{fwpltc\tau}, \upsilon_{\tau}, \Theta_{\tau}, \varphi_{cpt\tau} \geq 0 \qquad \forall s \in S, f \in F, w \in W, c \in C, m \in M, p \in P, l \in L, t \in T, \tau \in \mathrm{T} \qquad (7.32)$$

$$y^{Su}_{s}, y^{Fa}_{fo}, y^{Wa}_{wo} \in [0;1] \qquad \forall s \in S, f \in F, w \in W \qquad (7.33)$$

Constraint (7.32) defines the non-negativity and constraint (7.33) the binary variables.

7.3.2 Model with Various Emission Policies

$$E_{t\tau} = \sum_{f}^{F}\sum_{o}^{O} FE_{fot} y_{fo}^{Fa} + \sum_{w}^{W}\sum_{o}^{O} WE_{wot}\, y_{wo}^{Wa} + \sum_{s}^{S}\sum_{f}^{F}\sum_{m}^{M}\sum_{p}^{P}\sum_{l}^{L} PE_{smt}\, x_{sfmplt\tau} + \sum_{f}^{F}\sum_{w}^{W}\sum_{p}^{P}\sum_{l}^{L} ME_{fpt}\, x_{fwplt\tau} + \sum_{w}^{W}\sum_{c}^{C}\sum_{p}^{P}\sum_{l}^{l} HE_{wpt}\, x_{wcplt\tau} + \sum_{w}^{W}\sum_{p}^{P} SE_{wpt} \frac{\left(h_{wp(t-1)c\tau} + h_{wptc\tau}\right)}{2} + \sum_{s}^{S}\sum_{f}^{F}\sum_{m}^{M}\sum_{p}^{P}\sum_{l}^{L} TE_{sfmlt}\, x_{sfmplt\tau} + \sum_{f}^{F}\sum_{w}^{W}\sum_{p}^{P}\sum_{l}^{L} TE_{fwplt}\, x_{fwplt\tau} + \sum_{w}^{W}\sum_{c}^{C}\sum_{p}^{P}\sum_{l}^{L} TE_{wcplt}\, x_{wcplt\tau} \quad \forall t \in T, \tau \in \mathrm{T} \qquad (7.34)$$

The number of generated emissions in each period and each scenario must be calculated in (7.34) to implement different emission policies. Periodic emissions cover emissions from operating production facilities and warehouses and the emissions from procurement, manufacturing, handling, stocking, and transportation activities.

$$E_{t\tau} \leq ECap_{t\tau} \quad \forall t \in T, \tau \in \mathrm{T} \qquad (7.35)$$

$$E_{t\tau} \geq 0 \quad \forall t \in T, \tau \in \mathrm{T} \qquad (7.36)$$

For the implementation of an emission cap scheme, constraint (7.35) ensures that the generated emissions do not exceed the imposed cap for each period, depending on the specific scenario. Constraint (7.36) ensures non-negativity of the generated emission variable.

Objective (7.15) must be altered to implement an emission tax. Therefore, in (7.37), in addition to the fixed and variable costs, the amount of tax is considered. The amount of tax is the sum over all periods of the multiplication of tax rate $\Omega_{t\tau}^{Tax}$ with the emissions generated in each period and scenario.

$$
\begin{aligned}
Z_1 = \sum_{\tau}^{\mathrm{T}} \rho_\tau \Bigg(& \sum_{s}^{S} SC_s \, y_s^{Su} + \sum_{f}^{F} \sum_{o}^{O} FC_{fo} \, y_{fo}^{Fa} + \sum_{w}^{W} \sum_{o}^{O} WC_{wo} \, y_{wo}^{Wa} \\
& + \sum_{s}^{S} \sum_{f}^{F} \sum_{m}^{M} \sum_{p}^{P} \sum_{l}^{L} \sum_{t}^{T} PC_{smt} \, x_{sfmplt\tau} \\
& + \sum_{f}^{F} \sum_{w}^{W} \sum_{p}^{P} \sum_{l}^{L} \sum_{t}^{T} MC_{fpt} \, x_{fwplt\tau} \\
& + \sum_{w}^{W} \sum_{c}^{C} \sum_{p}^{P} \sum_{l}^{L} \sum_{t}^{T} HC_{wpt} \, x_{wcplt\tau} \\
& + \sum_{w}^{W} \sum_{p}^{P} \sum_{t}^{T} \sum_{c}^{C} SC_{wpt} \frac{\left(h_{wp(t-1)c\tau} + h_{wptc\tau}\right)}{2} \\
& + \sum_{s}^{S} \sum_{f}^{F} \sum_{m}^{M} \sum_{p}^{P} \sum_{l}^{L} \sum_{t}^{T} TC_{sfmlt} \, x_{sfmplt\tau} \\
& + \sum_{f}^{F} \sum_{w}^{W} \sum_{p}^{P} \sum_{l}^{L} \sum_{t}^{T} TC_{fwplt} \, x_{fwplt\tau} \\
& + \sum_{w}^{W} \sum_{c}^{C} \sum_{p}^{P} \sum_{l}^{L} \sum_{t}^{T} TC_{wcplt} \, x_{wcplt\tau} + \sum_{t}^{T} \Omega_{t\tau}^{Tax} \, E_{t\tau} \Bigg) \\
& + \lambda \sum_{\tau}^{\mathrm{T}} \rho_\tau \left[\nu_\tau - \sum_{\tau'}^{\mathrm{T}} \rho_{\tau'} (\nu_{\tau'}) + 2\Theta_\tau \right] \\
& + \omega \sum_{\tau}^{\mathrm{T}} \rho_\tau \sum_{c}^{C} \sum_{p}^{P} \sum_{t}^{T} \varphi_{cpt\tau}
\end{aligned}
\tag{7.37}
$$

To implement a cap and trade system, first the number of allowances that have to be bought or can be sold must be calculated. Constraint (7.39) determines these values. Variable $\alpha_{t\tau}^{-}$ calculates the emission allowances that will be sold, and variable $\alpha_{t\tau}^{+}$ accounts for the additional emission allowances that must be bought. Objective function (7.15) has to be altered in the form of (7.38). In addition to the fixed and variables costs, the difference between additionally needed and excess emission allowances in each period and scenario are multiplied by the market price of these allowances $\Omega_{t\tau}^{CAT}$. The result is summed over all periods. Constraint (7.40) ensures that $\alpha_{t\tau}^{-}$ and $\alpha_{t\tau}^{+}$ are non-negative.

$$
\begin{aligned}
Z_1 = \sum_{\tau}^{\mathrm{T}} \rho_\tau \Bigg(& \sum_{s}^{S} SC_s \, y_s^{Su} + \sum_{f}^{F} \sum_{o}^{O} FC_{fo} \, y_{fo}^{Fa} + \sum_{w}^{W} \sum_{o}^{O} WC_{wo} \, y_{wo}^{Wa} \\
& + \sum_{s}^{S} \sum_{f}^{F} \sum_{m}^{M} \sum_{p}^{P} \sum_{l}^{L} \sum_{t}^{T} PC_{smt} \, x_{sfmplt\tau} \\
& + \sum_{f}^{F} \sum_{w}^{W} \sum_{p}^{P} \sum_{l}^{L} \sum_{t}^{T} MC_{fpt} \, x_{fwplt\tau} \\
& + \sum_{w}^{W} \sum_{c}^{C} \sum_{p}^{P} \sum_{l}^{L} \sum_{t}^{T} HC_{wpt} \, x_{wcplt\tau} \\
& + \sum_{w}^{W} \sum_{p}^{P} \sum_{t}^{T} \sum_{c}^{C} SC_{wpt} \frac{\left(h_{wp(t-1)c\tau} + h_{wptc\tau}\right)}{2} \\
& + \sum_{s}^{S} \sum_{f}^{F} \sum_{m}^{M} \sum_{p}^{P} \sum_{l}^{L} \sum_{t}^{T} TC_{sfmlt} \, x_{sfmplt\tau} \\
& + \sum_{f}^{F} \sum_{w}^{W} \sum_{p}^{P} \sum_{l}^{L} \sum_{t}^{T} TC_{fwplt} \, x_{fwplt\tau} \\
& + \sum_{w}^{W} \sum_{c}^{C} \sum_{p}^{P} \sum_{l}^{L} \sum_{t}^{T} TC_{wcplt} \, x_{wcplt\tau} + \sum_{t}^{T} \Omega_{t\tau}^{CAT} \left(\alpha_{t\tau}^{+} - \alpha_{t\tau}^{-}\right) \Bigg) \\
& + \lambda \sum_{\tau}^{\mathrm{T}} \rho_\tau \left[\nu_\tau - \sum_{\tau'}^{\mathrm{T}} \rho_{\tau'} (\nu_{\tau'}) + 2\Theta_\tau \right] \\
& + \omega \sum_{\tau}^{\mathrm{T}} \rho_\tau \sum_{c}^{C} \sum_{p}^{P} \sum_{t}^{T} \varphi_{cpt\tau}
\end{aligned}
\qquad (7.38)
$$

$$E_{t\tau} + \alpha_{t\tau}^{-} = ECap_{t\tau} + \alpha_{t\tau}^{+} \qquad \forall t \in T, \tau \in \mathrm{T} \qquad (7.39)$$

$$\alpha_{t\tau}^{+}, \alpha_{t\tau}^{-} \geq 0 \qquad \forall t \in T, \tau \in \mathrm{T} \qquad (7.40)$$

The emission offset system is implemented by calculating the generated emissions that exceed the imposed cap in each period and scenario (7.42). Objective (7.15) then has to be altered to (7.41). The additional term calculates the cost of buying additional allowances. These costs are derived from the sum over all periods of the number of additional allowances $\beta_{t\tau}$, multiplied by the allowance price $\Omega_{t\tau}^{Off}$. Constraint (7.43) makes sure that $\beta_{t\tau}$ takes no negative value.

$$Z_1 = \sum_{\tau}^{\mathrm{T}} \rho_\tau \left(\sum_{s}^{S} SC_s\, y_s^{Su} + \sum_{f}^{F}\sum_{o}^{O} FC_{fo}\, y_{fo}^{Fa} + \sum_{w}^{W}\sum_{o}^{O} WC_{wo}\, y_{wo}^{Wa} \right. \tag{7.41}$$
$$+ \sum_{s}^{S}\sum_{f}^{F}\sum_{m}^{M}\sum_{p}^{P}\sum_{l}^{L}\sum_{t}^{T} PC_{smt}\, x_{sfmplt\tau}$$
$$+ \sum_{f}^{F}\sum_{w}^{W}\sum_{p}^{P}\sum_{l}^{L}\sum_{t}^{T} MC_{fpt}\, x_{fwplt\tau}$$
$$+ \sum_{w}^{W}\sum_{c}^{C}\sum_{p}^{P}\sum_{l}^{L}\sum_{t}^{T} HC_{wpt}\, x_{wcplt\tau}$$
$$+ \sum_{w}^{W}\sum_{p}^{P}\sum_{t}^{T}\sum_{c}^{C} SC_{wpt} \frac{\left(h_{wp(t-1)c\tau} + h_{wptc\tau}\right)}{2}$$
$$+ \sum_{s}^{S}\sum_{f}^{F}\sum_{m}^{M}\sum_{p}^{P}\sum_{l}^{L}\sum_{t}^{T} TC_{sfmlt}\, x_{sfmplt\tau}$$
$$+ \sum_{f}^{F}\sum_{w}^{W}\sum_{p}^{P}\sum_{l}^{L}\sum_{t}^{T} TC_{fwplt}\, x_{fwplt\tau}$$
$$\left. + \sum_{w}^{W}\sum_{c}^{C}\sum_{p}^{P}\sum_{l}^{L}\sum_{t}^{T} TC_{wcplt}\, x_{wcplt\tau} + \sum_{t}^{T} \Omega_{t\tau}^{Off}\, \beta_{t\tau} \right)$$
$$+ \lambda \sum_{\tau}^{\mathrm{T}} \rho_\tau \left[\nu_\tau - \sum_{\tau'}^{\mathrm{T}} \rho_{\tau'}(\nu_{\tau'}) + 2\Theta_\tau \right]$$
$$+ \omega \sum_{\tau}^{\mathrm{T}} \rho_\tau \sum_{c}^{C}\sum_{p}^{P}\sum_{t}^{T} \varphi_{cpt\tau}$$

$$E_{t\tau} = ECap_{t\tau} + \beta_{t\tau} \qquad \forall t \in T, \tau \in \mathrm{T} \tag{7.42}$$

$$\beta_{t\tau} \geq 0 \qquad \forall t \in T, \tau \in \mathrm{T} \tag{7.43}$$

7.4 Data Generation Process

The general data generation process is based on the procedure described in chapter 5.3. Different scenarios must be defined to include uncertainties in demand and in the design of emission policies. In this chapter, three realizations of demands are considered. It is assumed that these depend on the economic situation. There is a poor scenario, a fair scenario, and a boom scenario. A scenario is assumed in which emission policies do not change over time, and another scenario in which the applied emission policies are tightened over time to incorporate uncertainties in the shape of emission policies. Therefore, six scenarios for each emission policy must be defined. For the poor scenario regarding demand, it is assumed that only 70% of the original demand can be realized; for the good scenario, 85% is assumed; and for the boom scenario, 100% of the original demand values can be realized. The different values for the applied emission policies are depicted in tables 7.1 to 7.3.

		Period		
Scenario	**Demand**	**t=1**	**t=2**	**t=3**
1	Poor	14,000	14,000	14,000
2	Poor	14,000	12,000	10,000
3	Good	14,000	14,000	14,000
4	Good	14,000	12,000	10,000
5	Boom	14,000	14,000	14,000
6	Boom	14,000	12,000	10,000

Table 7.1: Scenario configuration under emission cap policy

		Period		
Scenario	**Demand**	**t=1**	**t=2**	**t=3**
1	Poor	75	75	75
2	Poor	75	90	120
3	Good	75	75	75
4	Good	75	90	120
5	Boom	75	75	75
6	Boom	75	90	120

Table 7.2: Scenario configuration under emission tax policy

		Period		
Scenario	**Demand**	**t=1**	**t=2**	**t=3**
1	Poor	12,000 / 75	12,000 / 75	12,000 / 75
2	Poor	12,000 / 75	10,000 / 90	8000 / 120
3	Good	12,000 / 75	12,000 / 75	12,000 / 75
4	Good	12,000 / 75	10,000 / 90	8000 / 120
5	Boom	12,000 / 75	12,000 / 75	12,000 / 75
6	Boom	12,000 / 75	10,000 / 90	8000 / 120

Table 7.3: Scenario configuration under emission cap and trade and emission offset policy

A Dirichlet distribution of size 1 is applied to generate different probabilities for the scenarios. Probabilities for the demand scenarios are calculated by summing the scenario probabilities of the same demand realization to compare a case without emission policies.

All numerical experiments are performed with IBM ILOG CPlex on an Intel Core i7-8750H 2.2 GHz machine with 16 GB Ram under Windows 10. The potential locations of suppliers, production facilities, warehouses, and customers are illustrated in Fig. 7.1. The size of the bubbles reflects the expected demand for customers and the maximum capacity for suppliers, production facilities, and warehouses.

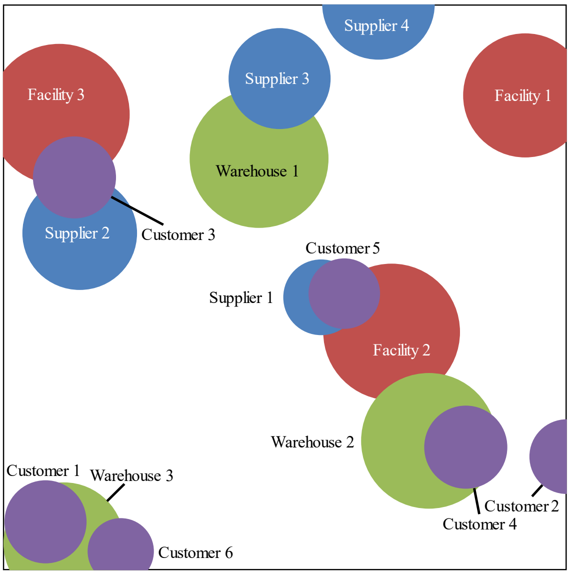

Figure 7.1: Location of potential suppliers, production facilities, and warehouses in the data example for chapter 7

7.5 Numerical Results

7.5.1 Results with Varying Order-to-Delivery Lead Time

For the analysis of the influence of different quoted OTLDT, the solution robustness parameter λ – which reflects the importance of total cost variability is set to 1. The model robustness parameter ω, which can be interpreted as penalty costs for not fulfilling demand, is set to 200.[349]

As depicted in Fig. 7.2 a), expected total costs generally decrease with increasing quoted OTDLT. In the absence of any emission policies, the expected total cost results are the lowest. Emission tax policy influences the expected total cost the most; the taxation of all generated emissions means that expected total costs are significantly higher than under any other examined policy. In contrast, under emission cap and trade, or emission offset policy, the expected total costs are only slightly higher than in the absence of an emission policy. In case of emission cap policy, even for some quoted OTDLT expected total cost can be lower compared to the situation without emission policies. In the generated

[349] Detailed results of the examinations in Chapter 7 can be found in appendix D.

numerical example, emission cap and trade and emission offset policies lead to similar results. The emission cap policy leads, with both low and high quoted OTDLTs, to lower total costs than either the emission offset or the emission cap and trade policy. However, although there is no pricing on emissions under an emission cap policy, expected total costs can be higher than under no emission policy.

In terms of total cost variability, emission cap policy can lead to lower results than without an emission policy applied, as Fig. 7.2 b) shows. Especially for low quoted OTDLTs, the total cost variability is low. This effect can be attributed to the limited solution space due to the hard constraint and lower demand fulfillment. With increasing quoted OTDLT, cost variability increases under an emission cap policy. Under price-based emission policies, cost variability is nearly the same under emission tax, emission cap and trade, and emission offset policies. For almost all quoted OTDLTs, apart from 83, the total cost variability is higher than when no emission policy is applied. Furthermore, in many cases, a longer quoted OTDLT can help to reduce the variability of total costs when no emission policy is applied. Under emission policies, this general observation cannot be made.

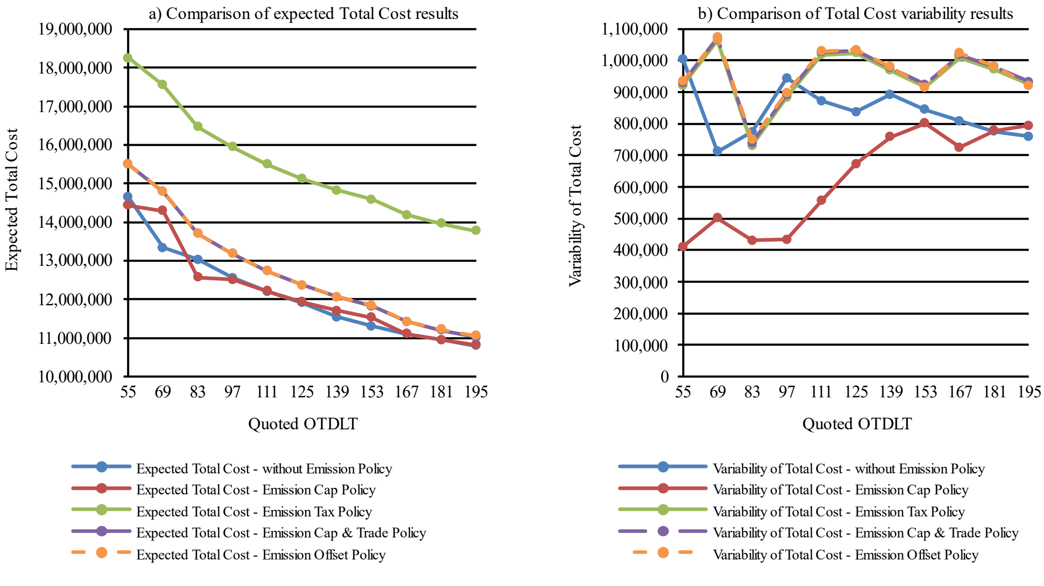

Figure 7.2: Comparison of expected total cost and total cost variability with varying OTDLT

Expected unfulfilled demand is influenced most strongly by the strict emission cap regulation, as Fig. 7.3 shows. Logarithmic display is used in this figure for suitable presentation. The strict emission cap policy leads to expected unfulfilled demand in most cases, but in general, longer quoted OTDLTs reduce the expected non-fulfillment. The market-based emission policies provide flexibility, which means the expected non-fulfillment is significantly lower, compared to the strict emission cap regulation. When no emission policy is applied, only for OTDLT of 69, 83, and 97, non-fulfillment is observed. Notably, an increase in expected unfulfilled demand under market-based emission policies leads to lower variability in total cost. This effect is not observed when no emission policy is applied. Under the emission cap policy, this effect is particularly evident for higher quoted OTDLTs, starting from 97 time units. With higher demand fulfillment total cost variability is increasing. The most likely explanation is that fulfilling demand with lower OTDLT is more expensive than the resulting penalty costs and the harsh emission regulation, which may be prohibitive for demand fulfillment. Furthermore, the difference between the demand scenarios is reduced due to the high unfulfilled demand, which mainly affects the high-demand scenario. Therefore, variability of total costs is lower. For an OTDLT higher than 55, without emission policies and with market-based emission policies, unfulfilled demand and higher total cost variability are accompanied by changes in location decisions.

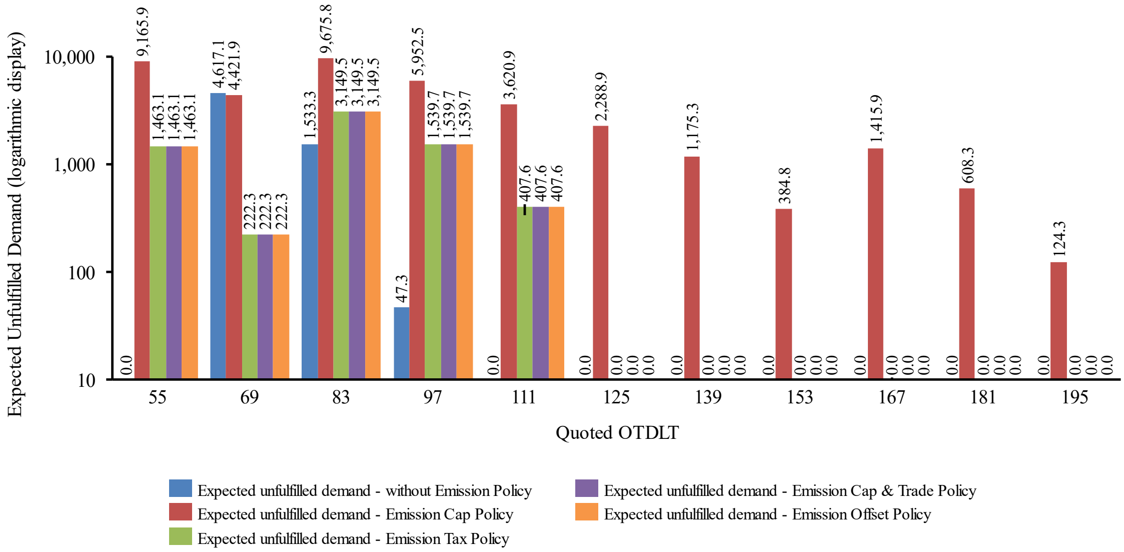

Figure 7.3: Comparison of expected unfulfilled demand with varying OTDLT

Expected total emissions generally decrease with increasing OTDLT, as Fig. 7.4 demonstrates. With low OTDLT, the emission cap policy leads to lower emissions than the market-based emission policies. Nevertheless, with a quoted OTDLT of 139, the cap loses its efficiency, and the other policies lead to lower emissions. The same observations as described in Chapter 5, can be made even under uncertainty. In general, in the given numerical example, all emission policies lower the expected total emission beneath the amounts generated in the absence of an emission policy. Hence, even with uncertain design of the emission policies, a beneficial effect on total emissions is evident. The static emission cap policy shows the same weakness under uncertainty. With changing OTDLT, the set cap may be insufficient to lead to an adequate reduction. Market-based emission policies have less impact with lower OTDLT, compared to emission cap policy, but always lead to a reduction in total emissions. As illustrated in Fig. 7.3, these policies offer higher flexibility, and demand fulfillment is generally higher. In most cases, emission tax and the emission cap and trade policy lead to similar expected total emissions even under uncertainty. Emission offset seems – especially for high OTDLT – to be slightly less effective. However, these effects are only comparable when the cap is appropriately chosen under both the emission cap and trade and the emission offset policy. In particular, under emission cap and trade, an unsuitable cap will lead to low emission prices and insufficient total emission reductions. As shown in Fig. 7.4 b), market-based policies can lead to significantly higher total emission costs. In particular, total emission costs are high with the emission tax policy. Therefore, expected total costs are significantly higher than under emission cap and trade or the emission offset policy. With high quoted OTDLT, an uncertain emission cap and trade policy can potentially lead to additional income or at least low emission cost. Therefore, the emission credit prices may decrease and the incentive to reduce total emissions will be lowered.

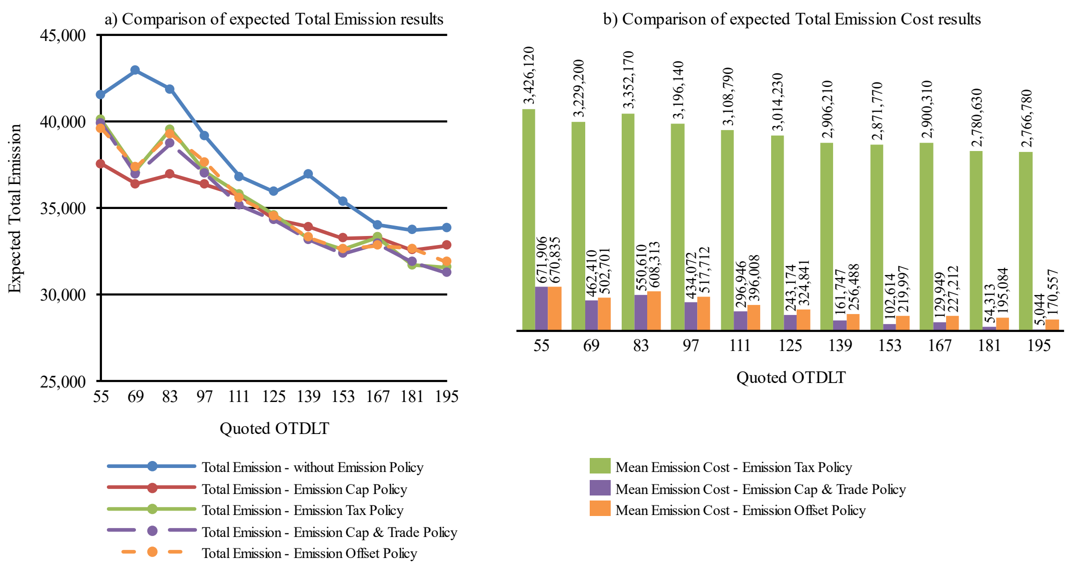

Figure 7.4: Comparison of total emission results and total emission cost with varying OTDLT

The selection of suppliers is not affected with varying quoted OTDLT, as Fig. 7.5 shows. In all cases, only three suppliers are selected. This point also reflects in available supplier capacity. Therefore, it appears that a certain capacity at suppliers is needed to hedge against uncertain demand, even when OTDLT is high. Furthermore, adding capacity is a well-known strategy to reduce delays and to deal with different risks.[350]

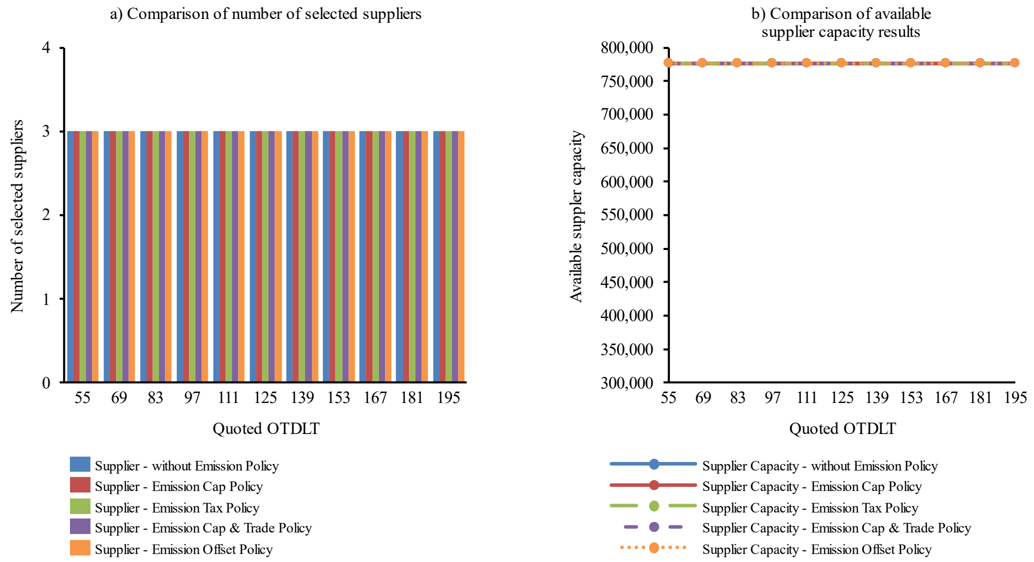

Figure 7.5: Comparison of number of selected suppliers and available supplier capacity with varying OTDLT

Varying OTDLT, in contrast to the selection of suppliers, has a strong influence on the number and capacity of established production facilities, as Fig. 7.6 indicates. Three production facilities are opened in the absence of emission policies for a quoted OTDLT of less than 69. With the reduction to two opened facilities with the low-capacity option, increases in expected unfulfilled demand, total cost variability, and expected total emissions are evident. Under emission policies, the reduction from three to two opened facilities is observed at quoted OTDLT of 83. This reduction leads to an increase in expected total emissions and expected unfulfilled demand. Total cost variability and expected total cost, in contrast, are decreasing.

[350] SODHI, M. S.; TANG, C. S., 2012, p. 56.

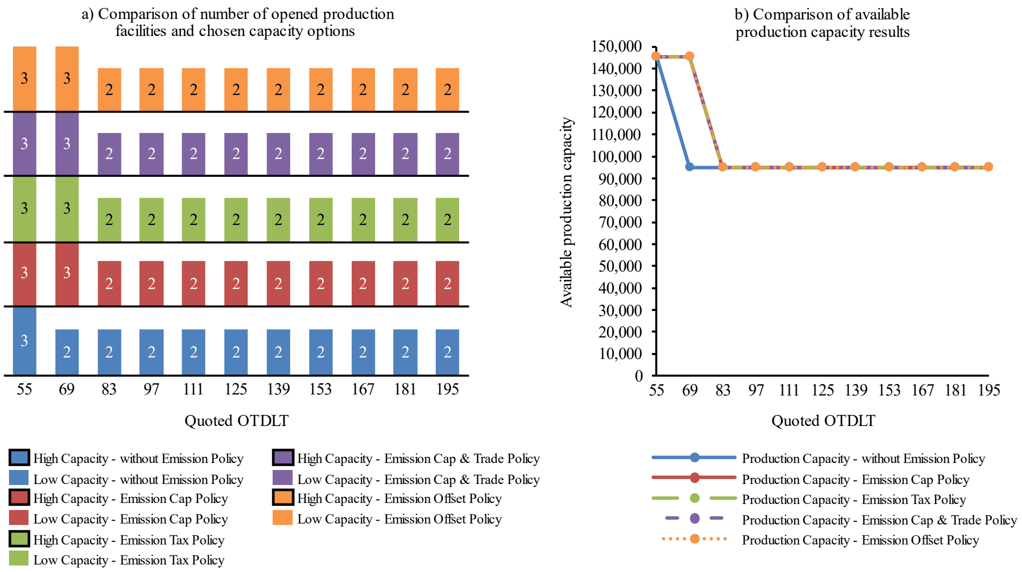

Figure 7.6: Comparison of opened production facilities and available production capacity with varying OTDLT

The number of selected warehouses and the available warehouse capacity are illustrated in Fig. 7.7. Without emission policies, for an OTDLT less than 139 all three warehouses are established in low-capacity configurations. With an OTDLT of 139 or above, the number of warehouses is reduced to two. With an OTDL of 195, two warehouses are again established; however, as shown in Fig. 7.7 b), another possible warehouse is established, and warehouse capacity is thus further reduced. Under price-based emission policies and emission cap policy, the reduction of established warehouses is evident with OTDLT higher than 153. With increasing OTDLT, no further reduction of warehouse capacity is observed.

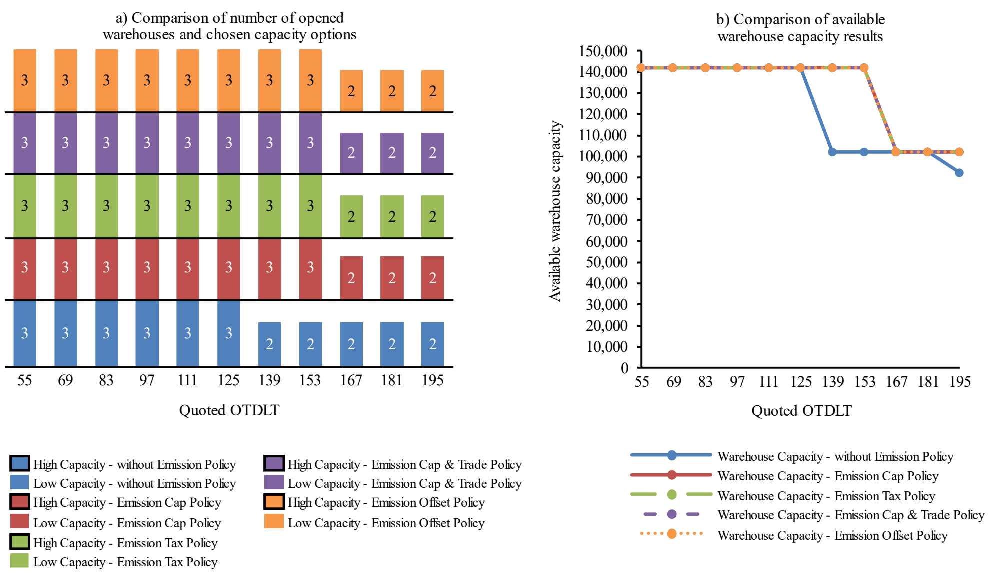

Figure 7.7: Comparison of opened warehouses and available warehouse capacity with varying OTDLT

Changes in quoted OTDLT also influence the expected use of logistic modes, as shown in Fig. 7.8. In general, a reduction of logistic mode 3 is evident with increasing OTDLT, whereas the shares of logistic mode 1 and 2 increase. Furthermore, all emission policies reduce the share of logistic mode 3, compared to the solutions without emission policies. In contrast, the use of logistic mode 2 increases in most observed cases. Because logistic mode 2 is less emission-intensive than logistic mode 3, reduced transport emissions can be expected. The share of logistic mode 1 is higher than when no emission policy is applied. Furthermore, given the higher share of cheaper logistic modes 1 and 2, transportation costs are likely to be lower when emission policies are applied.

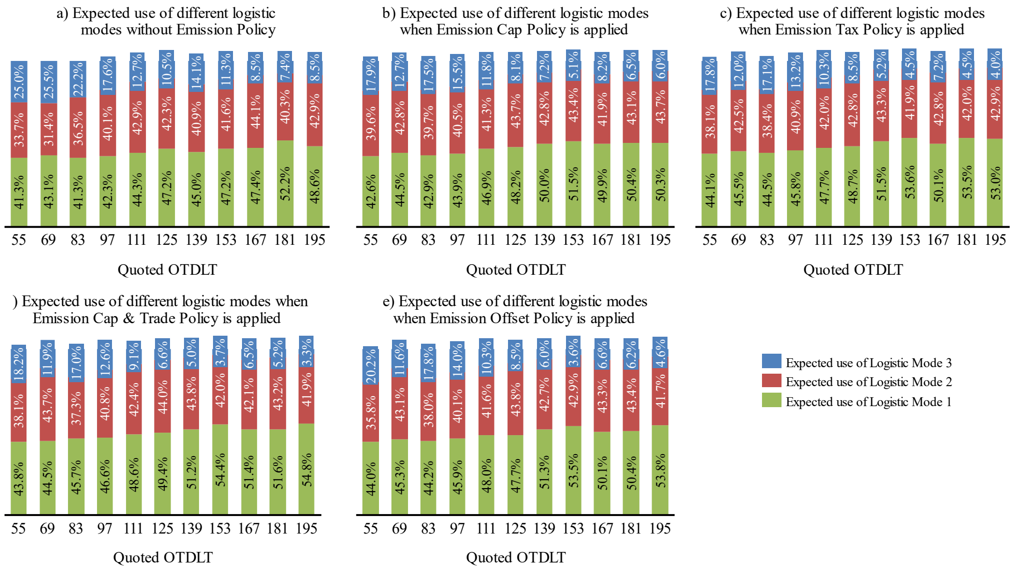

Figure 7.8: Expected use of different logistic modes with varying OTDLT

The expected use of different logistic modes also influences the expected average number of goods in stock, as illustrated in Fig. 7.9. With a low quoted OTDLT, the expected average number of goods in stock is rather high under all emission policies. Without emission policies, the number of goods in stock is significantly lower. Only with OTDLT of 69, stocking levels are higher than with any emission policy applied. With increasing OTDLT, a decrease in stock levels is observed. Furthermore, an outliner is evident when production facilities are closed. A marked increase in the expected average number of goods in stock is evident when the number of production facilities is reduced from three to two. This effect is also seen when the number of warehouses is reduced. Under the emission cap policy, the expected average goods in stock are below the values obtained when no emission policy is applied. Compared to the other policy results, this result entailed higher unfulfilled demand, which could render higher inventories redundant. Furthermore, a trade-off between the use of different logistic modes and expected stock levels is evident. In general, when stock levels are lower, the shares of logistic modes 2 and 3 are higher than under other policies. As shown in Fig. 7.9 b), the market-based emission policies generally increase the stock levels compared to the results without an emission policy. Emission cap policy, in contrast, can lead to a stocking level reduction. Because higher stock levels are well-known measures against uncertainty, it seems possible that the price-based emission policies offer greater flexibility to deal with risks.

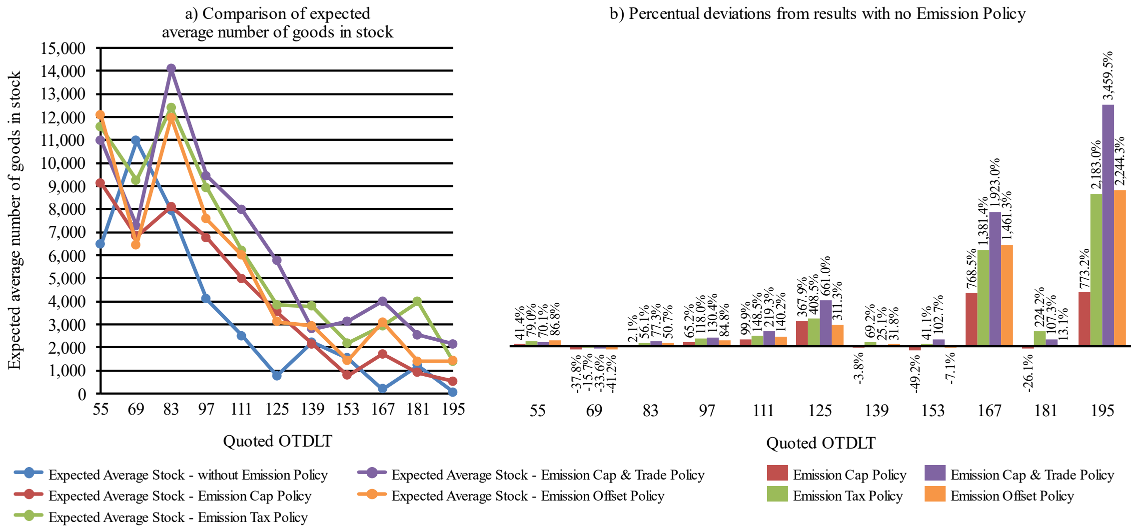

Figure 7.9: Comparison of expected average number of goods in stock and deviations from results with no emission policy

7.5.2 Results with Varying Weighting Factor for Cost Variability

To examine the influence of the weighting factor for cost variability, OTDLT is set to 125, and the factor for model robustness parameter ω is set to a sufficiently high value to guarantee demand fulfillment.

As shown in Fig. 7.10 a), with a higher solution robustness parameter λ, expected total costs increase. With emission policies, an increase between λ of 0.8 and 1 can be observed. Without emission policies, the increase starts with λ of 0.6. This increase in expected total cost accompanies a decrease in total cost variability. Therefore, the generated gap between the optimal solutions of each scenario decrease. The observed decrease in total cost variability is highest in the case of no emission policy, emission tax, or emission cap and trade policy. Emission cap and trade and emission tax policies lead to similar results for total cost variability. Emission offset policy leads to lower variability with a low λ, compared to both other policies. Beyond λ of 0.8, the total cost variability results are similar to the other price-based policies. The emission cap policy with a low λ generates lower variability in total cost even compared to no emission policy. With increasing λ, variability decreases, but not as much as the variability decreases in the absence of emission policies. However, total cost variability remains beneath the variability caused by the price-based emission policies. Therefore, the variability caused by uncertainty about the design of the specific emission policy and uncertainty about the actual demand leads to higher variability in total cost. Furthermore, as shown in the previous chapters, the expected total cost also increases in the presence of emission policies.

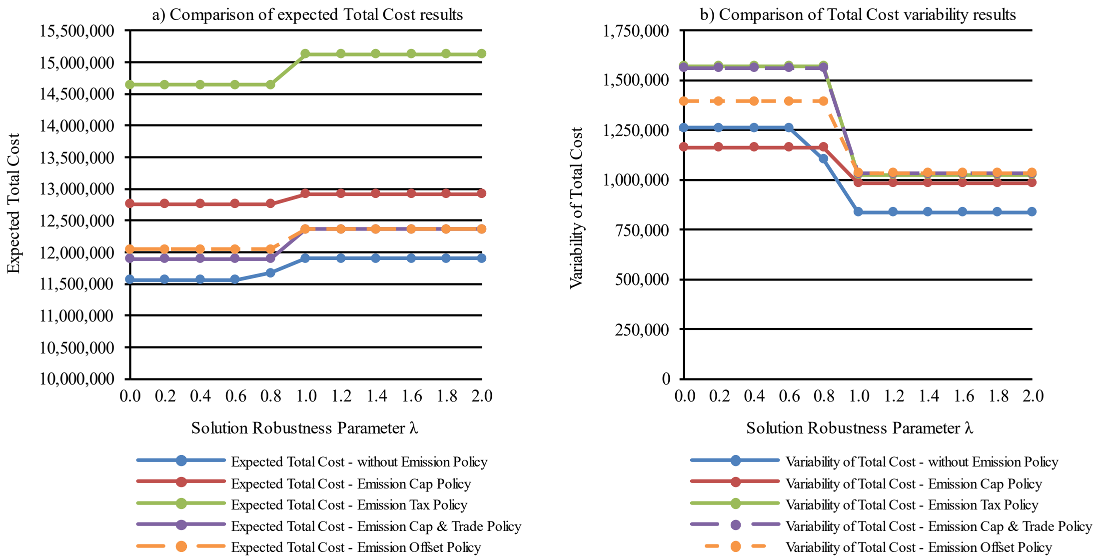

Figure 7.10: Comparison of expected total cost and total cost variability with varying λ

Expected total emissions are illustrated in Fig. 7.11 a). With increasing λ, expected total emissions generally decrease in the case of no emission policy applied.

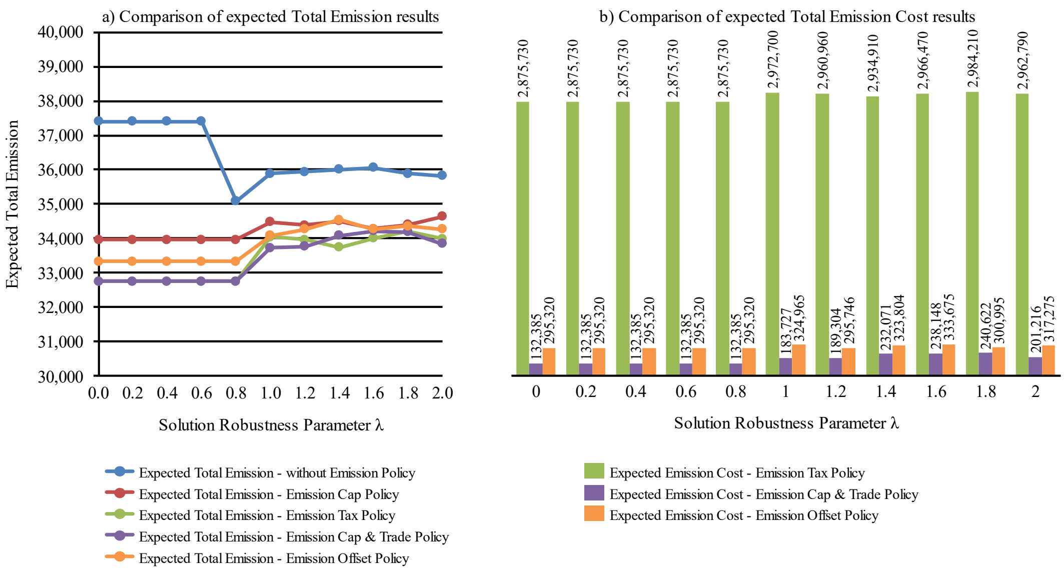

Figure 7.11: Comparison of total emission results and total emission cost with varying λ

On the other hand, in presence of emission policies, an increase of expected total emissions is evident for λ higher than 0.8. Therefore, with a reduction of total cost variability and where no emission policy is applied, a reduction of expected total emissions can be observed. Under emission policies, variability reduction leads to increased expected total emissions. However, all emission policies lead to expected total emissions below the level obtained when no emission policy is applied.[351] For price-based emission policies, the expected total emission cost is illustrated in Fig. 7.11 b). These expected costs reflect the generated total emission amounts. Furthermore, they make up high proportions of the expected total cost increase compared to applying no emission policy.

Supplier selection is, in the given numerical example, unaffected by different values of λ. As Fig. 7.12 a) shows, three suppliers are always selected, regardless of which emission policy is applied. The available capacity of suppliers, shown in Fig. 7.12 b), is stable, which indicates that no change of suppliers occurred.

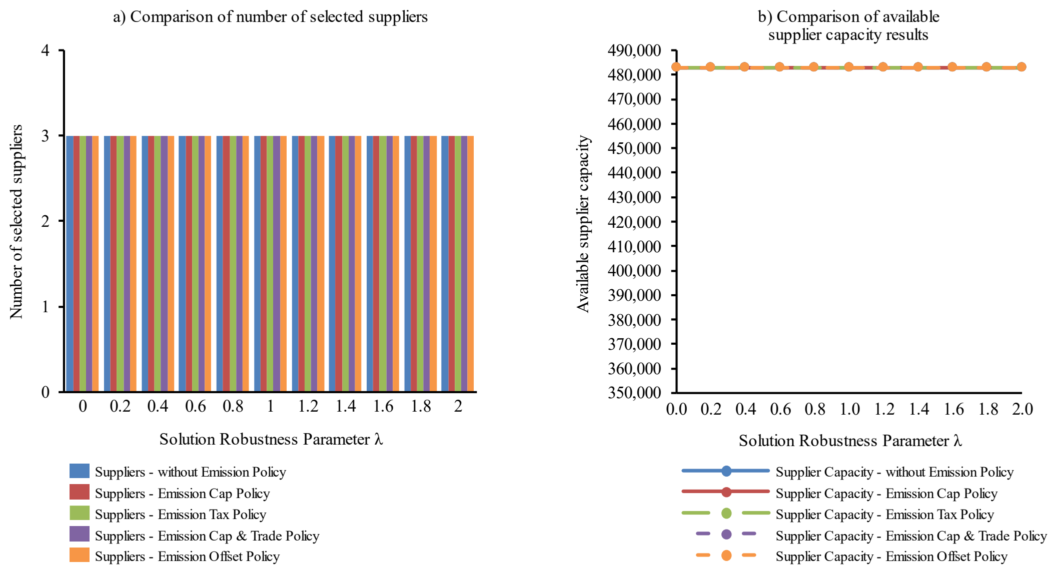

Figure 7.12: Comparison of number of selected suppliers and available supplier capacity with varying λ

The selection of production facilities is stable, as Fig. 7.13 indicates. Two production facilities with low-capacity configurations are established under price-based emission policies and without an emission policy. This selection does not differ with varying λ. In the case of a strict emission cap policy, three facilities with low-capacity options are always opened. In order to deal with a strict command and control policy, it seems favorable to gain flexibility on the basis of more production facilities. Furthermore, as Fig. 7.13 b) indicates, no shifts in production capacity can be observed with varying λ.

[351] Differences in the results of emission cap policy between chapter 7.5.1 and 7.5.2 result from the different ω. In 7.5.1 not fulfilling demand is possible, whereas in chapter 7.5.2 demand is always fulfilled.

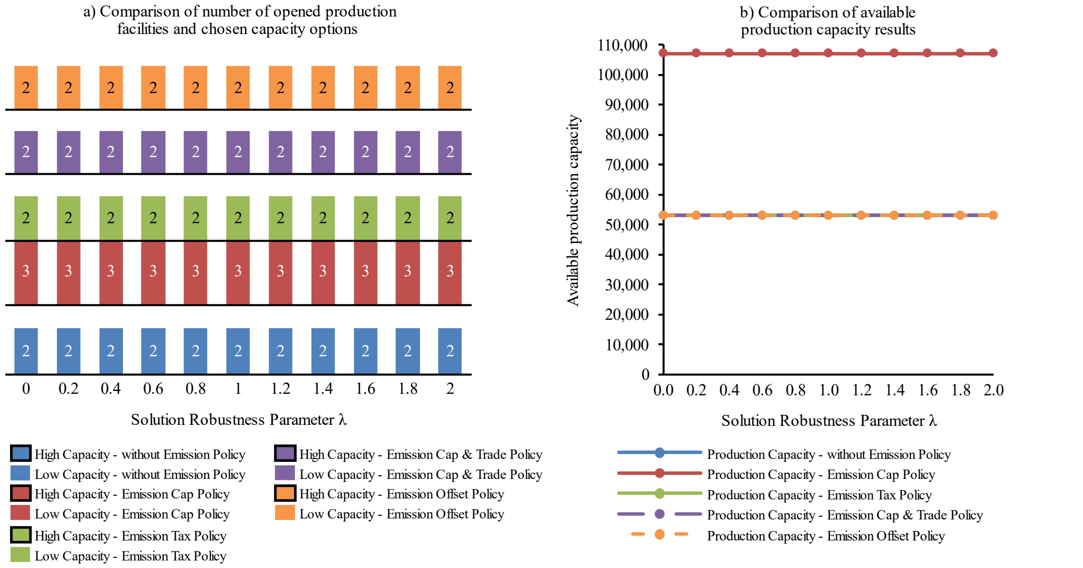

Figure 7.13: Comparison of opened production facilities and available production capacity with varying λ

When no emission policy is applied, the height of λ determines the number of established warehouses, as Fig. 7.14 a) shows. The number of warehouses is increased from two to three to reduce the variability of total costs. When emission policies are enacted, three warehouses are always established, and only the low-capacity option is chosen. As in the case of no emission policy, a higher number of warehouses – and, therefore, a higher warehouse capacity (see Fig. 7.14 b)) – can help to reduce total cost variability. With enacted emission policies, it always seems favorable to establish a higher number of warehouses to deal with these policies' restrictions. Evidently, it is also favorable to open more warehouses rather than to enhance warehouse capacity, as the low-capacity option is always chosen.

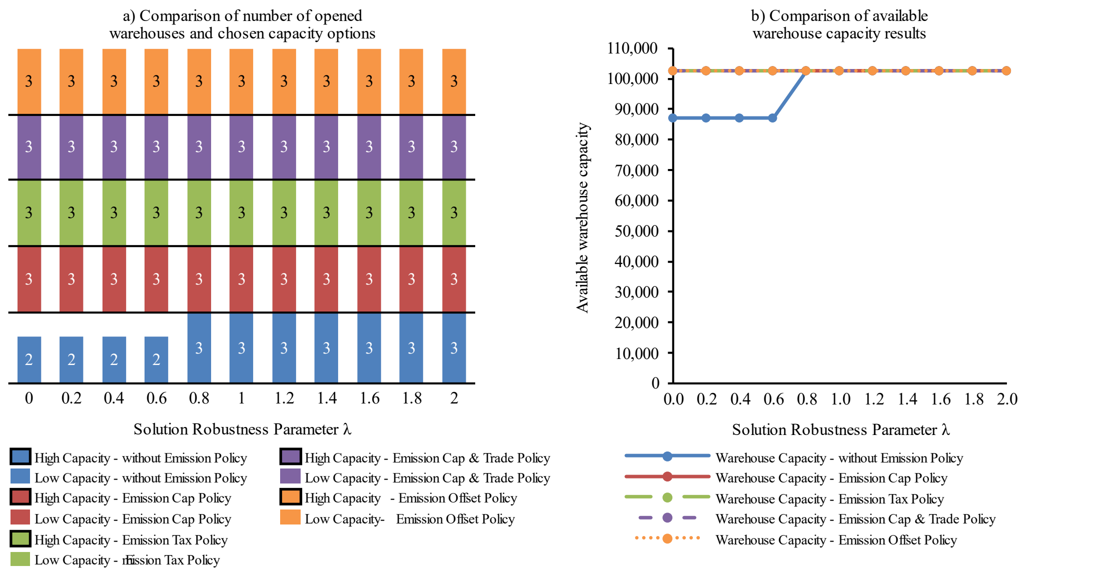

Figure 7.14: Comparison of opened warehouses and available warehouse capacity with varying λ

The expected use of different logistic modes changes differently according to λ when no emission policy is imposed compared to when an emission policy is enacted, as shown in Fig. 7.15. Without emission policies enacted, the expected use of logistic mode 3 decreases with increasing λ, whereas the use of logistic modes 2 and 1 increases. With enacted emission policies, an increase in logistic mode 3 is evident. Under market-based regulation, the use of logistic modes 2 and 1 decreases. By contrast, under the emission cap policy, an increase in logistic mode 2 is evident, whereas logistic mode 1 (low-emission mode) decreased. Even if logistic mode 3 increases under the emission cap policy, the share stays below those under market-based policies. This may be partially compensated for by the increased share of logistic mode 2.

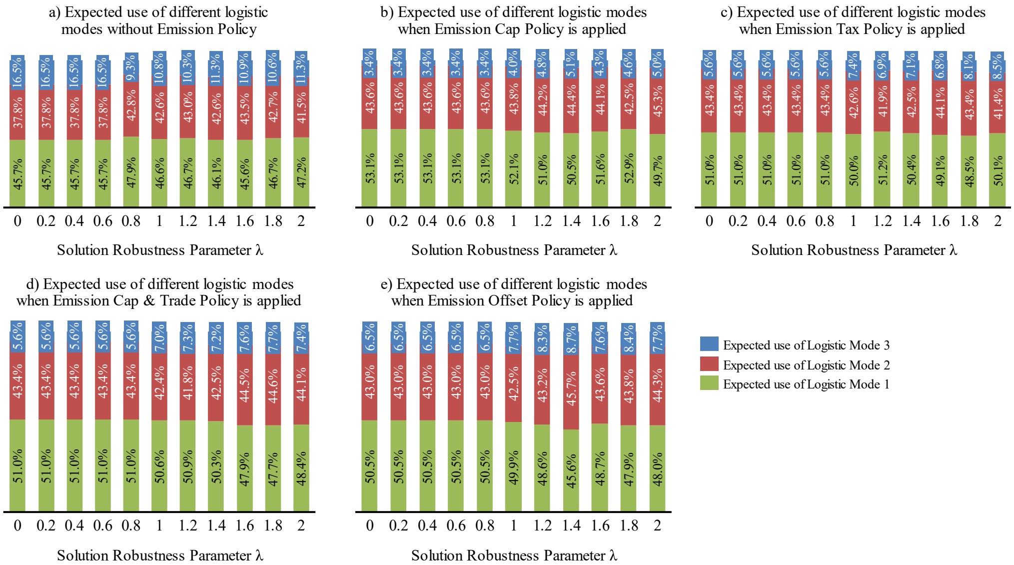

Figure 7.15: Expected use of different logistic modes with varying λ

The expected share of different logistic modes also reflects the expected average number of goods in stock, as shown in Fig. 7.16. As long as no change in total cost variability is observed, stock levels are stable. With decreased variability, with no enacted emission policy, stock levels vary strongly. Furthermore, the use of logistic mode 2 increases along with decreasing stock levels. In the case of an uncertain emission cap policy, stock levels are relatively stable - only a slight increase is observed. By contrast, with uncertain market-based emission policies, stock levels increase strongly. The increase in emission-intensive logistic modes and the higher stock levels with increasing λ can explain the increasing expected total cost and total emission. As Fig. 7.16 b) shows, starting from the λ that leads to a decrease in total cost variability, stock levels under uncertain market-based emission policies are significantly higher. Under uncertain emission cap policy, stock levels are reduced compared to the results without an emission policy. The use of different logistic modes mainly explains the fluctuation of stock levels. With a higher share of faster modes, lower stock levels are required.

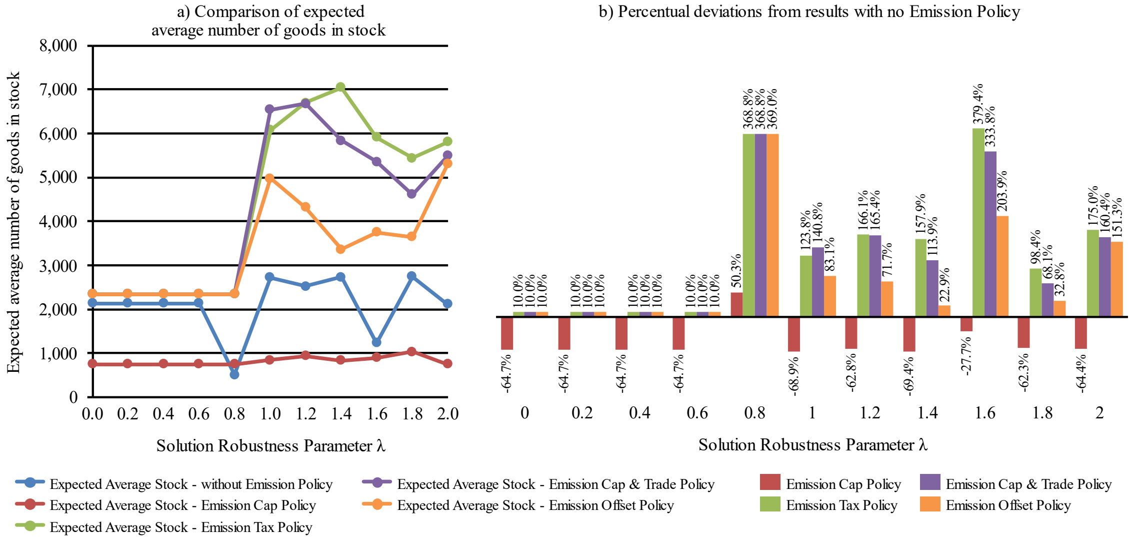

Figure 7.16: Comparison of expected average number of goods in stock with varying λ

7.5.3 Results with Varying Model Robustness

For the analysis of the influence of the model robustness parameter ω, the solution robustness parameter λ is set to 1. The OTDLT is fixed at a value of 125.

Figure 7.17 shows the influence of ω on expected total cost (a) and on the variability of total costs (b). With ω of 0, total costs are, in all examined policy cases, zero. Even with ω of 100, a significant increase is evident for the cases of no emission policy applied, emission cap, emission cap and trade, emission tax, and emission offset policy. With higher ω, expected total costs are increasing. No further change in expected total costs is evident with ω higher than 200 without emission policy and with marked based policies. Similar results are evident for the variability of the total cost: at ω of 100, it increases only slightly. However, there is a further, significant, increase until the parameter reaches the value of 200. After that, the variability of the total cost remains at the same level. A different result is obtained when considering the uncertainties in the design of the emission cap policy. With ω of 100, a substantial increase in expected total cost is evident. With ω of more than 200, the expected total costs stagnate. Only with a robustness parameter of more than 500 a further increase can be examined. With higher ω the total costs stagnate. The variability of the total cost also follows a different course than for the other emission policies. Initially, the variability increases strongly between ω of 100 and 200 under the emission cap policy. After that, a decrease in the variability is evident, but then it increases slightly again. Only between ω of 500 and 600 does the variability of the total costs increase strongly and with higher ω a slighter increase can be observed under the emission cap policy.

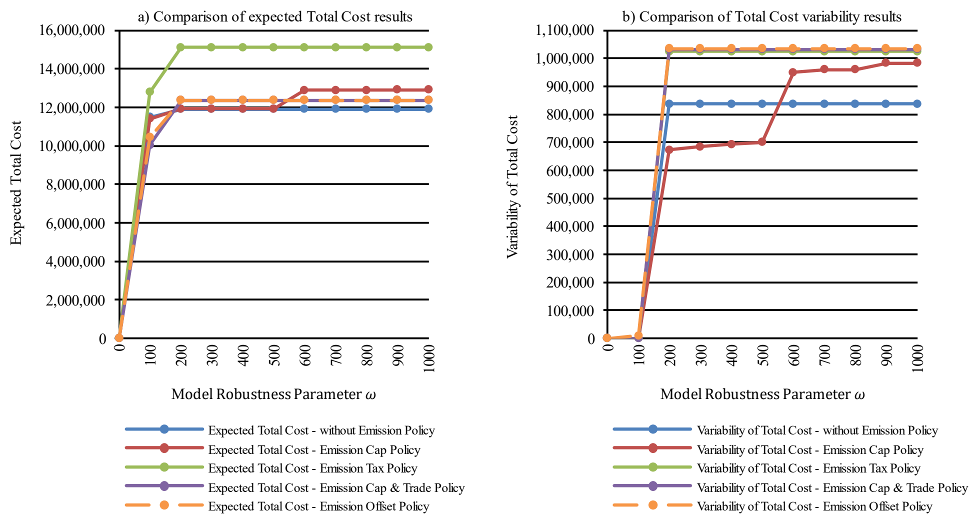

Figure 7.17: Comparison of expected Total Cost and Total Cost variability with varying ω

The development of total cost and the variability of the total costs strongly depend on the unmet demand, as shown in Fig. 7.18. With a ω of 0, a large part of the demand is unmet, regardless of the emission policy applied. Thus, the differences in the demand uncertainty scenarios become smaller, and the variability between these scenarios is reduced. Due to the lower met demand, the total cost decreases.

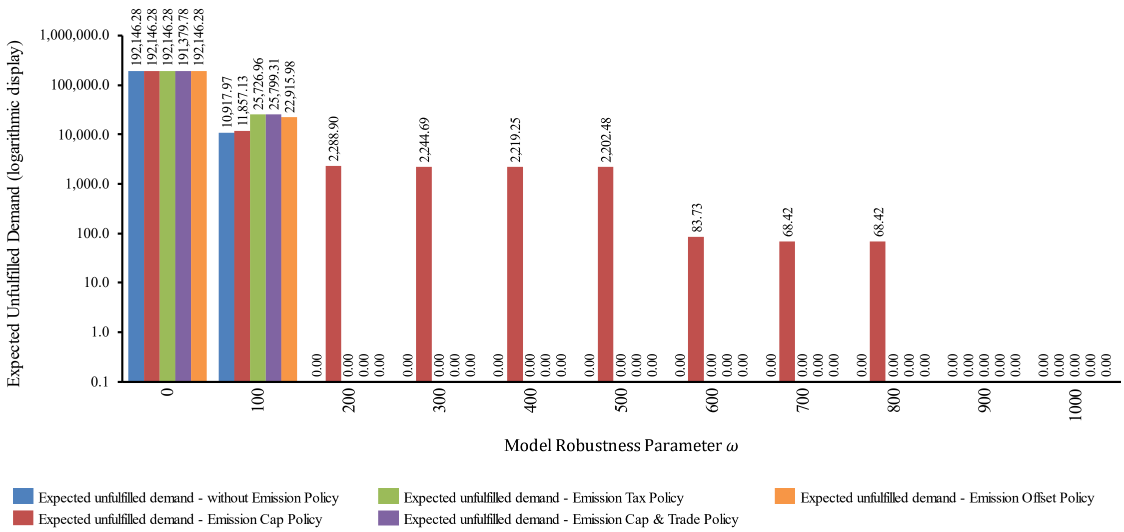

Figure 7.18: Comparison of expected unfulfilled demand with varying ω

With ω of 100, the unmet demand is partially reduced. The lowest value is achieved in the case of no emission policy. Emission tax, and cap and trade policy lead to the same non-fulfillment. Emission offset policy leads to slightly less unfulfilled demand and emission cap policy leads to unfulfillment nearly in the height of the case without emission policy. At ω of 200, there is no more demand shortfall. The exception is the emission cap policy under uncertainty, but a reduction of the unmet demand is evident here. Under this emission policy, total demand is only met with ω of 900, or higher, and thus the variability of the total costs does not change further. It can be assumed that the shortfall results primarily from the scenarios with the strict emission cap and high demand.

The expected total emissions are shown in Fig. 7.19 a). Due to the high proportion of unmet demand, the expected total emissions are zero at ω of 0. Only with emission cap and trade policy a small portion of demand is fulfilled in order to compensate for the sold certificates. Therefore, expected total emissions are slightly higher under this policy. As ω increases, total emissions also increase initially, with or without an emissions policy. If no emissions policy is used, or a price- or market-based emissions policy is enacted, total expected emissions remain relatively constant even as ω continues to increase above 200. However, expected emissions are lower when price-based emission policies are applied than when no emission policy is enacted. Further, total emissions are rather similar under an emission tax and an emission cap and trade policy. The emission offset policy leads to slightly higher expected total emissions. Under an emission cap policy, expected emissions increase sharply up to ω of 100. They then decrease again slightly up to ω of 200. With higher ω, a stronger decrease in total expected emissions can be observed, starting from ω of 500. This level is maintained up to ω of 800. After that, total emissions also increase again under this emission policy and reach the levels obtained under the market-based emission policies. However, the complete fulfillment of expected demand seems to vastly increase total emissions under the emission cap policy.

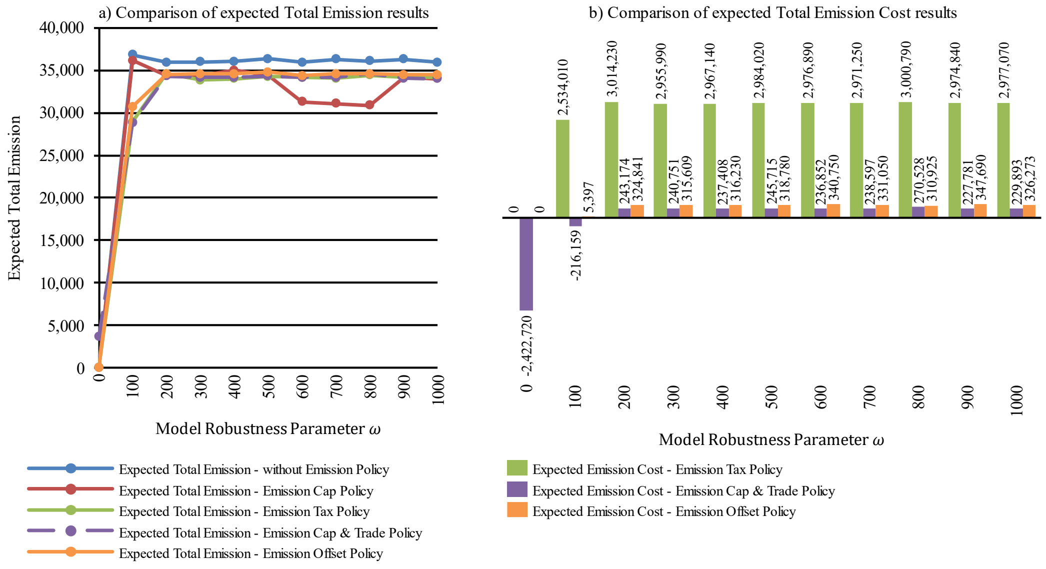

Figure 7.19: Comparison of total emission results and total emission cost with varying ω

As shown in Fig. 7.19 b), expected total emission costs differ strongly between the price-based emission policies. These differences make up high proportions of the differences in expected total costs. Furthermore, the emission tax policy causes the highest additional costs, whereas the emission cap and offset policy result in lower total costs. With ω of 0 and 100, the emission cap and trade policy actually can be a source of additional income in the given example.

The number of selected suppliers and the available supplier capacity are illustrated in Fig. 7.20. With each ω, despite of ω of 0 for all other policies than cap and trade, three suppliers are selected. Under cap and trade policy already 3 suppliers are selected in order to partially fulfill demand. As depicted in Fig. 7.20 b), a switch in suppliers occurs when ω is larger than zero under cap and trade policy. High unfulfilled demand means that a smaller supplier can be selected. With higher fulfillment rates, this supplier is neglected and a supplier with greater capacity is chosen. Therefore, established supplier capacity is highly dependent on expected demand and to demand fulfillment.

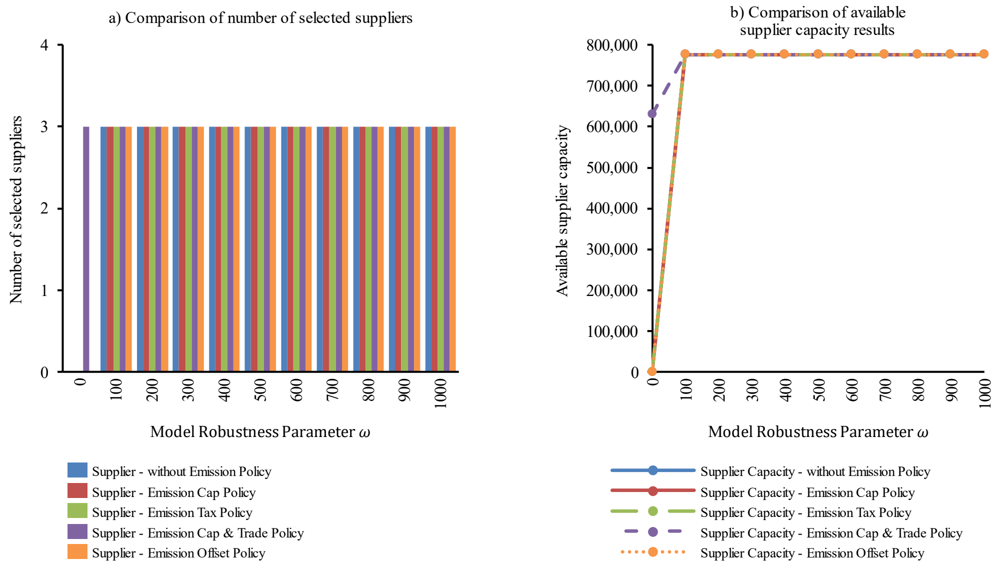

Figure 7.20: Comparison of number of selected suppliers and available supplier capacity with varying ω

In addition, the selection of production facilities and their respective capacity options depend on ω, as shown in Fig. 7.21. With ω of zero, only one facility with a low-capacity option is established under emission cap and trade policy. For all other policies no facility is established at all, because of no demand fulfillment. With decreasing unfulfilled demand due to higher ω, two facilities with low-capacity options are opened. Production capacity increases, as illustrated in Fig. 7.21 b). Without any emission policy and with market-based emission policies, no further changes in facility selection are evident. With an emission cap policy, production capacity slightly decreases at ω of 600 due to the switch to production another production facility in low-capacity configuration. This also leads to higher variability of total costs. At ω of 900, three facilities are opened, and production capacity is increased. Furthermore, an increase in the variability of total cost and expected total emissions is evident with this decision. However, under an emission cap policy, this configuration leads to the fulfillment of expected total demand.

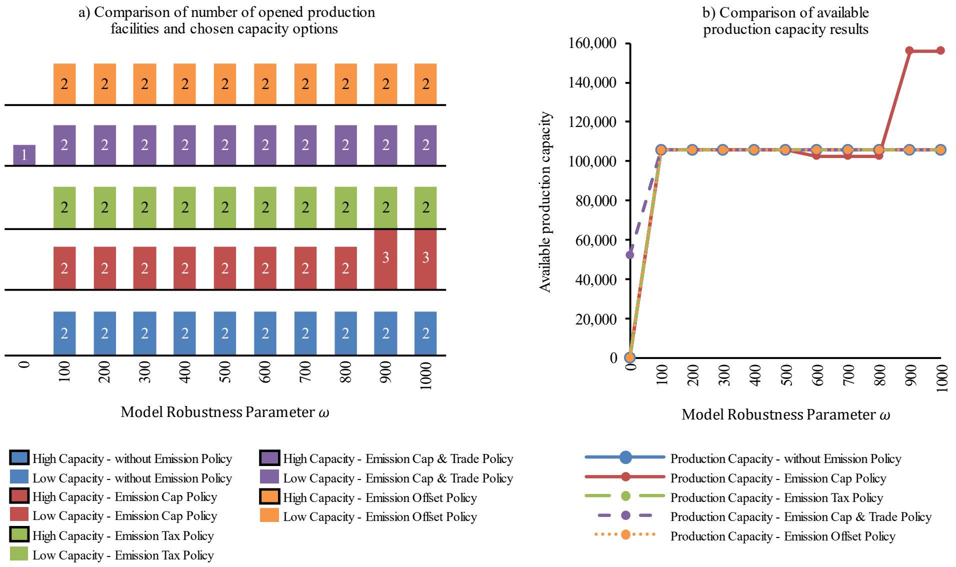

Figure 7.21: Comparison of opened production facilities and available production capacity with varying ω

With ω of zero, only one warehouse with low capacity is established under emission cap and trade policy, as shown in Fig. 7.22. Under all other policies no warehouses are established due to no demand fulfillment. Without an emission policy or with a market-based emission policy, for ω of 100 two warehouses are established in low-capacity configuration, and three warehouses are established for ω of 200 and higher. The same applies for the emission cap regime, but for ω of 600 to 800 only two low-capacity warehouses are selected.

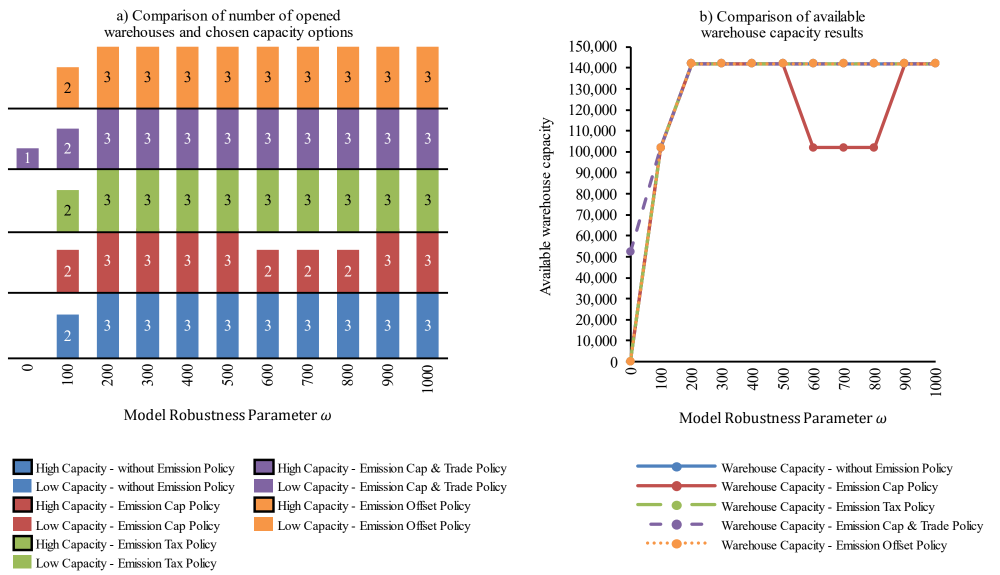

Figure 7.22: Comparison of opened warehouses and available warehouse capacity according to varying ω

Furthermore, Fig. 7.23 b) indicates that the same warehouses, in case of 2 or 3 selected ones, are chosen as under the market-based emission policies. With high values of ω and complete demand fulfillment, again, three warehouses are established. As already seen by the reduction of production facilities under an emission cap, the reduction of established warehouses may reduce the expected total emission. However, demand under this configuration is not entirely fulfilled.

When ω is zero, no goods are expected to be shipped despite under emission cap and trade policy, as Fig. 7.23 indicates. Under this policy most goods are shipped with logistics mode 1. With higher values of ω, and therefore higher demand fulfillment, the share of logistic mode 1 is significantly reduced under emission cap and trade regulation.

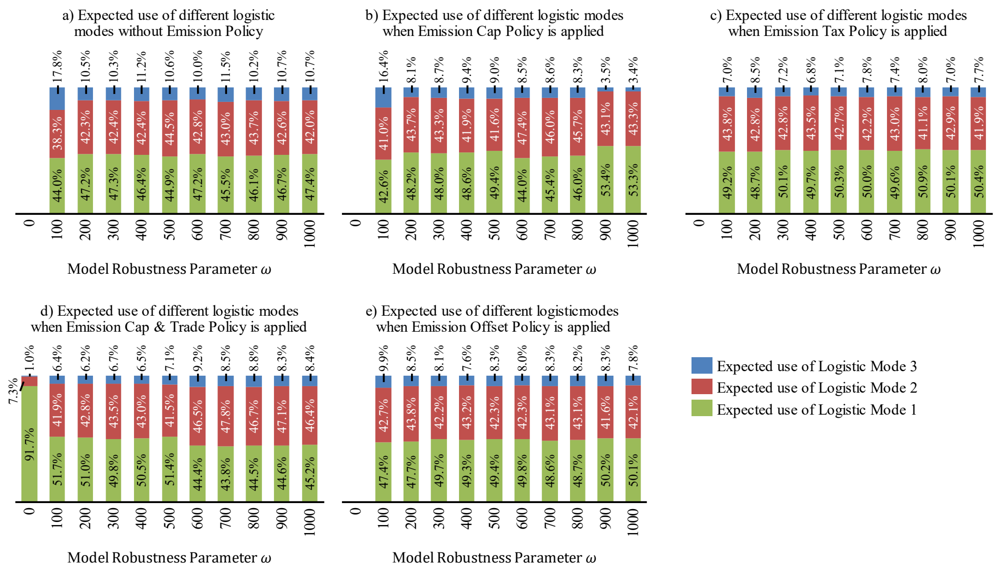

Figure 7.23: Expected use of different logistic modes with varying ω

Logistic modes 2 and 3 are used around 50 % beginning from a ω of 100, and at higher values of ω the shares of these modes remain mostly constant. Greater differences are evident under the emission cap policy when the number of warehouses and production facilities is reduced. In this case, the use of logistic modes 2 and 3 are further increased to sustain the quoted OTDLT. Emission cap and trade policy leads to higher expected use of logistic mode 2 and 3 for ω values between 600 and 900. Compared to the emission tax policy, which leads to similar expected total emission results, stock levels are reduced, as Fig. 7.24 shows. Therefore, it can be estimated that stock levels and the use of fast logistic modes influence each other.

In general, average stock levels per period are zero with ω of zero. Only under emission cap and trade a small number of goods are stored. With increasing demand fulfillment, average number of goods in stock also increase. The largest increase is observed under the emission cap and trade and the emission tax policies. After the first increase, stock levels tend to decrease slightly but remain high. Emission offset also leads to a significant increase in stock levels, when unfulfillment in demand is lowered with ω of 100; however, the average number of goods in stock remains, in most cases, below the levels obtained under emission tax and the emission cap and trade policy.

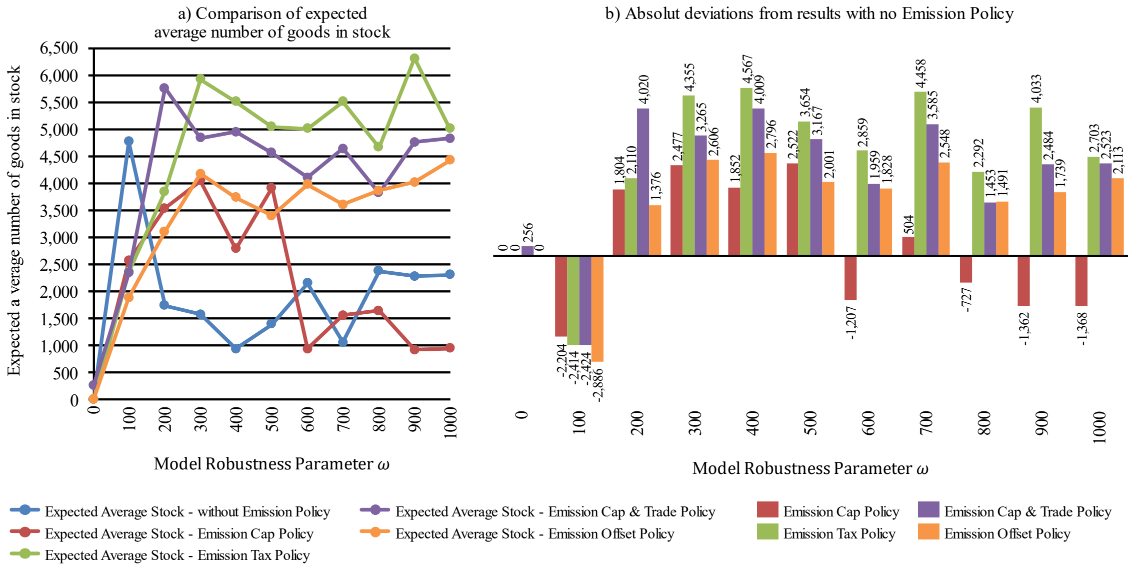

Figure 7.24: Comparison of expected average number of goods in stock and absolute deviations from results without emission policy with varying ω

Without emission policies, the average number of goods in stock is smaller starting from ω of 200, but fluctuations in stock levels are higher compared to applied price-based emission policies. Emission cap policy also increases the average amount of goods on stock, with ω bigger than zero, but even with higher ω, stock levels often stay below the levels without emission policies. The third established production facility, under this emission policy, may lead to reduction in stocking levels. This finding is also illustrated in Fig. 7.24 b). In most cases, uncertainty in market-based emission policies leads to a marked increase in stock levels compared to the situation with no emission policy, whereas an emission cap policy tends to lower the average number of goods in stock. Furthermore, a trade-off between using faster logistic modes and stock levels can be observed. It appears that higher stock levels can be beneficial for dealing with uncertainties in the design of market-based emission policies.

7.6 Conclusion

In general, as shown in Fig. 7.25, the robust approach significantly reduces the variability of total cost compared to the expected values of deterministic solutions. Solution robustness factor λ of 1 and a sufficiently high ω are assumed to guarantee demand fulfillment, for the purposes of comparing results. Reductions in variability of total costs are accompanied by a small increase in expected total cost. Under an emission cap policy, the increase in total costs is more than twice as high as under other emission policies. This can be attributed to the strict requirements under this regime. Scenarios with increasing demand are particularly strongly affected by this policy, leading to an increase in total cost to meet the requirements. In the overall optimization across all scenarios, the supply chain design for the scenarios with low demand must be adjusted accordingly. The price- or market-based policies offer more flexibility to deal with the specific regulations, which means that a smaller increase in total cost can be observed.

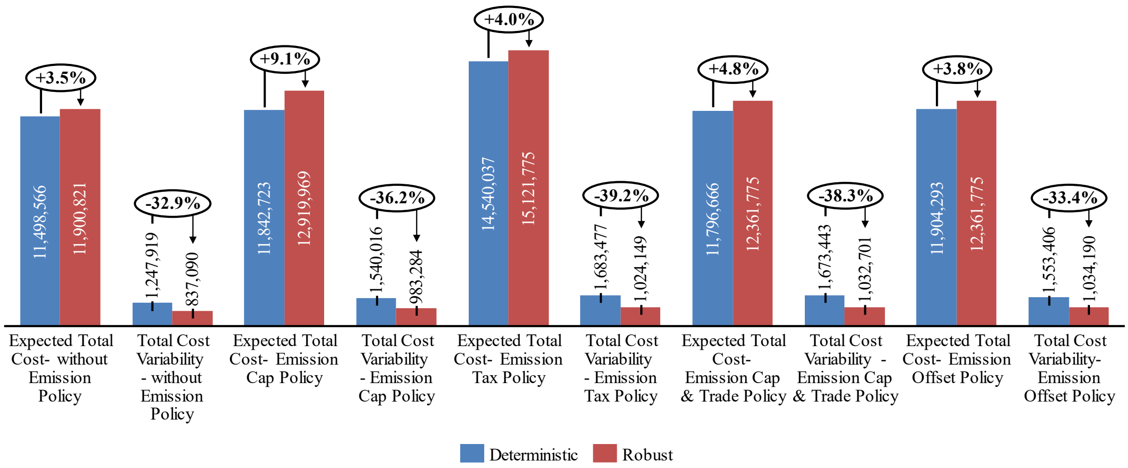

Figure 7.25: Comparison of deterministic and robust solutions

Furthermore, quoted OTDLT affects the expected total cost. As illustrated in Fig. 7.26 a), with increasing OTDLT, the expected total cost strongly decrease, compared to the results with an OTDLT of 55. Furthermore, without emission policies variability of total costs can be reduced with increasing OTDLT. For price-based emission policies significant deviations of variability of total cost can be observed with OTDLT of 69 and 83. With higher lead times the deviations from results with OTDLT of 55 are less significant, but under these policies, quoting longer OTDLT does not necessarily lead to reduction in total cost variability. In contrast to the reductions in total cost, the variability of total cost does not steadily decrease with higher OTDLT. The emission cap policy can lead to an increase in variability of total costs.

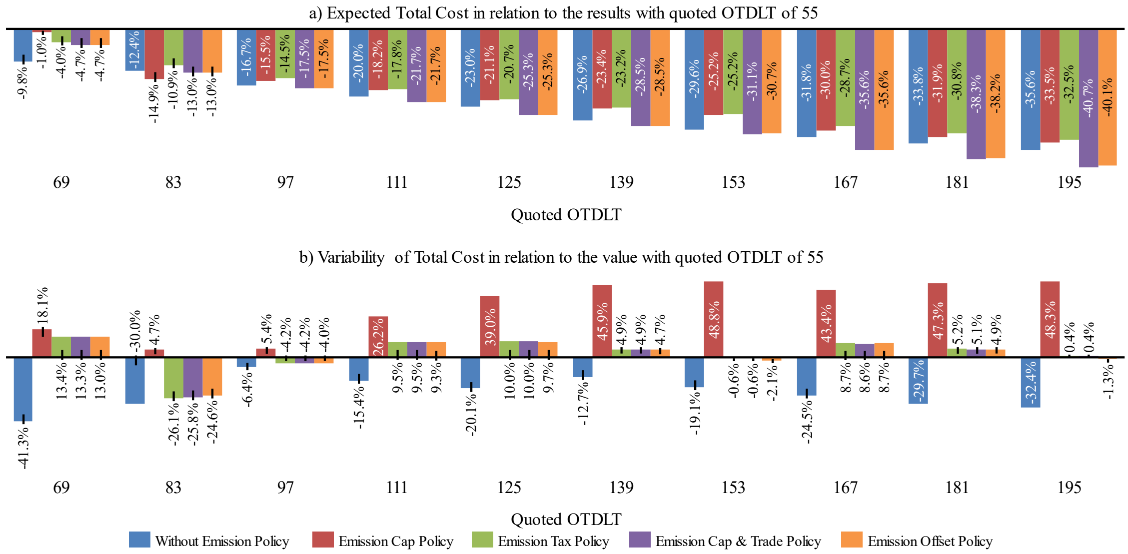

Figure 7.26: Comparison of expected total cost and total cost variability in relation to results with quoted OTDLT of 55

As shown in Fig. 7.26 b), increasing OTDLT leads to an increasing variability of total costs, compared to the results with OTDLT of 55. This increase can be attributed to the fact that as OTDLT increases, the differences between demand scenarios become larger. Furthermore, the strict emission cap – in contrast to the more flexible market-based policies – severely restricts the design options for the supply chain.

The results for total cost and total cost variability are stable at low values of λ. Changes occur with λ of 0.8 without emission policies, and for λ of 1 when emission policies are applied. The results are constant with λ valued higher than 1. As Fig. 7.27 a) shows, with OTDLT of 125 and sufficiently high ω to guarantee demand fulfillment, total cost increases with higher values of λ. Different policies lead to different increases in the expected total cost. The greatest increase occurred under the emission cap and trade policy and the lowest increase under the emission cap policy.

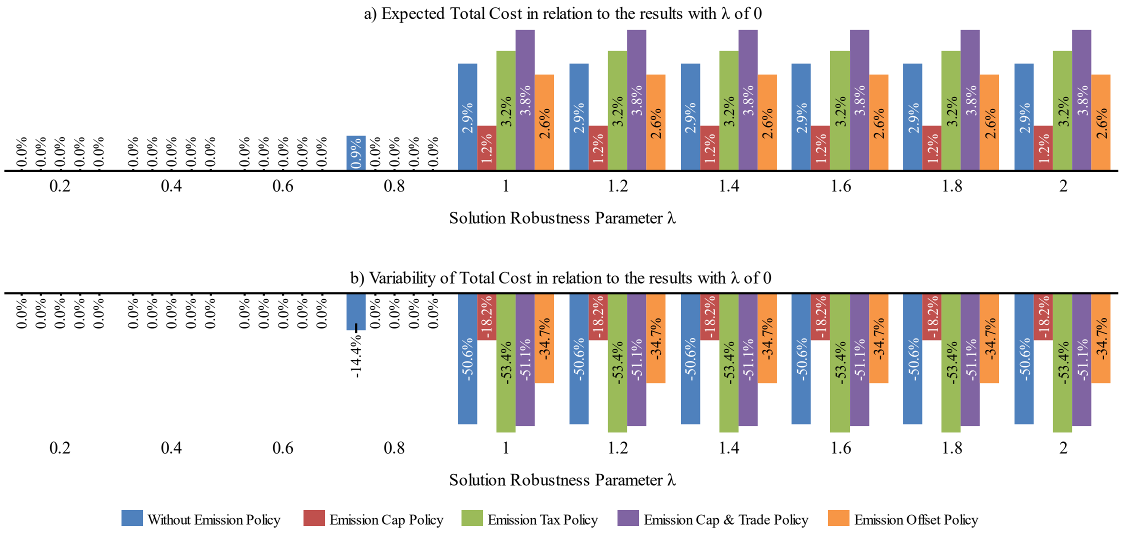

Figure 7.27: Comparison of expected total cost and total cost variability to results with λ of 0

As shown in Fig. 7.27 b), the variability of total cost decreases to the least extent under an emission cap policy. Without emission policies or under an emission tax or an emission cap and trade policy, variability can be reduced by more than 50%. A strict command and control policy offers less flexibility to deal with different scenarios. More flexible market-based emission policies, on the other hand, offer opportunities to hedge against uncertainties.

To analyze the effects of the solution robustness parameter on different emission policies, next to the robust results two scenario groups are observed:

- the results with demand uncertainty under the less strict emission policies (Pol.-Scen. 1) consisting of scenarios 1, 3, and 5
- the results with demand uncertainty under the stricter policies (Pol.-Scen- 2) consisting of scenarios 2, 4, and 6.

As shown in Fig. 7.28, a higher value of λ may lead to expected total cost solutions close to the results for Pol.-Scen. 2.

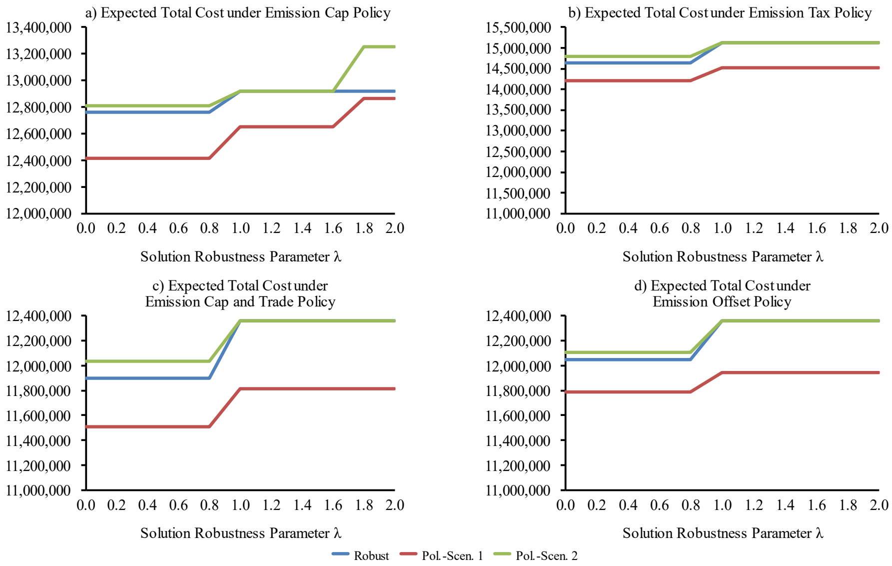

Figure 7.28: Expected total cost of different emission policies with varying λ

These results depend on the assigned possibility of the various scenarios. However, with higher values of λ, the supply chain design is similar to the design under a strict emission policy. Although future emission policies are uncertain, in general, stricter policies are expected. Therefore, a long-term emission policy strategy by the government would be beneficial for companies to configure their supply chains according to the planned regulations.

In addition, the model robustness factor ω displays different influences under different emission policies. With higher fulfillment of the expected demand, the expected total cost increases significantly, as shown in Fig. 7.29 a). When ω is high, and non-fulfillment of expected demand is thus low, only with emission cap policy slight decreases in expected total cost can be realized. A percentual decrease of expected total cost, compared to results with ω of 1000, can only be observed with an ω of 200 in case of price-based emission policies and without emission policy. Only with such low ω demand is not completely fulfilled. Under emission cap, expected total cost can at least be reduced by 7.7 % with ω lower than 600. With ω smaller than 200 reduction becomes higher But, as already mentioned, this reduction is caused by not fulfilling demand completely. Variability of total cost also increases with higher values of ω. With greater fulfillment of expected demand, the variability of total cost increases significantly. Fig. 7.29 b) shows that with low values of ω (0 and 100) total cost variability can be reduced to zero, despite under emission offset policy. Here a small increase can be observed. With higher fulfillment of expected demand, variability of total cost is dramatically increasing without emission policies and with price-based emission policies. Under emission cap policy, the increase is slower, because demand is only fulfilled at high values of ω. Therefore, especially with the emission cap policy, the connection between expected non-fulfillment and total cost variability is clear.

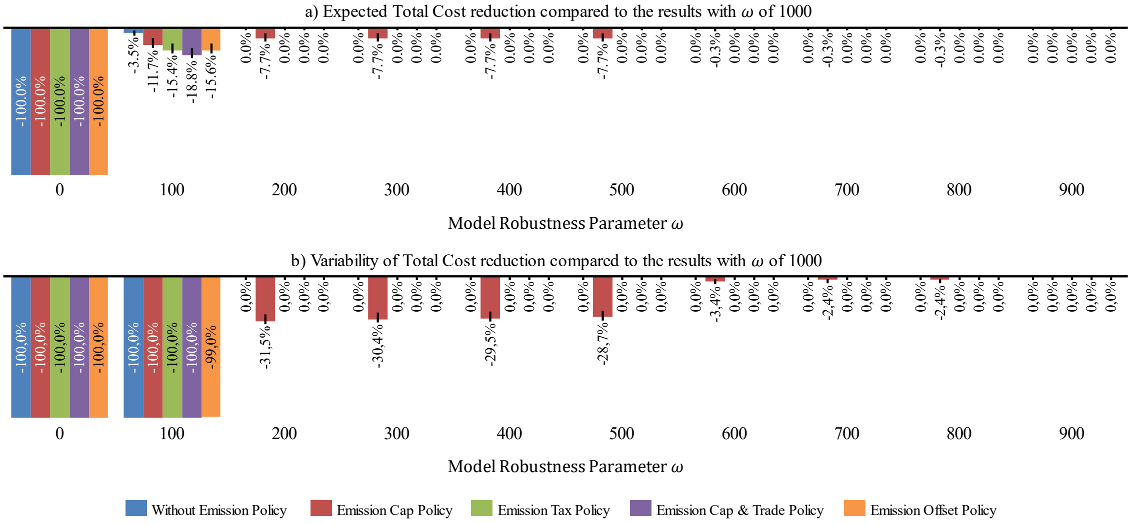

Figure 7.29: Comparison of expected total cost and total cost variability in relation to results with ω of 0

In general, the results depend strongly on the given numerical data example. Neverthe-less, some general insights are obtained:

- Uncertainty in the emission policy design potentially increases the expected total cost and may force companies to adopt a costly supply chain design.
- Quoting a long OTDLT may be beneficial to deal with uncertainties. In addition to the expected total cost, the variability of total costs can be reduced without emission policies. With emission policies in charge, at least a reduction in ex-pected total cost can be observed.
- Flexible emission policies, such as emission tax, emission cap and trade, and emission offset policy, offer companies an opportunity to deal with various un-certainties. Primarily, fulfillment of the expected demand is achieved with lower ω compared to under an emission cap policy.
- Strict command and control policies, such as an emission cap policy, lead to higher costs for demand fulfillment. Therefore, not fulfilling all expected demand may be a suitable strategy for companies. It may be beneficial to calculate non-fulfillment in high demand and strict policy scenarios to achieve a lower expected total cost.

- Especially for market-based emission policies, increasing the stock level seems to be a suitable strategy to deal with uncertainties in demand and uncertainties in the design of emission policies.
- Facility selection depends largely on the emission policy applied. Furthermore, quoted OTDLT and the model robustness factor ω can significantly influence such decisions.
- Also, under uncertainties, suitably designed emission policies lead to decreasing expected total emissions. A higher solution robustness factor λ can lead to an increase in expected total emissions.
- Regarding the general effects on expected total cost and emissions, the results for different emission policies are similar to those discussed in previous chapters.

8 Supply Chain Design Considering country-specific Emission Policies Quoted Order-to-Delivery Lead Time

8.1 Relevance and Assumptions

With the ratification of the Paris Agreement, 189 of 197 countries agreed to create a sustainable low-carbon future.[352] The agreement sets reduction targets for developed and emerging economies worldwide regarding their GHG emissions. Although most countries agree with these common goals, on November 4th 2019, the United States of America – a major GHG emitter – withdraw for some time from this agreement under the Trump administration.[353] Furthermore, according to the WORLD BANK, there were only 61 GHG emission pricing initiatives in 2020, covering about 22.3% of global GHG emissions. Prices for GHG emissions in these initiatives range between 0.07 US$ and 119.43 US$ per ton of emission.[354] The prices are not fully comparable due to exemptions, different allocation modes, and covered sectors; nonetheless, the incentive for companies to lower their GHG emissions depends mainly on the country in which they are generated. Furthermore, most developing countries agreed to lower the GHG emissions in their jurisdictions, but most have no pricing initiative launched as yet.[355] The emission regulation schemes implemented in most countries do not cover imports from other economic areas. Therefore, imports from non-regulated countries incur no emission cost. In some

[352] Cf. UNFCCC, 2020.
[353] Cf. UNITED NATIONS TREATY COLLECTION, 2020.
[354] Cf. WORLD BANK GROUP, 2020.
[355] Cf. WORLD BANK GROUP, 2020.

industries, emission policies increase the production costs by up to 40%, which means some companies relocate their production facilities to outside the regulated regions.[356] A major problem caused by shifting production to unregulated economic areas is undermining of the effort to lower global emission levels; indeed, emissions in countries without emission policies are increasing. Reasons for shifting production include a possible cost advantage for companies based in unregulated countries and the resulting incentive for regulated country-based companies to relocate production to enjoy this advantage. The problem of carbon leakage is discussed by politicians, who propose – for example – carbon tariffs to avoid the offshoring of production facilities.[357] Carbon leakage is thus a significant problem for policymakers but can be an opportunity for companies to lower their costs.[358] The incentives to offshore activities in less developed countries can be reinforced by traditional offshoring incentives such as lower production costs and lower wages in those countries.[359] Nonetheless, outsourcing activities to unregulated countries plays an important role in global GHG emissions. For example, China's GHG emissions from exports account for about 27% to 35% of China's total emission.[360] According to a study by DAVIS AND CALDEIRA, the top importers of emissions are developed countries such as the United States of America, Japan, the United Kingdom, Germany, and France. In contrast, the main exporters of emissions are developing countries such as China, Russia, countries in the Middle East, South Africa, and Ukraine.[361] Those net exporters are usually countries with weak or even no emission policy adoption.[362]

In the early 2000s, a new tendency of reshoring occurred in which companies decided to move plants and parts of their management services back to their home countries. These tendencies were driven by increasing production costs in less developed countries; competitive improvements in home countries; and greater operational flexibility from a reduced distance among suppliers, production facilities, and markets.[363] Furthermore, shorter lead times, lower inventory costs, and higher flexibility are important factors for

[356] Cf. DRAKE, D. F., 2011, p. 1f; KUIK, O.; GERLAGH, R., 2003, p. 98; MORGENSTERN, R. D. ET AL., 2007, p. 104.
[357] Cf. VON DER LEYEN, U., 2019, p. 5.
[358] Cf. ZHOU, Y. ET AL., 2017, p. 1542f.
[359] Cf. PIATANESI, B.; ARAUZO-CAROD, J., 2019, p. 806.
[360] MINX, J. C. ET AL., 2011, p. 9150; WEBER, C. L. ET AL., 2008, p. 3574; WEI, B.; FANG, X.; WANG, Y., 2011, p. 307.
[361] DAVIS, S. J.; CALDEIRA, K., 2010, p. 5691.
[362] Cf. WORLD BANK GROUP, 2020.
[363] Cf. PIATANESI, B.; ARAUZO-CAROD, J., 2019, p. 807; BARBIERI, P. ET AL., 2018, p. 80.

reshoring tendencies.[364] Nowadays, many companies compete by quoting short lead times. However, quoting short lead times but not fulfilling customers' expectations because of delays can lower customer satisfaction.[365] Customer service consists of many elements, with speed and delivery lead time being critical factors.[366] Therefore, a trade-off occurs between the lowest possible cost and some flexibility to satisfy customer demands. Lead times play an important role in this context, but emission policies increase the costs, especially for energy-intensive industries. A supply chain design model is proposed to examine this problem covering different country-specific emission policies and quoted OTDLTs.

The proposed model is based on the following assumptions:

- It is a discrete deterministic model with a finite number of potential suppliers, manufacturing sites, warehouses, and planning periods.
- There is a fixed number of customer regions.
- Suppliers have a fixed capacity for every raw material they provide.
- The planning horizon covers several strategic planning periods.
- Three logistic modes are available, and full truck loads are assumed for each transportation process. Logistic modes differ in cost, speed, and generated emissions. Logistic mode 1 offers low cost, emissions, and speed, whereas logistic mode 3 offers high cost, emission, and speed. Logistic mode 2 is characterized by medium cost, emissions, and speed.
- Capacities of suppliers are restricted.
- Capacities of production facilities and warehouses are restricted to the chosen capacity option.
- Potential suppliers, production facilities, and warehouses can be placed in three different countries.
- The same production and handling process quality is assumed at all suppliers, production facilities, and warehouses.

[364] Cf. Di Mauro, C. et al., 2018, p. 110; Robinson, P. K.; Hsieh, L., 2016, p. 92; Stentoft, J.; Mikkelsen, O. S.; Johnsen, T. E., 2015, p. 6.
[365] Cf. Spearman, M. L.; Zhang, R. Q., 1999, p. 290.
[366] Cf. Sterling, J. U.; Lambert, D. M., 1989, p. 18f.

- Country 1 is a developed country that has implemented an emission cap and trade system, Country 2 is an emerging country that has imposed an emission tax, and Country 3 is a non-developed country with no emission policy.
- The company can use emission offset to internalize its emissions in Country 3.
- Emissions from transportation activities are added to the emissions of the country in which the transportation activities start.

8.2 Model Development

The model's objective function aims to minimize total cost over all periods. The first three terms are fixed costs for supplier selection, production facility location, and warehouse location.

$$\begin{aligned} Z_1 = {} & \sum_{s}^{S} SC_s\, y_s^{Su} + \sum_{f}^{F}\sum_{o}^{O} FC_{fo}\, y_{fo}^{Fa} + \sum_{w}^{W}\sum_{o}^{O} WC_{wo}\, y_{wo}^{Wa} \\ & + \sum_{s}^{S}\sum_{f}^{F}\sum_{m}^{M}\sum_{p}^{P}\sum_{l}^{L}\sum_{t}^{T} PC_{smt}\, x_{sfmplt} \\ & + \sum_{f}^{F}\sum_{w}^{W}\sum_{p}^{P}\sum_{l}^{L}\sum_{t}^{T} MC_{fpt}\, x_{fwplt} \\ & + \sum_{w}^{W}\sum_{c}^{C}\sum_{p}^{P}\sum_{l}^{L}\sum_{t}^{T} HC_{wpt}\, x_{wcplt} \\ & + \sum_{w}^{W}\sum_{p}^{P}\sum_{t}^{T}\sum_{c}^{C} SC_{wpt} \frac{\left(h_{wp(t-1)c} + h_{wptc}\right)}{2} \\ & + \sum_{s}^{S}\sum_{f}^{F}\sum_{m}^{M}\sum_{p}^{P}\sum_{l}^{L}\sum_{t}^{T} TC_{sfmlt}\, x_{sfmplt} \\ & + \sum_{f}^{F}\sum_{w}^{W}\sum_{p}^{P}\sum_{l}^{L}\sum_{t}^{T} TC_{fwplt}\, x_{fwplt} \\ & + \sum_{w}^{W}\sum_{c}^{C}\sum_{p}^{P}\sum_{l}^{L}\sum_{t}^{T} TC_{wcplt}\, x_{wcplt} \\ & + \sum_{t}^{T} \Omega^{CAT} \left(\alpha_{ta=1}^{+} - \alpha_{ta=1}^{-}\right) + \sum_{t}^{T} \Omega^{Tax}\, E_{ta=2} \\ & + \sum_{t}^{T} \Omega^{Off}\, \beta_{ta=3} \end{aligned} \tag{8.1}$$

The successive terms account for the costs for purchasing raw materials, manufacturing costs at production facilities, handling, and storage costs at warehouses, transporting materials from suppliers to production facilities, transporting products from production facilities to warehouses, and shipping to the final customers. The last three terms determine the costs of the applied emission policies in the different countries. As assumed for the developed country, a cap and trade system is installed. Therefore, the costs and earnings of selling and buying emission credits are calculated. In the semi-developed country, an emission tax is applied, and the second last term calculates the costs that occur under this tax. In the undeveloped country an emission offset system is applied, and the last term thus accounts for the costs of offsetting emissions in this country.

Constraint (8.2) ensures that the demand of each customer in each period is fulfilled. Constraint (8.3) determines the flows between production facilities and warehouses and the stock level at each warehouse. According to the bill of materials, the flows of needed raw materials are determined in constraint (8.4).

$$D_{cpt} = \sum_{w}^{W} \sum_{l}^{L} x_{wcplt} \qquad \forall c \in C, p \in P, t \in T \qquad (8.2)$$

$$\sum_{c}^{C} \sum_{l}^{L} x_{wcplt} + \sum_{c}^{C} h_{wptc} = \sum_{f}^{F} \sum_{l}^{L} x_{fwplt} + \sum_{c}^{C} h_{wp(t-1)c} \qquad \forall w \in W, p \in P, t \in T \qquad (8.3)$$

$$\sum_{w}^{W} \sum_{p}^{P} \sum_{l}^{L} x_{fwplt} \, BOM_{mp} = \sum_{s}^{S} \sum_{p}^{P} \sum_{l}^{L} x_{sfmplt} \qquad \forall f \in F, m \in M, t \in T \qquad (8.4)$$

Constraints (8.5), (8.6), (8.7), and (8.8) are capacity constraints that ensure that no more materials and products can be procured, produced, handled, and stocked than the actual capacity of an established facility allows. Constraints (8.9) and (8.10) ensure that only one capacity option can be chosen for each production facility and each warehouse.

$$\sum_{f}^{F} \sum_{p}^{P} \sum_{l}^{L} x_{sfmplt} \leq Cap_{sm}^{Su} y_{s}^{Su} \qquad \forall s \in S, m \in M, t \in T \qquad (8.5)$$

$$\sum_{w}^{W} \sum_{p}^{P} \sum_{l}^{L} x_{fwplt} \leq \sum_{o}^{O} Cap_{fo}^{Fa} \, y_{fo}^{Fa} \qquad \forall f \in F, t \in T \qquad (8.6)$$

$$\sum_{c}^{C} \sum_{p}^{P} \sum_{l}^{L} x_{wcplt} \leq \sum_{o}^{O} Cap_{wo}^{Wa} \, y_{wo}^{Wa} \qquad \forall w \in W, t \in T \qquad (8.7)$$

$$\sum_{p}^{P}\sum_{c}^{C} h_{wptc} \leq \sum_{o}^{O} Cap_{wo}^{Wa}\, y_{wo}^{Wa} \qquad \forall w \in W, t \in T \qquad (8.8)$$

$$\sum_{o}^{O} y_{fo}^{Fa} \leq 1 \qquad \forall f \in F \qquad (8.9)$$

$$\sum_{o}^{O} y_{wo}^{Wa} \leq 1 \qquad \forall w \in W \qquad (8.10)$$

Constraint (8.11) determines the maximum OTDLT. Every order placed by a customer in period t must be fulfilled within this time. In (8.12), the actual OTDLT is calculated. Therefore, the transportation lead times of materials and products for goods that are not in stock are calculated, as are the manufacturing, handling, and delivery lead times. Constraint (8.13) determines the number of products that are not in stock and therefore must be delivered from a facility. Constraint (8.14) is applied to ensure that these quantities are within the regular flow of goods. In (8.15), the additionally needed materials for fulfilling a customer order during a period are calculated, and (8.16) ensures that these material flows are within the regular flows.

$$MaxLT \geq OTD_{cpt} \qquad \forall c \in C, p \in P, t \in T \qquad (8.11)$$

$$\begin{aligned} OTD_{cpt} \geq\ & LT_{smt}^{Su}\delta_{sfmpltc}^{SF} + LT_{fpt}^{Fa}\delta_{fwpltc}^{FW} \\ & + LT_{wpt}^{Wa}x_{wcplt} + LT_{sfmlt}\delta_{sfmpltc}^{SF} \\ & + LT_{fwplt}\delta_{fwpltc}^{FW} + LT_{wcplt}x_{wcplt} \end{aligned} \qquad \begin{aligned} &\forall s \in S, f \in F, w \in W, \\ &c \in C, m \in M, p \in P, \\ &l \in L, t \in T \end{aligned} \qquad (8.12)$$

$$\sum_{l}^{L} x_{wcplt} - h_{wp(t-1)c} = \sum_{f}^{F}\sum_{l}^{L} \delta_{fwpltc}^{FW} \qquad \begin{aligned} &\forall w \in W, p \in P, t \in T, \\ &c \in C \end{aligned} \qquad (8.13)$$

$$x_{fwplt} \geq \sum_{c}^{C} \delta_{fwpltc}^{FW} \qquad \begin{aligned} &\forall, f \in F, w \in W, \\ &p \in P, l \in L, t \in T \end{aligned} \qquad (8.14)$$

$$\sum_{w}^{W}\sum_{l}^{L} \delta_{fwpltc}^{FW}\, BOM_{mp} = \sum_{s}^{S}\sum_{l}^{L} \delta_{sfmpltc}^{SF} \qquad \begin{aligned} &\forall f \in F, c \in C, m \in M, \\ &p \in P, t \in T \end{aligned} \qquad (8.15)$$

$$x_{sfmplt} \geq \sum_{c}^{C} \delta_{sfmpltc}^{SF} \qquad \begin{aligned} &\forall s \in S, f \in F, m \in M, \\ &p \in P, l \in L, t \in T \end{aligned} \qquad (8.16)$$

Constraint (8.17) calculates the actual number of emissions for each period and each country. Fixed emissions for operating production facilities and warehouses are taken into account, as are emissions from purchasing, manufacturing, handling, stocking, and transportation. In (8.18), the additional needed or excess emission credits in the developed country are calculated, and in (8.19) the number of emissions that have to be offset in the emission offset system are calculated.

$$E_{ta} = \sum_{f}^{F_a}\sum_{o}^{O} FE_{fot} y_{fo}^{Fa} + \sum_{w}^{W_a}\sum_{o}^{O} WE_{wot}\, y_{wo}^{Wa} + \sum_{s}^{S_a}\sum_{f}^{F}\sum_{m}^{M}\sum_{p}^{P}\sum_{l}^{L} PE_{smt}\, x_{sfmplt} + \sum_{f}^{F_a}\sum_{w}^{W}\sum_{p}^{P}\sum_{l}^{L} ME_{fpt}\, x_{fwplt} + \sum_{w}^{W_a}\sum_{c}^{C}\sum_{p}^{P}\sum_{l}^{l} HE_{wpt}\, x_{wcplt} + \sum_{w}^{W_a}\sum_{p}^{P}\sum_{c}^{C} SE_{wpt} \frac{\left(h_{wp(t-1)c} + h_{wptc}\right)}{2} + \sum_{s}^{S_a}\sum_{f}^{F}\sum_{m}^{M}\sum_{p}^{P}\sum_{l}^{L} TE_{sfmlt}\, x_{sfmplt} + \sum_{f}^{F_a}\sum_{w}^{W}\sum_{p}^{P}\sum_{l}^{L} TE_{fwplt}\, x_{fwplt} + \sum_{w}^{W_a}\sum_{c}^{C}\sum_{p}^{P}\sum_{l}^{L} TE_{wcplt}\, x_{wcplt} \qquad \forall a \in A, t \in T \qquad (8.17)$$

$$E_{ta} + \alpha_{ta}^{-} = ECap_a + \alpha_{ta}^{+} \qquad \forall t \in T, a = 1 \qquad (8.18)$$

$$E_{ta} = ECap_a + \beta_{ta} \qquad \forall t \in T, a = 3 \qquad (8.19)$$

Constraint (8.20) specifies the non-negative variables, and (8.21) determines the binary variables.

$$x_{sfmplt}, x_{fwplt}, x_{wcplt}, h_{wptc}, \delta_{sfmpltc}^{SF}, \delta_{fwpltc}^{FW}, E_{ta}, \alpha_{ta}^{+}, \alpha_{ta}^{-}, \beta_{ta} \geq 0 \qquad \forall s \in S, f \in F, w \in W, c \in C, m \in M, p \in P, l \in L, t \in T, a \in A \qquad (8.20)$$

$$y_s^{Su}, y_{fo}^{Fa}, y_{wo}^{Wa} \in [0;1] \qquad \forall s \in S, f \in F, w \in W \qquad (8.21)$$

8.3 Data Generation Process

The model is evaluated through application to a random data set. The data set is generated as follows:

To determine which suppliers, production facilities, warehouses, and customers are located in a specific country, the number of distinct entities are assigned to each considered country a. It is ensured that each country is the home of at least one supplier, production facility, and warehouse. Customer clusters are located only in countries 1 and 2, and it is ensured that Country 1 possesses the most customer clusters.

For the location of suppliers, production facilities, warehouses, and customers, the approach proposed by Melkote and Daskin[367] is applied. A node on a 15000 x 15000 grid represents every location. The x and y coordinates for the three considered countries are randomly generated according to the distributions in Table 8.1.

Country	x-coordinate	y-coordinate
1	U[0, 6500]	U[0, 6500]
2	U[8500, 15000]	U[0, 6500]
3	U[5000, 15000]	U[8500, 15000]

Table 8.1: Distributions for coordinate generation

The distance between the different entities is measured as a Euclidean metric. The distance between two locations is multiplied by a factor for each mode and the result is divided by the capacity factor of each mode to calculate transportation costs for each logistic mode. For the three modes, cost factors of $[0.03, 0.3, 2.3]$ and capacity factors of $[300, 40, 90]$ are assumed. The costs for raw materials are multiplied by a number generated from uniform distribution $U[0.01, 0{,}075]$, and the costs for products are multiplied by a random number from $U[0.075, 0.20]$ to differentiate between raw materials and final products. The distance between two possibly connected locations is divided by a speed factor for each logistic mode to determine transportation lead times. These factors are assumed to be [20, 60, 400] for the three considered modes. Each value between the locations is divided by the sum of maximum demand of all periods to attain the lead times for transportation activities between production facilities, warehouses, and customers. For transportation lead times between suppliers and production facilities, the value is divided by the maximum demand of all periods, multiplied by the bill of materials. Transportation emissions are calculated by multiplying the distance between the locations by the emission factor for each logistic mode, assumed as $[0.0002, 0.015, 0.02]$. In the same way as the determination of transportation costs, these values are multiplied by the raw material or product factor and divided by the capacity factor of each logistic mode.

[367] Cf. MELKOTE, S.; DASKIN, M. S., 2001, p. 484.

Costs for purchasing, manufacturing, handling, and stocking are generated from uniform distributions given in Table 8.2. The generated values are multiplied for each period by a random number from uniform distribution U[0.9, 1.1] to cover periodic shifts. To depict differences between the countries, the costs for each facility in each country are multiplied by a number from $[1 - a * 0.25]$, where a is the country's index, starting with $a = 0$. It is assumed that the higher the index value is, the less developed the country and therefore the lower the costs.

	Purchasing	Manufacturing	Handling	Stocking
Cost	$U[0.5, 1.5]$	$U[15, 32]$	$U[0.05, 1.5]$	$U[18,28]$
Emission	$U[0.002, 0.04]$	$U[0.02, 0.2]$	$U[0.0003, 0.003]$	$U[0.003, 0.03]$

Table 8.2: Distributions for purchasing, manufacturing, handling, and stocking processes

The equivalent emission values are generated from distributions shown in Table 8.2. These values are multiplied by a random number from uniform distribution U[0.9, 1.1] to cover periodic shifts. To include country-specific differences, the values for facilities in specific countries are multiplied by a number from $[1 + 0.75 * a]$, where a is the index of countries, starting from a = 0. In contrast to costs, it is assumed that the less developed countries generate higher emissions.

To determine purchasing lead times, production lead times, and handling lead times, it is assumed that these lead times are converse to the equivalent cost; that is, the most expensive process is also the fastest process. Procurement lead times are calculated by 1 minus the procurement costs of the supplier for the specific material in a specific period, divided by the maximum cost for this material. The resulting value is divided by 20. Manufacturing and handling lead times are calculated in the same way, but values for manufacturing lead times are then divided by 10, and for handling lead times they are divided by 300.

Each demand realization for each customer is randomly generated from uniform distribution $U[10000, 20000]$ for each product and each period. The maximum demand from all periods over all customers is calculated to determine the capacities of production facilities and warehouses. All possible entities are required to guarantee the maximum periodic demand. The needed capacity is then divided by the number of possible warehouses and multiplied by a random number generated from the distribution $U[1, 3]$. It is assumed that there are two capacity options for each production facility and each warehouse. Therefore, option 1 is 50% of the determined capacity, and option 2 is the total capacity.

Regarding the bill of materials, it is assumed that different amounts of supplier material are needed for every final product. To generate a bill of materials for every raw material and every final product, an integer value in the distribution $U[1, 3]$ is assigned. It is ensured that every raw material is assigned, and it is checked whether every final product needs more than one raw material. Suppliers' capacity is calculated by the actual demand for finished products multiplied by the needed raw materials. This amount is divided by the number of suppliers. Finally, the base capacity of each supplier is multiplied by a randomly generated number from uniform distribution $U[1, 3]$.

It is assumed that fixed costs are dependent on the capacity of a facility. Therefore, a formulation based on the suggestion of CORTINHAL AND CAPTIVO[368] is used:

$$f_i = U[x_1, y_1] + U[x_2, y_2] * \sqrt{a_i}$$

$U[x_1, y_1]$ and $U[x_2, y_2]$ are uniform distributions in the range $[x_1, y_1]$ and $[x_2, y_2]$, and a_{io} is the capacity of the specific facility with capacity option o. For data generation of the fixed costs, the following formulations are used:

- Costs for selecting a supplier: $U[5000 * S, 10000 * S] + U[1500, 3000] * \sqrt{a_s}$
- Setup costs of a production facility: $U[12000 * F, 24000 * F] + U[9000,16000] * \sqrt{a_{fo}}$
- Setup costs of a warehouse: $U[8000 * W, 16000 * W] + U[4000,8000] * \sqrt{a_{wo}}$

The values are multiplied by a country factor of [1, 0.8, 0.6] to ensure country-specific differences.

A function equivalent of the function for the fix costs is used to generate emissions for operating production facilities and warehouses:

- Operation emissions of production facilities: $[100 * F, 200 * F] + U[0.3, 3.0] * \sqrt{a_{fo}}$
- Operation emissions of warehouses: $U[50 * W, 100 * W] + U[0.2, 2.0] * \sqrt{a_{wo}}$

[368] Cf. CORTINHAL, M. J.; CAPTIVO, M. E., 2003, p. 345.

For periodic differences, the generated values are multiplied by a number from uniform distribution $U[0.9, 1.1]$ for each period. The values are multiplied by a factor for each country, specified by [1, 1.75. 2.5] to derive differences for each country.

Fig. 8.1 illustrates the generated locations of suppliers, production facilities, warehouses, and customers. The size of the bubbles reflects the maximum capacity or demand. The capacity of suppliers is scaled according to the generated bill of materials.

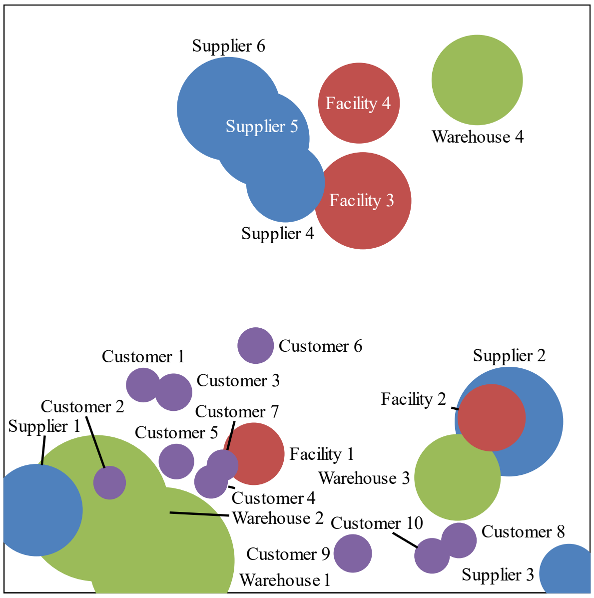

Figure 8.1: Location of potential suppliers, production facilities, and warehouses in the data example for chapter 8

8.4 Numerical Results

8.4.1 Results with Varying Order-to-Delivery Lead Time

In this section, the influences of OTDLT on a supply chain that covers three countries are examined. Three cases are developed:[369]

- Case 1: No emission policy is enforced in any country.
- Case 2: Country 1 enforces an emission cap and trade regulation, where the cap is set to 6,000 emission units, and the emission credit price is 75 monetary units. Country 2 enforces an emission tax with a tax rate of 30 monetary units. In Country 3, the company uses an emission offset scheme and sets the cap to 75,000 emission units. The price for emission allowances is 15 monetary units.
- Case 3: There is an equal global emission tax, and the tax rate is set to 75 monetary units.

[369] Detailed results of the examinations in Chapter 8 can be found in appendix E.

Fig. 8.2 illustrates the total costs for the three cases with varying OTDLT (a) and total emissions (b). With low quoted OTDLT, total costs are higher for every examined case and decrease with increasing OTDLT. When no emission policy is applied, total costs are lower than in the two other cases. With country-specific emission policies in Case 2, total costs are slightly higher when OTDLT is low, compared to Case 1. With increasing quoted OTDLT, this difference decreases. When a global equal emission tax (Case 3) is applied, total costs significantly increase compared to cases 1 and 2. With higher quoted OTDLT, total cost also decreases in Case 3, but the difference in the results for the other two cases remains relatively stable. By contrast, under an equal emission tax, significantly lower total emission results are evident. The differences in total emission between Case 3 and cases 1 and 2 widen with higher quoted OTDLT. For Case 1, increasing OTDLT only slightly affects total emissions. Moreover, the country-specific emission policies in Case 2 do not necessarily lead to a total emission reduction. Under some conditions, increases in the total emission compared to Case 1 are even observed. Therefore, having different emission policies in charge does not necessarily lead to reductions in total emission.

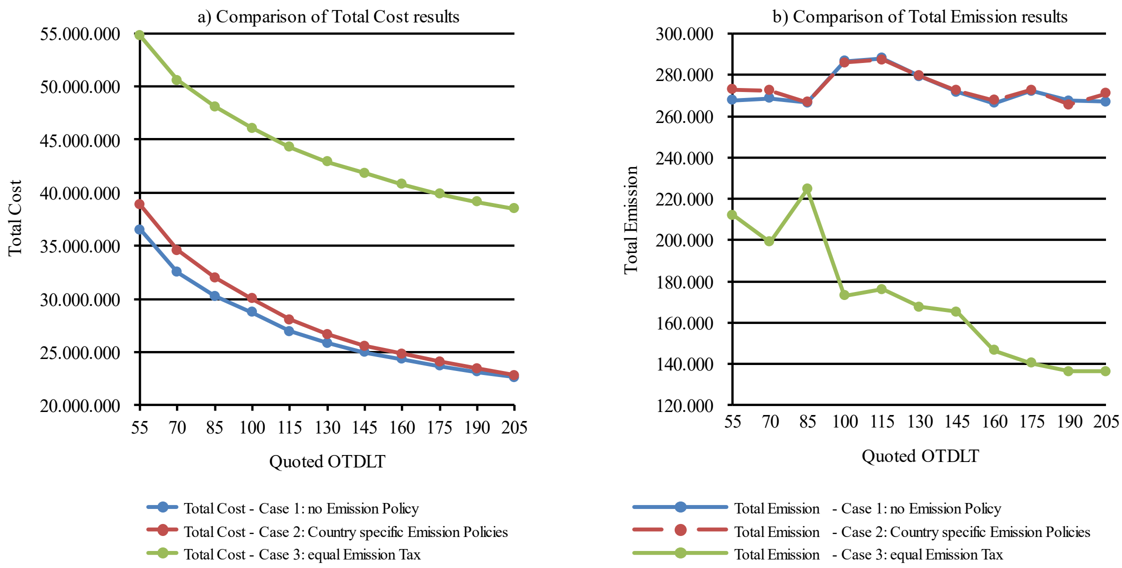

Figure 8.2: Comparison of total cost and total emission results with varying OTDLT

As Fig. 8.3 indicates, the source of generated emissions changes for cases 1 and 2 with increasing OTDLT. Higher OTDLT offers more possibilities for offshoring supply chain activities; hence, a higher share of generated total emissions occurs in the less developed countries when quoted OTDLT is high. In contrast, with global emission tax, a reduction of emission by Country 3 can be observed. The share of emissions from countries 1 and 2, by contrast, increases. The high tax rate cannibalizes the cost benefits of Country 3, and countries 1 and 2 could provide more beneficial locations for suppliers, production facilities, and warehouses.

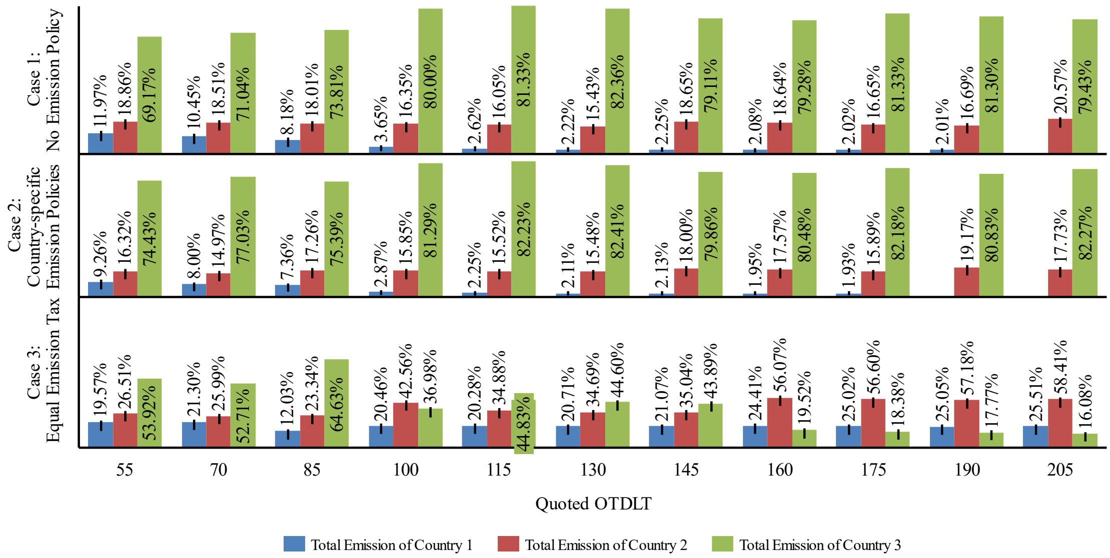

Figure 8.3: Comparison of country-specific total emissions with varying OTDLT

As tables 8.3 to 8.5 indicate, selected suppliers, established production facilities, and warehouses are strongly affected by quoted OTDLT and the kind of emission policy that is applied.

Case 1

	Country 1				Country 2				Country 3					
Quoted OTDLT	Supplier 1	Facility 1	Warehouse 1	Warehouse 2	Supplier 2	Supplier 3	Facility 2	Warehouse 3	Supplier 4	Supplier 5	Supplier 6	Facility 3	Facility 4	Warehouse 4
55	X	L	L	L	X	X	L	L	X	X	X	L	L	L
70	X	L		L		X	L	L	X	X	X	L	L	L
85		L		L		X	L	L	X	X	X	L	L	L
100	X			L		X	L	L	X	X	X	L	H	L
115				L		X	L	L	X	X	X	L	H	L
130				L		X	L	L	X	X	X	L	H	L
145				L		X	L	L	X	X	X	L	L	L
160				L		X	L	L	X	X	X	L	L	L
175				L			L	L	X	X	X	L	L	L
190				L			L	L	X	X	X	L	L	L
205						X	L	H			X	L	L	L

Table 8.3: Selected suppliers and established production facilities and warehouses with varying OTDLT in Case 1[370]

[370] For all tables in chapter 8.4.1 to 8.4.4, X means that a specific supplier is selected, L means a specific production facility or warehouse is established with low-capacity option, H means a specific production facility or warehouse is established with high capacity option.

In Case 1, as OTDLT increases, the number of suppliers in countries 1 and 2 is reduced, and most raw materials are purchased in Country 3. Furthermore, production facilities in Country 1 are closed, and warehouse 2 is not established with a high quoted OTDLT. A high OTDLT offers the possibility to offshore supply chain activities to low-cost countries and to reduce costs.

		Country 1				**Country 2**				**Country 3**					
	Quoted OTDLT	Supplier 1	Facility 1	Warehouse 1	Warehouse 2	Supplier 2	Supplier 3	Facility 2	Warehouse 3	Supplier 4	Supplier 5	Supplier 6	Facility 3	Facility 4	Warehouse 4
Case 2	55	X	L	L	L	X	X	L	L	X	X	X	L	H	L
	70	X	L	L	L		X	L	L	X	X	X	L	H	L
	85		L		L		X	L	L	X	X	X	L	L	L
	100	X			L		X	L	L	X	X	X	L	H	L
	115				L		X	L	L	X	X	X	L	H	L
	130				L		X	L	L	X	X	X	L	H	L
	145				L		X	L	L	X	X	X	L	L	L
	160				L		X	L	L	X	X	X	L	L	L
	175				L			L	L	X	X	X	L	L	L
	190						X	L	H	X	X	X	L	L	L
	205							L	H	X	X	X	L	L	L

Table 8.4: Selected suppliers and established production facilities and warehouses with varying OTDLT in Case 2

		Country 1				**Country 2**				**Country 3**					
	Quoted OTDLT	Supplier 1	Facility 1	Warehouse 1	Warehouse 2	Supplier 2	Supplier 3	Facility 2	Warehouse 3	Supplier 4	Supplier 5	Supplier 6	Facility 3	Facility 4	Warehouse 4
Case 3	55	X	H	L	L	X	X	L	L	X	X	X	L	L	L
	70	X	H	L	L		X	L	L	X	X	X	L	L	
	85	X	L		L		X	L	L	X	X	X	L	L	L
	100	X	H		L		X	H	H	X	X	X	L		
	115	X	H		L		X	L	H	X	X	X	L		
	130	X	H		L		X	L	H	X	X	X	L		
	145	X	H		L		X	L	H	X		X	L		
	160	X	H		L		X	H	H	X	X	X			
	175	X	H		L		X	H	H	X	X	X			
	190	X	H		L		X	H	H	X	X	X			
	205	X	H		L		X	H	H	X		X			

Table 8.5: Selected suppliers and established production facilities and warehouses with varying OTDLT in Case 3

In Case 2, the same development is evident. However, due to the stricter emission policies in developed countries, the offshoring tendencies regarding Country 3 occur even for a low OTDLT. This also indicates a shift of sources of emissions, as shown in Fig. 8.3. With very high OTDLT, the share of emissions in Country 1 is reduced, whereas it increases for countries 2 and 3. By contrast, with equal global emission tax, the cost advantages of the less developed countries are undermined by the tax. The cost increases in these countries lead to a higher concentration of production facilities and warehouses in Country 1. Furthermore, the supplier in Country 1 is consistently contracted, which might reduce the transport emissions.

The share of procured raw materials in each country is illustrated in Fig. 8.4 in detail. For cases 1 and 2, only a small share of raw materials is purchased from the Country 1 supplier when quoted OTDLT is relatively low. With high OTDLT quoted, most raw materials are sourced in Country 3. Higher quoted OTDLT offers the possibility to offshore sourcing activities to less developed countries and to take advantage of lower prices for raw materials.

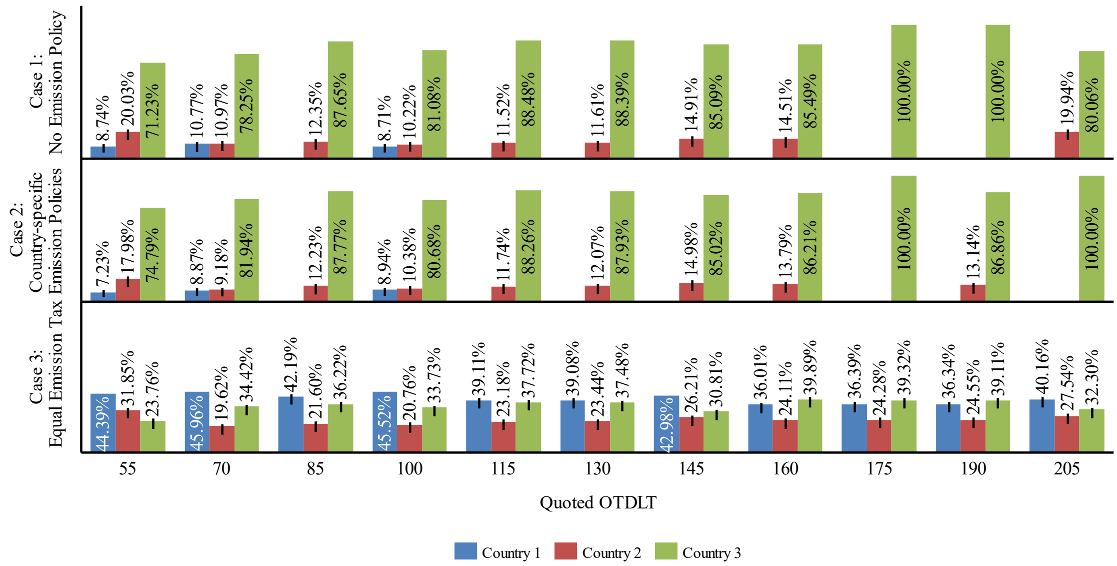

Figure 8.4: Share of procured raw materials from different countries with varying OTDLT

With different emission policies in charge (Case 2), this development can be amplified. With equal taxation (Case 3), the cost advantages of the less developed countries are compensated. Therefore, in the given numerical example, a higher number of raw materials is procured from the supplier in Country 1. Additional needed materials can be sourced from the other countries and shipped with less emission-intensive logistic modes, especially when quoted OTDLT is high.

For produced goods, similar observations can be made, as Fig. 8.5 indicates. In cases 1 and 2, most products are manufactured in Country 3, even for a low quoted OTDLT. The share of goods from Country 1 is at first relatively constant, but even with an OTDLT of 100, production is stopped. These quantities are then divided between countries 2 and 3. In Case 3, most production activities take place in Country 1. With higher lead times, production in Country 3 is stopped. With high OTDLT, the production shares of countries 1 and 2 are nearly equal. Because of the longer OTDLT, stock levels are less important. Therefore, cheaper production in Country 3 is unnecessary to fill the stock. Furthermore, the cost advantages of Country 3 are less significant than in cases 1 and 2.

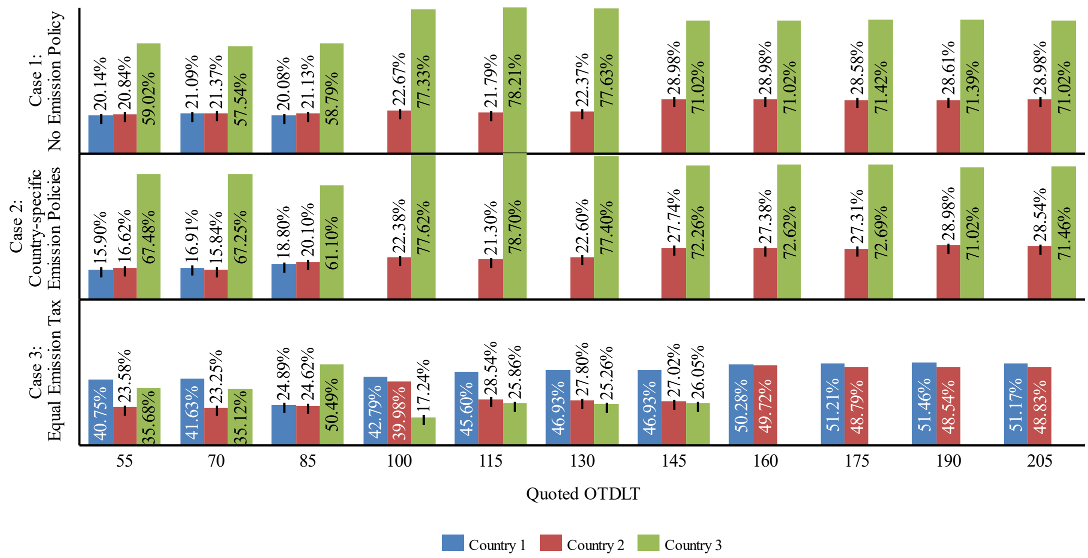

Figure 8.5: Share of produced goods in different countries with varying OTDLT

Similar observations are made when the share of handled goods in warehouses of each country is examined. As Fig. 8.6 shows, with low OTDLT, a high share of goods is always handled in Country 1. For Case 2, a lower share of products is handled in this country than in cases 2 and 3. The share of produced goods in Country 1 decreases with increasing OTDLT in cases 1 and 2. With high OTDLT, most products are handled in Country 2, whereas warehouses are closed in Country 1 when quoted OTDLT is high. In Case 3, the share of produced goods in Country 3 is low, and with higher quoted OTLDT, the production in this country is stopped. A shift from warehousing a high share of goods in Country 1 to Country 2 can be observed. In contrast to cases 1 and 2, in Case 3, even with high OTDLT, a high proportion of goods is handled in Country 1. Therefore, the offshoring of warehousing activities seems beneficial in cases 1 and 2. In Case 2 especially, the incentive to offshore warehousing is strong because of the weak emission policies in countries 2 and 3. In Case 3, a tendency to achieve cost benefits by offshoring activities to Country 2 can be observed, but the high-emission Country 3 is mostly not considered an appropriate location for warehouses.

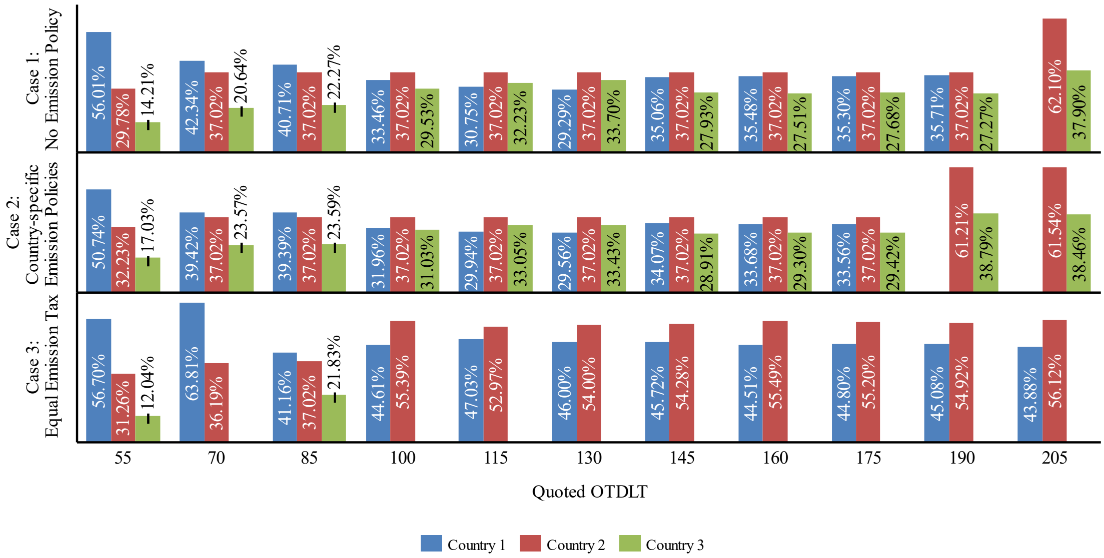

Figure 8.6: Share of handled goods in warehouses of different countries with varying OTDLT

Similar results are evident for all three cases regarding the use of different logistic modes, as Fig. 8.7 shows. For better comparability, transported raw materials are scaled by the bill of materials. With increasing quoted OTDLT, the share of logistic mode 3 decreases, whereas the share of logistic mode 2 increases. For logistic mode 1, a slight decrease is observed in each scenario. In cases 1 and 2, when quoted OTDLT is high, the share of logistic mode 3 increases again, mainly because of the closure of warehouses in Country 1. The use of logistic mode 3 is mainly influenced by location decisions and the average number of goods in stock.

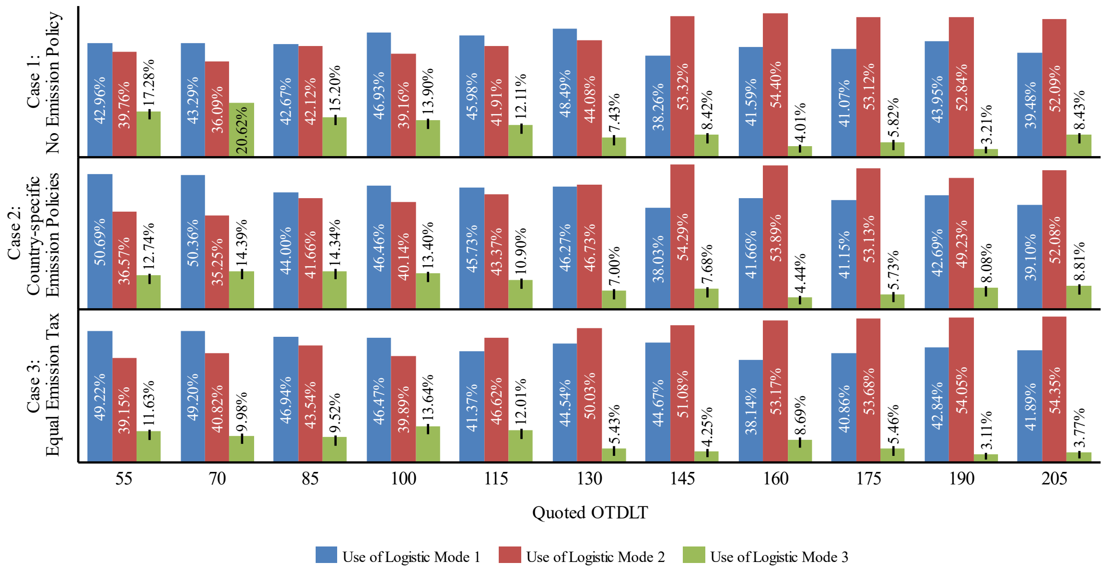

Figure 8.7: Use of different logistic modes with varying quoted OTDLT

The average number of goods in stock for each observed case is illustrated in Fig. 8.8. With increasing quoted OTDLTs, the average number of goods in stock decreases in every examined case. When emission policies are applied, a higher average number of stocks are observed for cases 2 and 3 than in Case 1. This finding is congruent with the results from previous chapters, which indicate that enforced emission policies can lead to higher stock levels. In cases 1 and 2, with higher quoted OTDLT, most goods are stocked in Country 3, up to the maximum of all stock being held there. Only with the closure of production facilities in Country 1 are inventories notably shifted to Country 2. In Case 3, with low quoted OTDLT, most of the stocks are kept in Country 1. With increasing OTDLT, stock-related activities are offshored to Country 2, where lower stock costs occur. Due to the high emission prices, the opportunity to keep stocks in Country 3 is evident only in exceptional cases. The high taxation of emissions for stock and the resulting longer transportation routes seem not to be economical in this case.

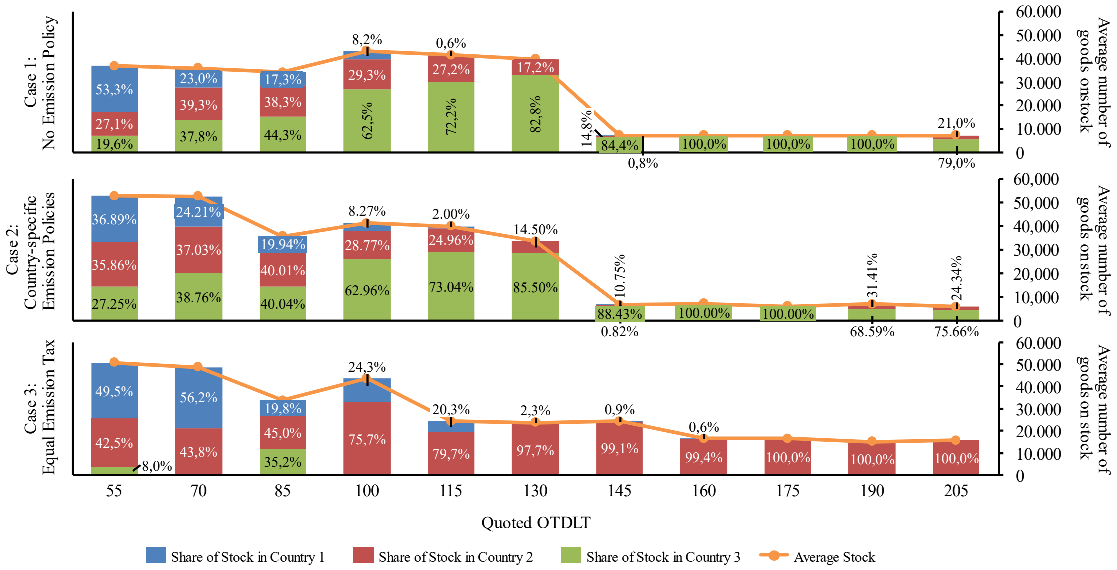

Figure 8.8: Comparison of stock-related activities with varying quoted OTDLT

8.4.2 Results with Emission Policy Variations in Country 1

This section examines the effects of changes in the design of the emission cap and trade system implemented in Country 1. A quoted OTDLT of 115 time units is assumed. Furthermore, for the evaluation, the setting of Case 2 is considered. Changes in emission cap per period, emission credit price, and an emission credit price dependent on the height of the cap are considered. The cap-dependent emission price is calculated as follows:

$$\Omega^{CAT} = 75 + (60 - ECap) * 0.0125.$$

Fig. 8.9 shows the total cost with varying emission cap (a) and varying emission credit price (b). For comparison, the results of Case 2 with OTDLT of 115 time units are illustrated. With a low cap per period, the total costs are higher than in Case 2 due to the higher cost of buying additional emission credits in Country 1. A linear decrease of total costs is evident with an increasing cap and stable emission credit prices, even with varying caps per period. A decrease is first evident in the case of a cap-dependent credit price because fewer additional credits are needed, or some could even be sold. With a cap higher than 7200 emission units, total costs start to increase. This can be attributed to the decreasing emission credit price and the resulting lower returns on the sales of credits. With increasing emission prices, the total costs decrease. Here, the higher returns from the higher prices of emission credits mean that additional income can be generated. Furthermore, by performing more supply chain activities in other countries, total emissions of Country 1 decrease. Moreover, additional cost benefits can be achieved by shifting to low-cost countries.

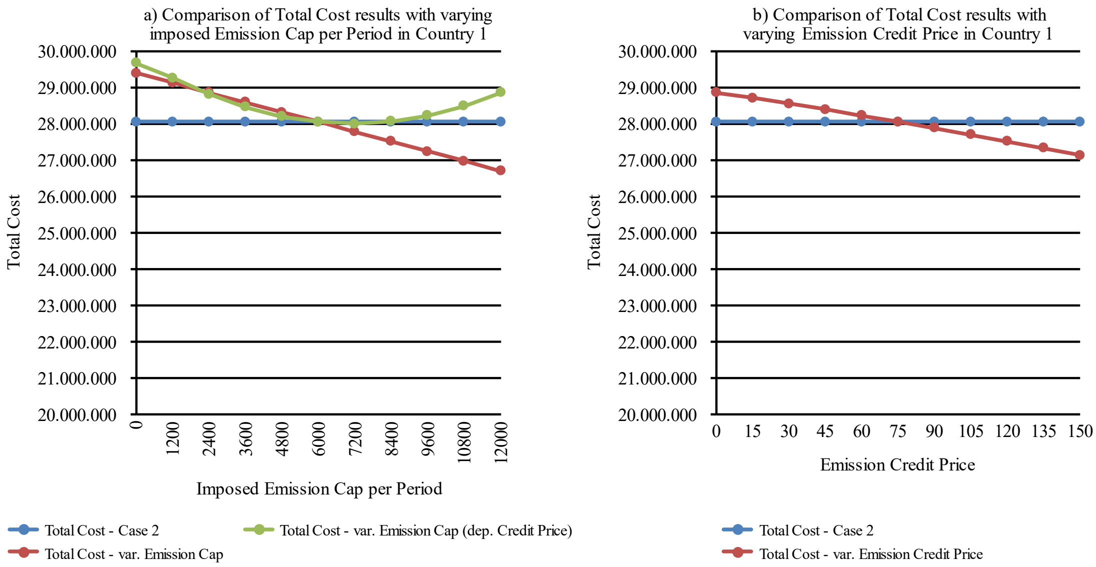

Figure 8.9: Comparison of total cost results with varying emission cap per period and varying emission credit price in Country 1

Total emission remains stable with a varying cap per period and a stable emission credit price, as Fig. 8.10 illustrates. This confirms the previous chapters' results that the emission cap level does not affect total emissions as long as the emission credit price remains the same. With an emission credit price that depends on the emission cap, total emissions are higher under low emission caps per period. As the emission cap per period increases, so do the total emissions decrease. Due to the low emission credit prices, because of the high emission cap, in Country 1, it seems beneficial to relocate some supply chain activities to this country. The costs for these activities are then less affected by the emission cap and trade system. However, less additional income can be generated because of the low emission credit prices. A reduction in total global emissions is also evident for low emission credit prices (Fig. 8.10 b)). By contrast, with higher prices for credits, the total emissions increase. Due to the higher prices, it appears to make sense to relocate supply chain activities to other countries so as to sell emission credits and generate additional income.

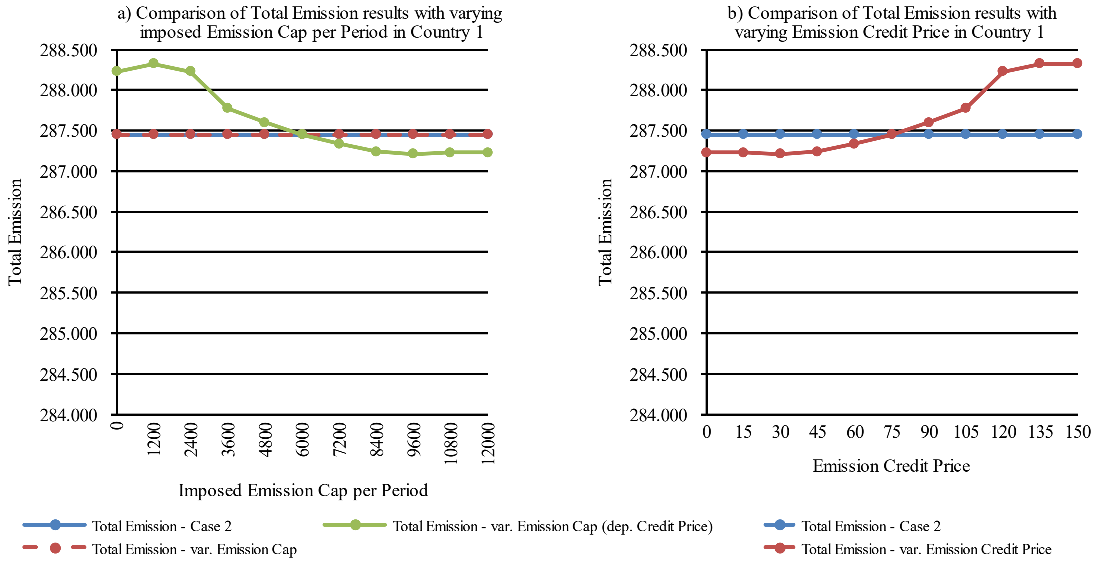

Figure 8.10: Comparison of total emissions with varying emission cap per period and varying emission credit price in Country 1

Fig. 8.11 illustrates the emission shifts to other countries with changes in the design of the cap and trade system in Country 1. With varying caps and fixed emission credit prices, no changes are observed. When emission credit prices depend on the height of the cap, an increasing cap – and therefore lower emission credit prices – results in a slight increase in total emission for Country 1. Most reductions in total global emission seem to result from shifting activities from Country 3 to Country 1. Furthermore, with increasing emission prices and a stable cap per period, activities tend to be shifted from Country 1 to emission-intensive Country 3, which means that total global emissions increase.

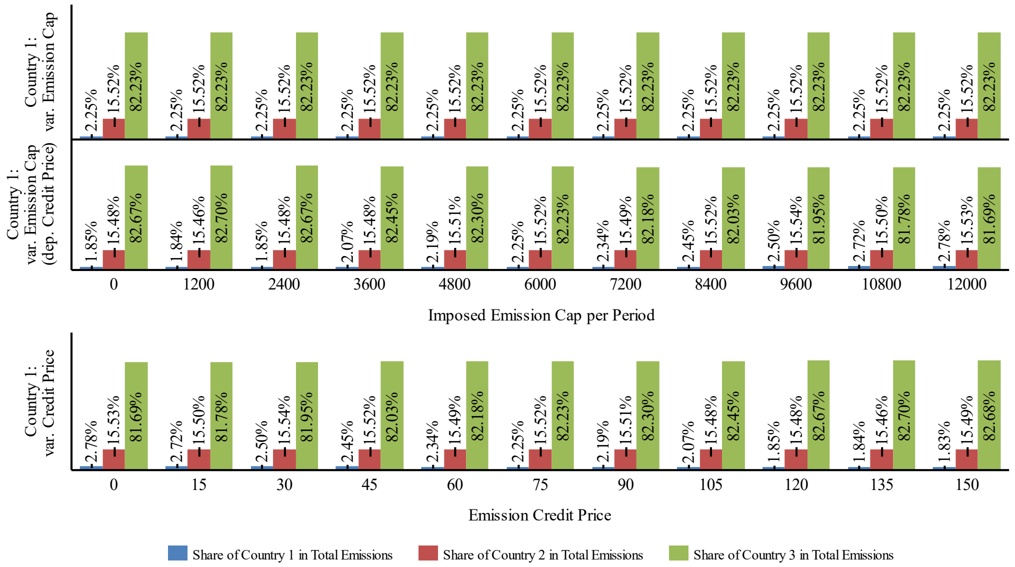

Figure 8.11: Share of different countries in total emission with varying emission cap per period and varying emission credit price in Country 1

As the figures above indicate, there are only slight changes in total costs and total emissions. No location decisions are affected by changes in the design of the emission cap and trade system of Country 1. Tables 8.6 to 8.8 show the location decisions with varying caps and emission prices. Due to the stability of the location decisions, only the extent of various activities in different countries changes.

Country 1: Varying emission cap

	Country 1				Country 2				Country 3					
Emission Cap per Period	Supplier 1	Facility 1	Warehouse 1	Warehouse 2	Supplier 2	Supplier 3	Facility 2	Warehouse 3	Supplier 4	Supplier 5	Supplier 6	Facility 3	Facility 4	Warehouse 4
0				L		X	L	L	X	X	X	L	H	L
1200				L		X	L	L	X	X	X	L	H	L
2400				L		X	L	L	X	X	X	L	H	L
3600				L		X	L	L	X	X	X	L	H	L
4800				L		X	L	L	X	X	X	L	H	L
6000				L		X	L	L	X	X	X	L	H	L
7200				L		X	L	L	X	X	X	L	H	L
8400				L		X	L	L	X	X	X	L	H	L
9600				L		X	L	L	X	X	X	L	H	L
10800				L		X	L	L	X	X	X	L	H	L
12000				L		X	L	L	X	X	X	L	H	L

Table 8.6: Selected suppliers and established production facilities and warehouses with varying emission cap per period in Country 1

Country 1: Varying emission cap (dep. Emission credit

Country 1 **Country 2** **Country 3**

Emission Cap per Period	Supplier 1	Facility 1	Warehouse 1	Warehouse 2	Supplier 2	Supplier 3	Facility 2	Warehouse 3	Supplier 4	Supplier 5	Supplier 6	Facility 3	Facility 4	Warehouse 4
0	X	H	L	L	X	X	L	L	X	X	X	L	L	L
1200	X	H	L	L		X	L	L	X	X	X	L	L	
2400		L		L		X	L	L	X	X	X	L	L	L
3600	X	H		L		X	H	H	X	X	X	L		
4800		H		L		X	L	H	X	X	X	L		
6000		H		L		X	L	H	X	X	X	L		
7200		H		L		X	L	H	X	X	X	L		
8400		H		L		X	H	H	X	X	X			
9600		H		L			H	H	X	X	X			
10800		H		L			H	H	X	X	X			
12000		H		L		X	H	H	X		X			

Table 8.7: Selected suppliers and established production facilities and warehouses with varying emission cap per period and cap dependent emission credit price in Country 1

Country 1: Varying emission credit price

Country 1 **Country 2** **Country 3**

Emission Credit Price	Supplier 1	Facility 1	Warehouse 1	Warehouse 2	Supplier 2	Supplier 3	Facility 2	Warehouse 3	Supplier 4	Supplier 5	Supplier 6	Facility 3	Facility 4	Warehouse 4
0				L		X	L	L	X	X	X	L	H	L
15				L		X	L	L	X	X	X	L	H	L
30				L		X	L	L	X	X	X	L	H	L
45				L		X	L	L	X	X	X	L	H	L
60				L		X	L	L	X	X	X	L	H	L
75				L		X	L	L	X	X	X	L	H	L
90				L		X	L	L	X	X	X	L	H	L
105				L		X	L	L	X	X	X	L	H	L
120				L		X	L	L	X	X	X	L	H	L
135				L		X	L	L	X	X	X	L	H	L
150				L		X	L	L	X	X	X	L	H	L

Table 8.8: Selected suppliers and established production facilities and warehouses with varying emission cap per period in Country 1

To illustrate which supply chain activities are shifted to other countries, Fig. 8.12 depicts the share of raw materials purchased in different countries. With a quoted OTDLT of 115, no raw materials are purchased in Country 1. Changes in the design of Country 1's emission cap and trade system does not influence the share of procured raw materials. In the given numerical example under the assumptions of Case 2, it does not make economic sense to purchase raw materials in Country 1, even when no emission policy is applied in this country (i.e. emission credit price is 0).

Figure 8.12: Share of procured raw materials in different countries with varying emission cap per period and varying emission credit price in Country 1

Similar observations are made regarding the production of goods, as Fig. 8.13 indicates. Under the assumptions of Case 2 in the given numerical example, no production occurs in Country 1.

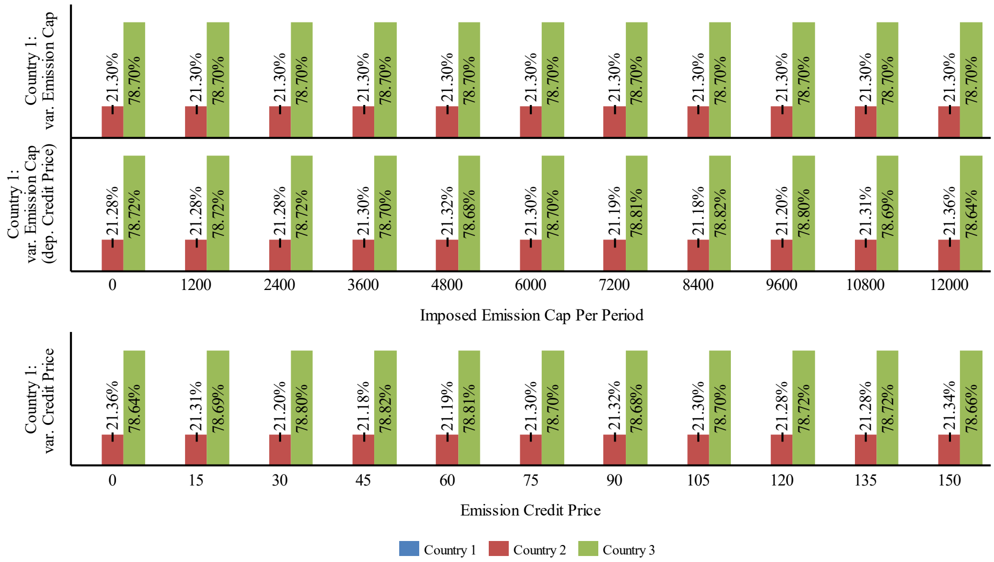

Figure 8.13: Share of produced goods in different countries with varying emission cap per period and varying emission credit price in Country 1

Fig. 8.14 illustrates the share of handled goods in the warehouses of different countries. With a varying emission cap per period under a fixed emission credit price, no changes are observed. In the case of an emission cap-dependent emission credit price, handled goods are shifted from Country 3 to Country 1 under conditions of a high cap per period and low emission prices. Furthermore, with low emission credit prices under a stable emission cap per period, a higher share of goods is handled in warehouses of Country 1. With increasing emission credit prices, more goods are handled in warehouses of Country 3. Therefore, the handling of materials in the high-emission country and the resulting longer transportation routes can increase the total emissions and lower the total costs.

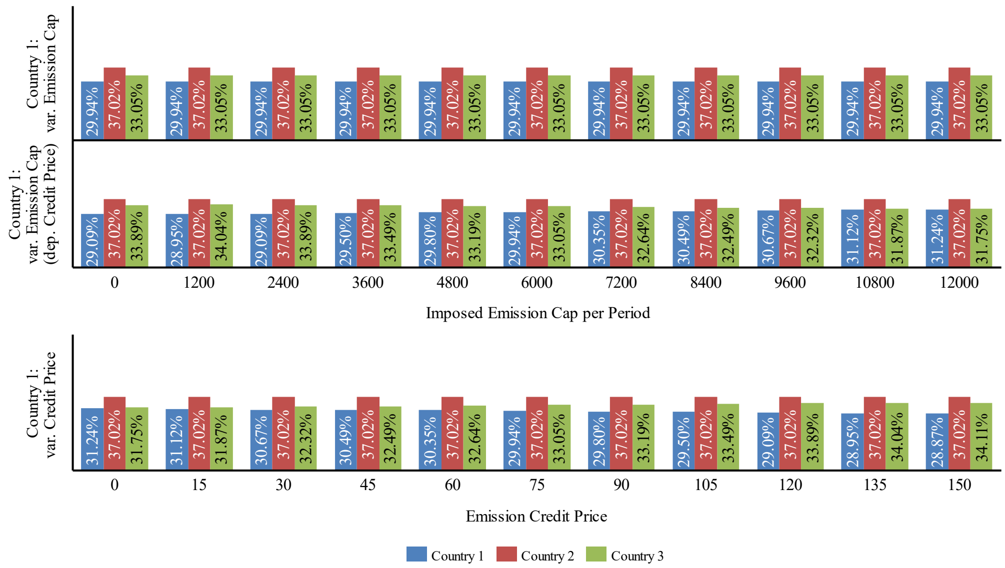

Figure 8.14: Share of handled goods in warehouses of different countries with varying emission cap per period and varying emission credit price in Country 1

The resulting longer transportation routes do not necessarily result in higher shares of the emission-intensive logistic mode 3, as Fig. 8.15 shows. With a varying cap per period and fixed emission credit prices, no changes occur in the share of logistic modes. With an emission-cap-dependent price, the share of logistic mode 3 is higher when the cap is high. The low prices for emission credits in Country 1 seem to render the use of logistic mode 3 economical. The greater use of logistic mode 3 means that the use of logistic modes 1 and 2 are reduced under weak emission regulation. The same development is noted for varying emission credit prices and a fixed cap. With low prices, a higher share of logistic mode 3 is used. When credit prices increase, the share of logistic mode 3 decreases. Furthermore, with a strict emission policy in Country 1, stock levels are slightly reduced, as Fig. 8.16 illustrates. Therefore, faster logistic modes are needed to meet the quoted OTDLT.

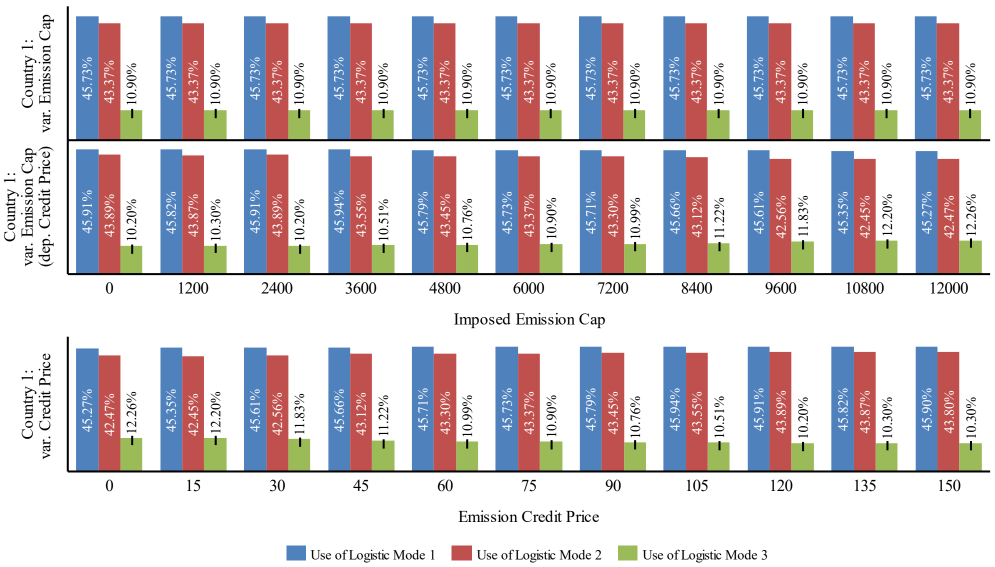

Figure 8.15: Use of different logistic modes with varying emission cap per period and varying emission credit price in Country 1

With fixed emission credit prices and a varying emission cap, no changes in stock activities are evident. With a stricter emission policy in Country 1 (a lower cap in the case of varying caps with cap-dependent credit prices, and higher credit prices with a fixed cap), the average number of goods in stock in Country 1 decreases. Overall, with a stricter policy, fewer goods are kept in stock in total. Nevertheless, not only stocks of Country 1 are, with higher emission credit prices, shifted to country 2. Also, a shift from Country 3 to Country 2 be observed. These shifts may additionally result in shorter transportation routes.

Figure 8.16: Comparison of stocking activities with varying emission cap per period and varying emission credit price in Country 1

8.4.3 Results with Emission Policy Variations in Country 2

In this examination of the effects of design changes in the emission tax policy of Country 2, a quoted OTDLT of 115 time units is assumed. The setting of Case 2 serves as the basis for these analyses.

As shown in Fig. 8.17 a), total costs under a low emission tax in Country 2, are below the basic results of Case 2. As the tax rate increases, the total costs rise sharply in a linear fashion. This increase is less marked beyond a tax rate of 90 monetary units, but there is still a slight increase. Total emissions also increase initially with an increasing emission tax rate, as shown in Fig. 8.17 b). Only at a tax rate of 90 monetary units is a significant decrease in total emissions evident. As the tax rate continues to rise, total emissions increase again slightly but drop substantially at a tax rate of 135 monetary units.

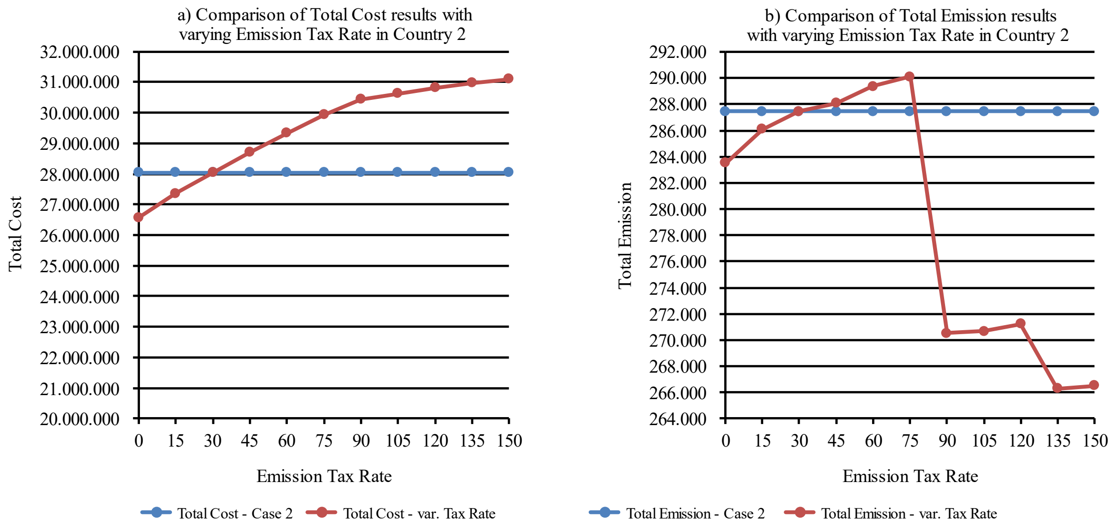

Figure 8.17: Comparison of total cost and total emissions with varying emission tax rates in Country 2

As illustrated in Fig. 8.18, an increasing tax rate in Country 2 is associated with declining total emissions in this country. With low emission tax rates, this reduction is linked to an increase in total emissions in Country 3. Therefore, the total global emissions increase. Thereafter, at a tax rate of 90 monetary units, a substantial decrease in total emission in Country 2 is evident. However, this is accompanied by an increase in the shares of total emissions by countries 1 and 3. A reduction in total global emissions can be achieved primarily through shifting supply chain activities to Country 1. Starting at an emission tax rate of 135 monetary units, Country 1's share of total emissions increases, whereas Country 2's share is reduced. This finding explains the further reduction in total global emissions. For a tax rate of 90 monetary units and higher, Country 3's share of total emissions remains relatively constant. Accordingly, it can be assumed that some supply chain activities will be shifted to Country 1.

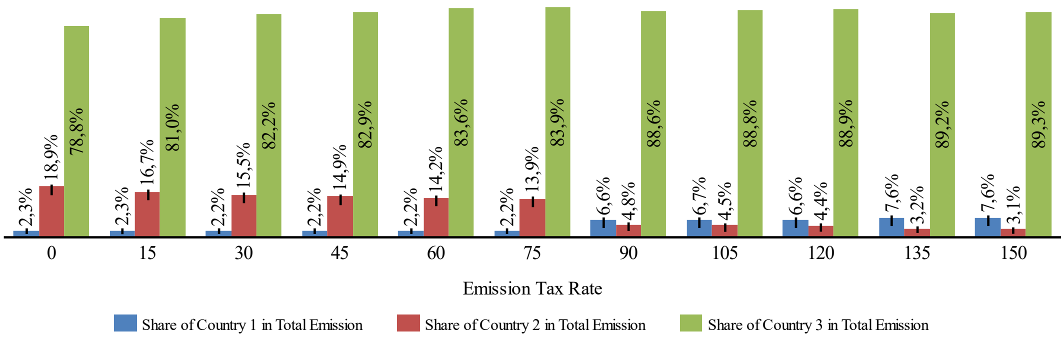

Figure 8.18: Share of different countries in total emission with varying emission cap per period and varying emission credit price in Country 2

The variation in the emission tax rate strongly influences location decisions, as shown in Table 8.9. With an emission tax rate of 90, the production facility in Country 2 is not established. This results in the establishment of the production facility in Country 1. This decision can lead to higher costs for establishing this facility and higher production costs, but lower emission costs associated with the emission tax in Country 2 (due to lower emissions from this country). With an emission tax of 135 monetary units, the selection of supplier 3 is waived, and the supplier from Country 1 is contracted instead. This means that further transport emissions can be reduced, which has a positive effect on total emissions.

Country 2: Varying emission tax rate

	Country 1				Country 2				Country 3					
Emission Credit Price	Supplier 1	Facility 1	Warehouse 1	Warehouse 2	Supplier 2	Supplier 3	Facility 2	Warehouse 3	Supplier 4	Supplier 5	Supplier 6	Facility 3	Facility 4	Warehouse 4
0				L		X	L	L	X	X	X	L		L
15				L		X	L	L	X	X	X	L		L
30				L		X	L	L	X	X	X	L		L
45				L		X	L	L	X	X	X	L		L
60				L		X	L	L	X	X	X	L		L
75				L		X	L	L	X	X	X	L		L
90		L		L		X		L	X	X	X	L		L
105		L		L		X		L	X	X	X	L		L
120		L		L		X		L	X	X	X	L		L
135	X	L		L				L	X	X	X	L		L
150	X	L		L				L	X	X	X	L		L

Table 8.9: Selected suppliers and established production facilities and warehouses with varying emission tax rates in Country 2

The location decisions also influence the share of various activities in the supply chain in the different countries, as shown in Fig. 8.19. As the tax rate increases, the share of raw materials procured in Country 2 decreases, while the share in Country 3 increases. At a tax rate of 135 monetary units, no raw materials are sourced in Country 2, and 13.3% of all raw materials are sourced in Country 1. This leads to a reduction in raw materials procured in Country 3. A similar trend with an increasing tax rate is evident in the share of goods produced. With increasing tax rates, the share of produced goods decreases for countries 2 and 3. Starting from a tax rate of 90 monetary units, no production takes place in Country 2, and almost 20% of goods are produced in Country 1. At a lower tax rate in Country 2, no production takes place in Country 1, and there is a reduction in the share of goods produced in Country 3. This leads to a reduction in total emissions, but also to an increase in total costs. The share of goods handled in the warehouses of Country 1 decreases when the tax rate in Country 2 increases, until the tax rate is 90 monetary units. Thereafter, the share increases. The share of transshipped goods in the warehouses of Country 2 is constant up to a tax rate of 90 monetary units. As the tax rate increases further, the share decreases. In contrast, the share of Country 2 increases up to a tax rate of 90, then decreases sharply, then increases again slightly. The large shifts to Country 1 can explain the decreasing total emissions. Shifting activities to Country 3 can explain the increase in total emissions.

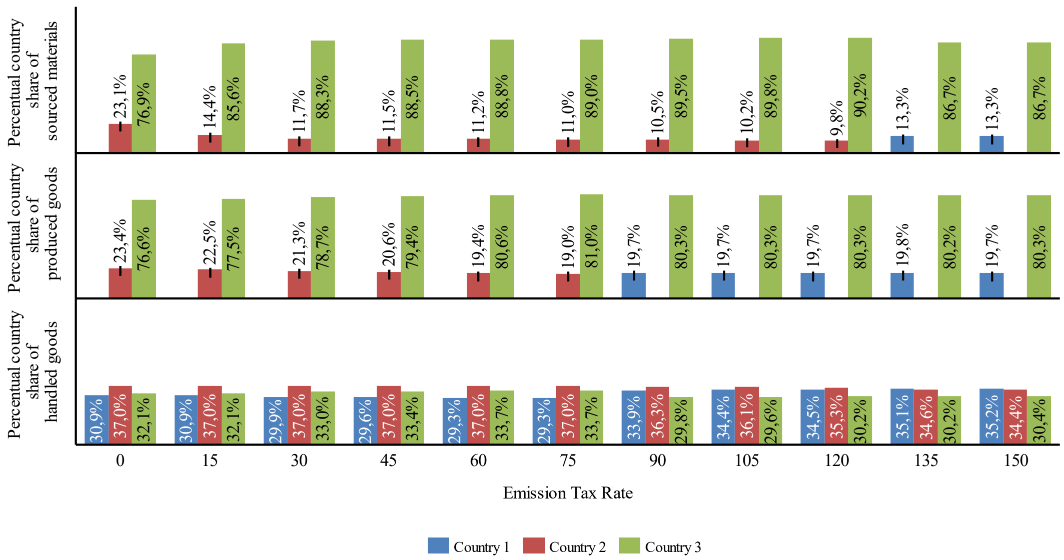

Figure 8.19: Share of different supply chain activities in different countries with varying emission tax rate in Country 2

The use of the different logistic modes is also affected by different emission tax rates in Country 2, as shown in Figure 8.20 a). As the tax rate increases, the share of logistic mode

1 increases and that of logistic mode 3 decreases. The share of logistic mode 2 also increases slightly but fluctuates for different values of the emission tax rate. The higher pressure on transport activities in Country 2 due to emission tax seems to encourage the use of less emission-intensive transport modes. In addition, locating plants closer to customers in Country 1 can shorten the transportation distances and the use of logistic modes. In addition, the higher share of slower logistic modes initially increases the average number of units in storage, as shown in Fig. 8.20 b). Above an emission tax rate of 90 monetary units, a decrease in the average number of units in stock is evident. Supply chain activities are shifted to Country 1 when the tax in Country 2 increases. However, the share of stock in Country 1 decreases at high tax rates, and the height of inventories in Country 3 increases. At a tax rate of 90 monetary units and above, no stocks are held in Country 1 but the share of Country 2 increases significantly, whereas the share of Country 3 decreases. At an emission tax rate of 105, the share of Country 2 again decreases slightly, while the share of Country 3 increases slightly. The overall decrease in average inventories can be explained by the fact that production and procurement activities are located in Country 1, which shortens transportation distances to customers in Country 1 and requires less inventory to meet the specified OTDLT. In addition, because of these shorter routes, inventory can be shifted to low-cost countries to reduce costs.

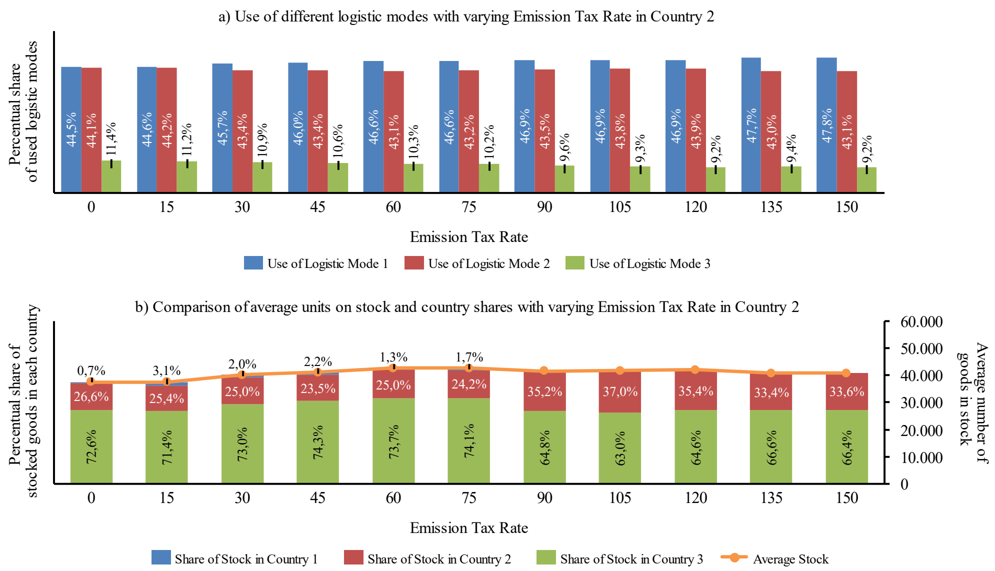

Figure 8.20: Use of different logistic modes and average goods in stock with varying emission tax in Country 2

8.4.4 Results with Emission Policy Variations in Country 3

The influences of the emission policy in Country 3 on the supply chain design are examined, and a quoted OTDLT of 115 times units is assumed. Case 2 serves as the basis for the following examination. Furthermore, in addition to the voluntary emission offset policy in most cases, the influences of an emission tax policy in Country 3 are examined.

The height of the imposed emission cap per period in Country 3 strongly influences the total cost, as Fig. 8.21 a) illustrates. With an increasing imposed cap per period, total costs decrease almost linear until the cap is 10,5000 emission units. From this point, further increase of the imposed cap per period has no significant influence on total costs. With a higher cap per period, fewer additional allowances have to be bought; therefore, total cost decreases. Furthermore, a higher cap may result in offshoring activities to Country 3, and additional cost benefits can be achieved. Under an emission offset policy, a slight cost increase is evident with increasing emission prices, shown in Fig. 8.20 b). With free emission allowances, total costs are slightly below the results of Case 2. Thereafter, total costs increase slightly until an allowance price of 45 monetary units. With a further increase in the allowance price, no changes in total costs are evident. In contrast, when an emission tax in Country 3 is levied, even slight increases in the tax rate would lead to high increases in total costs. Up to a tax rate of 45 monetary units, total cost increases significantly and almost linearly. As the tax rate continues to rise, the slope decreases, but an apparent increase in total costs is still evident.

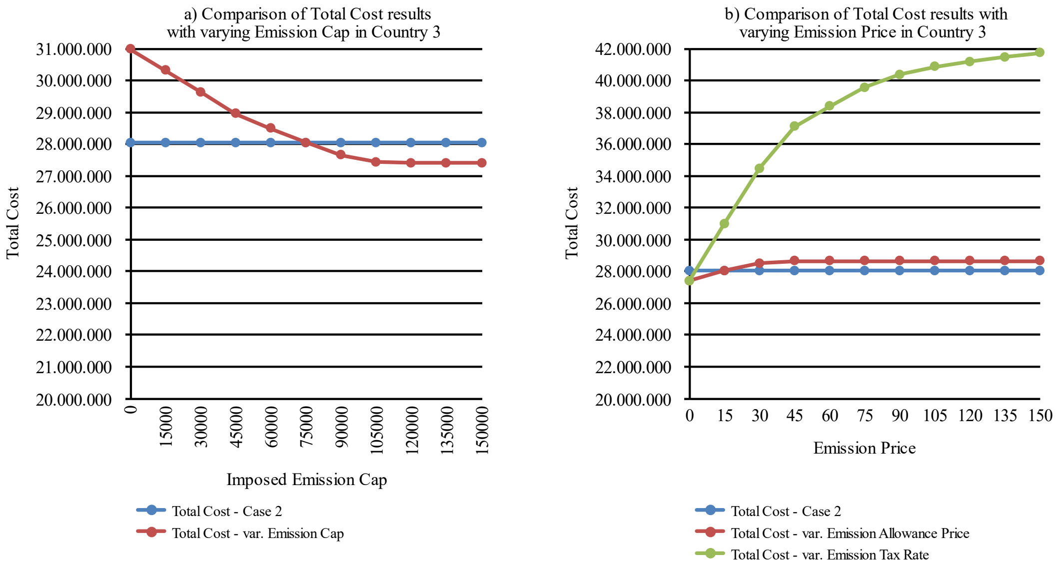

Figure 8.21: Comparison of total cost results with varying emission cap per period and varying emission prices in Country 3

Total emission amounts are influenced by the different values of the imposed emission cap period in Country 3, as shown in Fig. 8.22 a). With a low cap per period, total emissions are slightly reduced compared to the results of Case 2. With increasing caps, initially the total emission increases slightly. Significant increases in total emissions are evident when the imposed cap per period is higher than 75,000 emission units. With an emission cap higher than 120,000 units, total emission amounts remain constant. In the case of varying allowance prices in Country 3's emission offset policy, initially, total emissions decrease slightly (see Fig. 8.22 b)). Once the price for emission allowances goes higher than 45 monetary units, no reductions in either total emissions or in total cost can be observed. By contrast, when Country 3 implements an emission tax policy, total emission significantly decreases as the emission tax rate increases. With a tax rate of more than 105 monetary units, total emissions are nearly halved compared to the results of Case 2. With the assumed high emission cap per period under an emission offset policy, the price significantly influences total emissions, compared to under the emission tax policy.

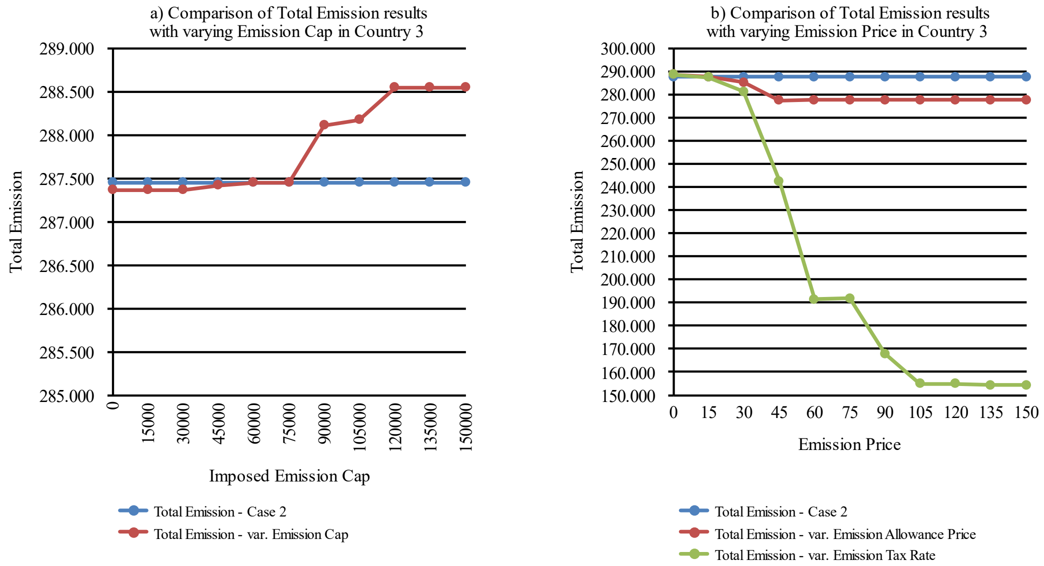

Figure 8.22: Comparison of total emission results with varying emission cap per period and varying emission price in Country 3

The increases and decreases in total emissions are mainly the result of changes in emission levels in the various countries, as shown in Fig. 8.23. The increase in the emission limit increases the share of emissions in Country 3, whereas the share in Country 2 is slightly reduced. The share of total emissions in Country 1 remains constant. Therefore, a higher cap makes it more attractive to perform supply chain activities in Country 3, since the higher cap results in lower costs from the emission offset scheme. Rising emission allowance prices have the opposite effect. A high price makes it less attractive to perform activities in Country 3, and as a result, various activities are shifted to Country 2 and – to a small extent – Country 1. The share of total emissions in Country 1 is slightly increased, and in Country 2 there is a significant increase in the share as the emission allowance price rises. These shifts reduce the share of total emissions in Country 3. The changes in the country shares are more pronounced if an emission tax is introduced in Country 3. While Country 3's share of total emissions is high at a low tax rate, the share falls sharply as the tax increases. Conversely, the share of total emissions in countries 1 and 2 increases significantly. Unlike the emission offset system, the emissions tax covers all emissions generated in Country 3 and has a much stronger impact on costs. Accordingly, it becomes far more lucrative for companies to perform their supply chain activities in countries 1 and 2.

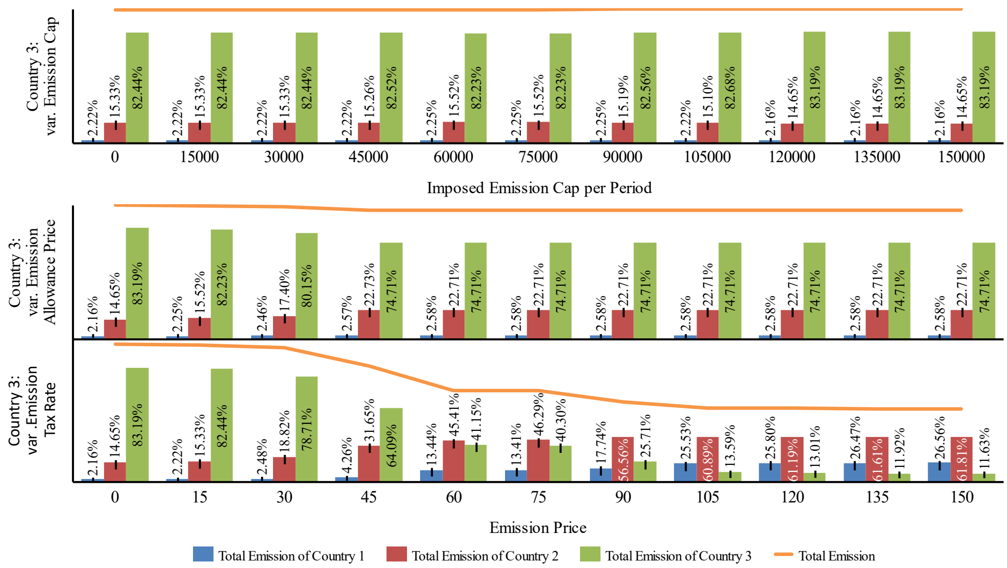

Figure 8.23: Share of different countries in total emission with varying emission cap per period and varying emission price in Country 3

As Table 8.10 indicates, under the emission offset policy in Country 3, variations in the cap per period do not influence location decisions. Variation of emission allowance prices leads to a capacity increase of the facility in Country 2 for an allowance price of 45 monetary units (Table 8.11). Furthermore, the capacity of facility 4 in Country 3 is reduced. This also explains the stronger decrease of total emissions at this allowance price. The tax rate in Country 3 can have a significant influence on location decisions, as Table 8.12 shows. With increasing tax rates, production facilities and warehouses in Country 3 are not established. Furthermore, the high emission tax in Country 3 leads to establishing production facilities in Country 1 and enhancing the production facilities in Country 2 to cover the needed production capacity. A second warehouse is established in Country 1 with a high tax rate in Country 3. Suppliers in Country 3 remain contracted under high tax rates, but in addition, the supplier in Country 1 and a second supplier in Country 2 are contracted. This probably leads to a better trade-off between purchasing costs and generated emissions.

Country 3: Varying emission cap		Country 1			Country 2				Country 3					
Emission Cap per Period	Supplier 1	Facility 1	Warehouse 1	Warehouse 2	Supplier 2	Supplier 3	Facility 2	Warehouse 3	Supplier 4	Supplier 5	Supplier 6	Facility 3	Facility 4	Warehouse 4
0				L		X	L	L	X	X	X	L	H	L
15000				L		X	L	L	X	X	X	L	H	L
30000				L		X	L	L	X	X	X	L	H	L
45000				L		X	L	L	X	X	X	L	H	L
60000				L		X	L	L	X	X	X	L	H	L
75000				L		X	L	L	X	X	X	L	H	L
90000				L		X	L	L	X	X	X	L	H	L
105000				L		X	L	L	X	X	X	L	H	L
120000				L		X	L	L	X	X	X	L	H	L
135000				L		X	L	L	X	X	X	L	H	L
150000				L		X	L	L	X	X	X	L	H	L

Table 8.10: Selected suppliers and established production facilities and warehouses with varying emission cap per period in Country 3

Country 3: Varying emission allowance price		Country 1			Country 2				Country 3					
Emission Credit Price	Supplier 1	Facility 1	Warehouse 1	Warehouse 2	Supplier 2	Supplier 3	Facility 2	Warehouse 3	Supplier 4	Supplier 5	Supplier 6	Facility 3	Facility 4	Warehouse 4
0				L		X	L	L	X	X	X	L	H	L
15				L		X	L	L	X	X	X	L	H	L
30				L		X	L	L	X	X	X	L	H	L
45				L		X	H	L	X	X	X	L	L	L
60				L		X	H	L	X	X	X	L	L	L
75				L		X	H	L	X	X	X	L	L	L
90				L		X	H	L	X	X	X	L	L	L
105				L		X	H	L	X	X	X	L	L	L
120				L		X	H	L	X	X	X	L	L	L
135				L		X	H	L	X	X	X	L	L	L
150				L		X	H	L	X	X	X	L	L	L

Table 8.11: Selected suppliers and established production facilities and warehouses with varying emission allowance prices in Country 3

Country 3: Varying emission tax rate

	Country 1				**Country 2**				**Country 3**					
Emission Credit Price	Supplier 1	Facility 1	Warehouse 1	Warehouse 2	Supplier 2	Supplier 3	Facility 2	Warehouse 3	Supplier 4	Supplier 5	Supplier 6	Facility 3	Facility 4	Warehouse 4
0				L		X	L	L	X	X	X	L	H	L
15				L		X	L	L	X	X	X	L	H	L
30				L		X	L	L	X	X	X	L	H	L
45	X			L		X	H	L	X	X	X	L	L	L
60	X	L		L		X	H	H	X	X	X	L		
75	X	L		L		X	H	H	X	X	X	L		
90	X	H		L	X	X	H	H	X		X	L		
105	X	H	L	L	X	X	H	L	X	X	X			
120	X	H	L	L	X	X	H	L	X	X	X			
135	X	H	L	L	X	X	H	L	X	X	X			
150	X	H	L	L	X	X	H	L	X	X	X			

Table 8.12: Selected suppliers and established production facilities and warehouses with varying emission tax rates in Country 3

Fig. 8.24 illustrates the shares of procured raw materials from each country associated with variations in the design of the emission policy in Country 3. With an increasing imposed cap per period, slight shifts are evident between countries 2 and 3. In general, the share of procured materials remains nearly constant. With varying emission allowance prices, a stronger shift from Country 3 to Country 2 occurs when the allowance price increases. However, starting from an allowance price of 45 monetary units, no further changes are observed. The highest changes are induced by the tax rate under the emission tax policy. With a low tax rate, no major shifts are discernible initially. At a tax rate of 30 monetary units, there is a clear shift from Country 3 to Country 2. When the tax reaches 45 monetary units, the supplier from Country 1 is contracted, and the quantity of raw materials procured in Country 3 is reduced accordingly and purchased in countries 1 and 2 instead. At a tax rate of 90 monetary units, the share of procured raw materials in Country 2 is significantly increased, mainly because another supplier is established in Country 2 and a supplier from Country 3 is not selected. The shares of countries 1 and 2 continue to increase slightly with high tax rates, but the share in Country 3 decreases slightly. Despite the high tax rates, suppliers in Country 3 are not abandoned, probably because it is still worthwhile to source certain materials from this country despite the strict emissions policy. However, it is also clear that only a stringent emissions policy leads to shifts in supplier selection. Variations in the mostly voluntary emission offset policy lead to almost no changes.

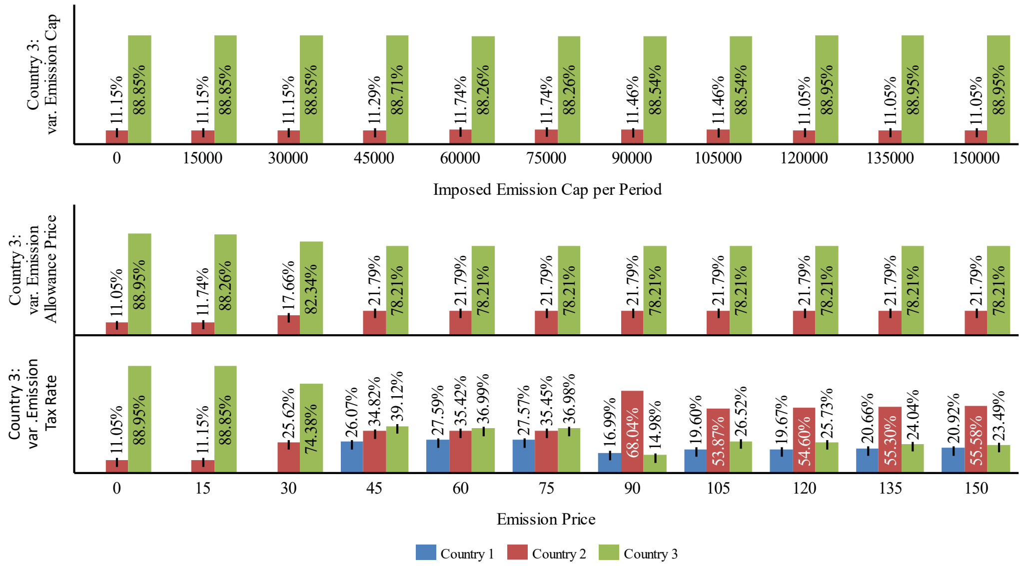

Figure 8.24: Share of procured raw materials in different countries with varying emission cap per period and varying emission price in Country 3

Similar changes are evident in the production of goods in different countries. As shown in Fig. 8.25, the impact of the emission cap per period is relatively small if the emission allowance price remains constant.

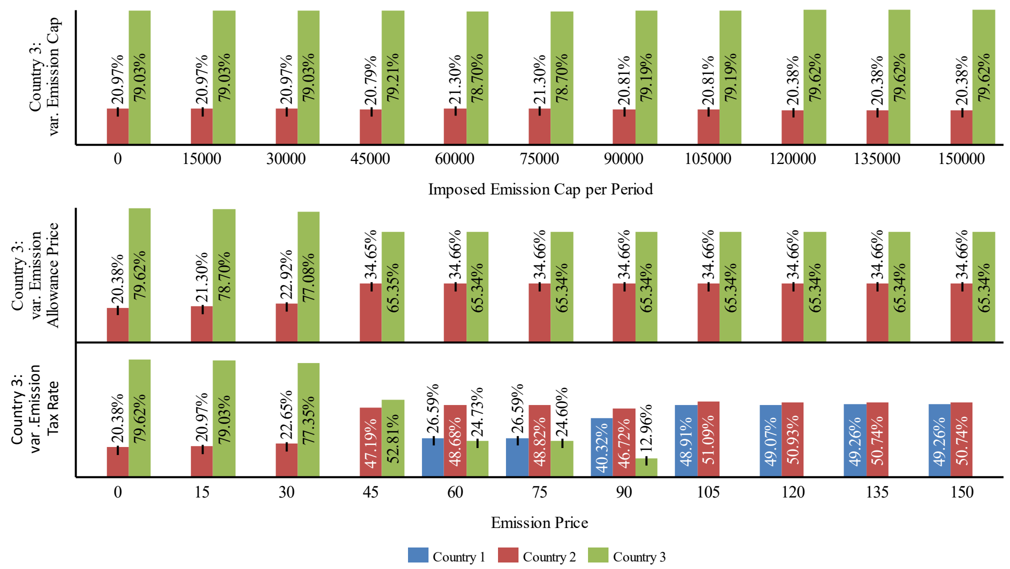

Figure 8.25:Share of produced goods in different countries with varying emission cap per period and varying emission price in Country 3

In Case 2, the same development can be observed. However, due to the stricter emission policies in developed countries, the tendency to offshore activities to Country 3 occurs even for lower OTDLTs. This also indicates a shift of sources of emissions, as shown in Fig. 8.3. With very high OTDLT, the share of emissions in Country 1 is reduced but increases in countries 2 and 3.

With an increasing emission cap per period in Country 3, a slight shift of handling activities is observed from warehouses of Country 1 to the warehouses of Country 3 (Fig. 8.26). The handling activities in warehouses of Country 2 are not affected at all. The shift in handling activities intensifies with increasing emission allowance prices. With higher prices for allowances in Country 3, handling activities are shifted from Country 3 to Country 1. Handling activities in Country 2 are unaffected. In fact, changes occur only when the emission allowance price is lower than 60 monetary units. With higher prices, no effect can be observed. The greatest influence on handling activities is evident when an emission tax policy is in charge in Country 3. With increasing tax rates, handling activities are shifted from Country 3 to Country 1. With a tax rate of 60 monetary units, no handling activities occur in Country 3, and no warehouse is established in this country. Most handling activities are performed in Country 2. Significant changes are observed with a tax rate of 95 emission units. About two-thirds of handling activities are performed in Country 1, and one-third is performed in Country 2. With further increasing tax rates, a slight increase in Country 1 and a slight decrease in Country 2 are evident.

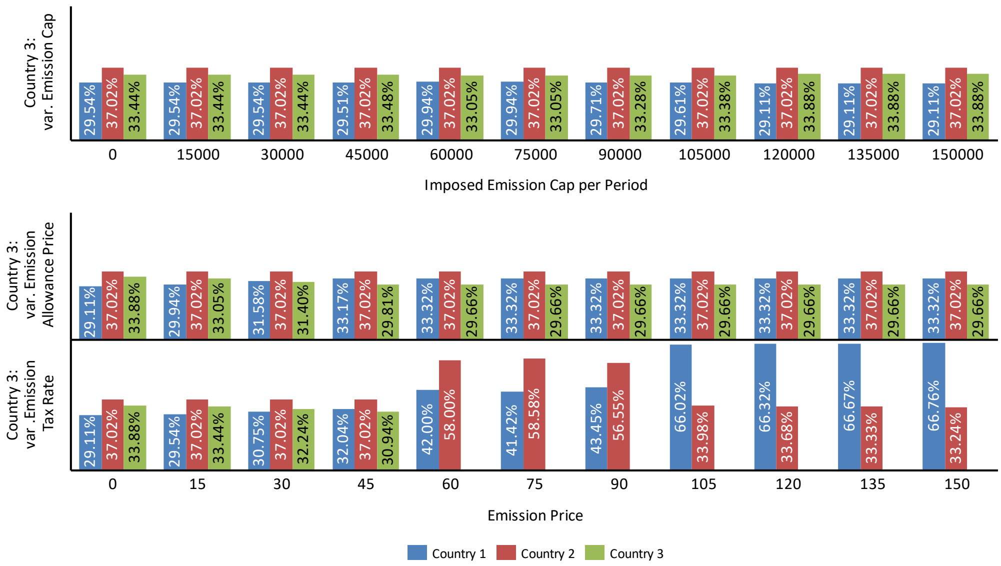

Figure 8.26: Share of handled goods in warehouses of different countries with varying emission cap per period and varying emission price in Country 3

The use of different logistic modes is hardly affected by the height of the emission cap per period in Country 3, as Fig. 8.27 shows. Small fluctuations (up to 1%) are noted, but generally the use of the logistic modes remains stable. With increasing emission allowance prices, the share of logistic mode 1 decreases, and the shares of modes 2 and 3 increase, up to an allowance price of 60 monetary units. With higher emission prices, no changes can be observed. The greater use of emission-intensive logistic modes can be explained by the shift of procurement and production activities from Country 3 to Country 1. Suppliers from Country 3 ship more raw materials to production facilities in Country 2 and may ship goods again to warehouses in Country 3, which means that transportation routes are increased. Faster logistic modes may be needed to meet the quoted OTDLT. When emission tax policy is implemented in Country 3, an increase of logistic mode 2 is evident under a high tax rate. Most of the changes occurring with higher tax rates can be explained by stock levels (illustrated in Fig. 8.28) and location decisions. Locating suppliers and facilities close to customers (nearshoring) can reduce the share of emission-intensive logistic modes, especially mode 3. On the other hand, lower stock levels increase the need for faster modes. Therefore, a trade-off between nearshoring of suppliers and facilities versus the number of goods in stock is evident, which strongly influences the use of different logistic modes. With the high emission tax rate in Country 3, fewer stocks need to be kept because the transportation routes are relatively short. Nevertheless, to meet quoted OTDLT, companies would find it economical to ship most goods using logistic mode 2.

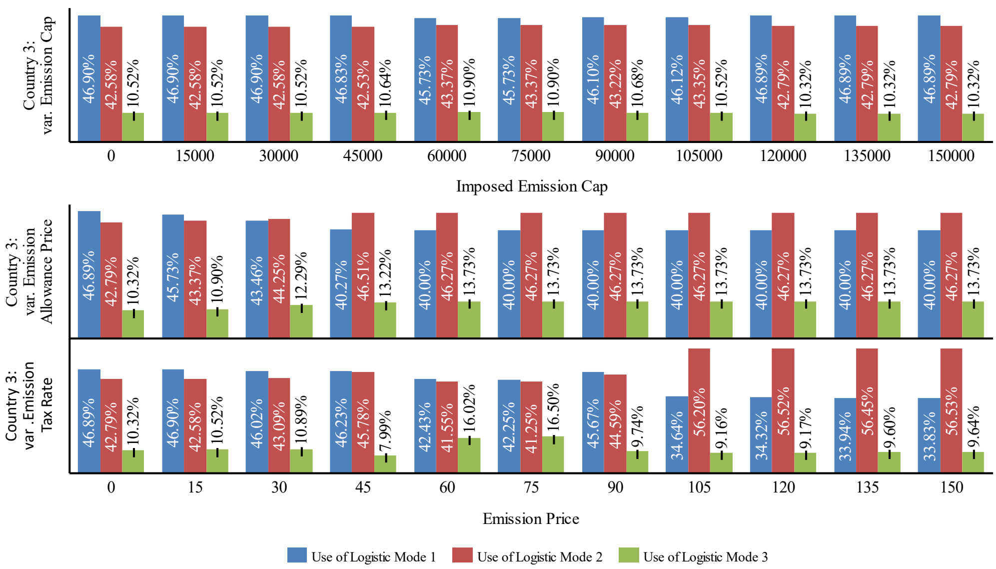

Figure 8.27: Use of different logistic modes with varying emission cap per period and varying emission price in Country 3

Only slight changes are evident for stock levels with varying emission caps per period. Between a cap per period of 45,000 and 105,000 emission units, stock levels decrease, and a small share of stocks is kept in Country 1. Emission allowance prices have a stronger influence on stock levels. With an increasing allowance price, stock levels generally decrease, and more goods are kept in stock in countries 1 and 2. The stock levels in warehouses of Country 3, by contrast, are increased. Furthermore, a decrease in stock levels can explain the higher share of faster logistic modes under high allowance prices. An emission tax policy in Country 3 would influence the stocking decisions even more strongly. With a tax rate of 60 monetary units, no stocks are kept in Country 3, and no warehouses are established. Stock levels generally decrease, apart from at a tax rate of 90 monetary units. The increase of average goods in stock can probably be explained by selecting fewer suppliers in Country 3 and the lower share of transportation mode 3. With further increasing tax rates, stock levels decrease, and inventories are held in almost equal proportions in countries 1 and 2.

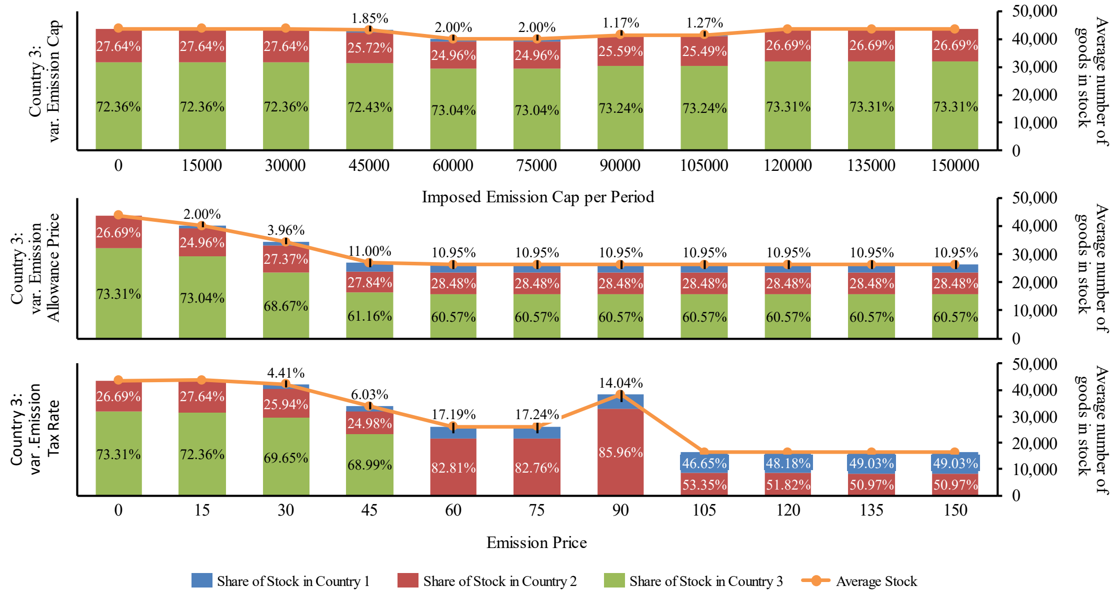

Figure 8.28: Comparison of stocking activities with varying emission cap per period and varying emission price in Country 3

8.5 Conclusion

In the analyses presented in chapters 5 through 7, the findings mainly showed that long quoted OTDLTs resulted in relatively low overall emissions and costs. However, under the assumptions and the example dataset in this chapter, this observation is not true in the global context. As shown in Fig. 8.29, although a reduction in total costs can be achieved in each of the three cases with longer quoted OTDLT, only in Case 3 is there also a reduction in total emissions. The possibility of relocating suppliers, production facilities, or warehouses and their processes to other more cost-effective countries offers companies great potential for cost reduction. With higher quoted OTLDTs, this offshoring becomes increasingly possible. However, if the countries to which activities are relocated have lower emission avoidance standards, total emissions might not necessarily be reduced. Although a low quoted OTDLT enables companies to keep fewer products in stock and to switch to low-emission logistic modes, the production of goods becomes significantly more emission-intensive. Longer transport routes may also make it necessary to use emission-intensive logistic modes. Even if differently designed emission policies are introduced, these can further increase the incentive for offshoring. The high emission costs in Country 1, for example, might mean that production is increasingly performed in countries that apply less stringent emission policies. This can lead to further cost advantages. In the case of uniform global taxation, this incentive effect is negated. Due to the uniform pricing of emissions, countries with low emission avoidance standards lose their cost advantage, and production tends to occur in countries with higher standards.

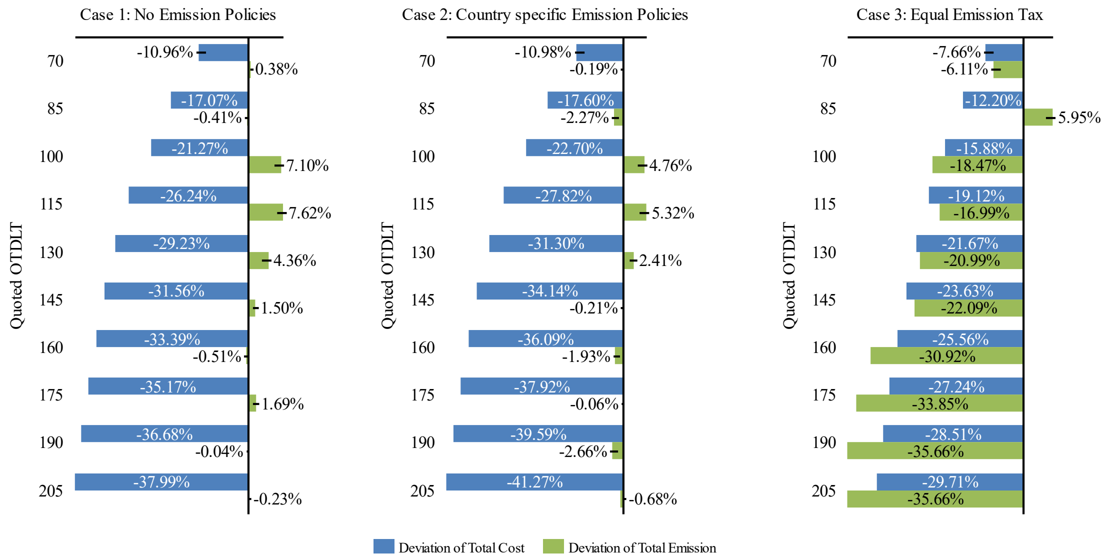

Figure 8.29: Percentual deviations in total cost and total emission results across the three examined cases for quoted OTDLT of 55

Furthermore, if the results for total cost and total emission in Case 1 are compared to the results in cases 2 and 3, it is evident that the use of an emission policy alone might not achieve total emission reductions. As shown in Fig. 8.30, an emission policy can lead to an increase in total cost but not necessarily to reduced total emissions. For Case 2, the different emission policies in the three countries lead to a moderate increase in total cost compared to Case 1. With higher quoted OTDLT, the differences decrease due to offshoring activities to countries with less strict emission regulations. Furthermore, as shown in Fig. 8.30 b), differences in the design of emission policies can lead to increased total emissions. Strict emission regulations in countries with high emission avoidance standards may simply increase the shift of supply chain activities to countries with lower emissions standards. In the given example, the cost advantage of low-cost and high-emission countries increases with stricter regulation in the high-cost and low-emission countries.

In Case 3, a marked increase in total cost is evident in comparison to Case 1. This is mainly because of the strict taxation of every generated emission unit. The difference increases with increasing quoted OTDLT, because offsetting – which leads to cost reduction in cases 1 and 2 – is not economic sensible in Case 3. However, equal taxation and a sufficient tax rate can lead to significant reductions in total emissions.

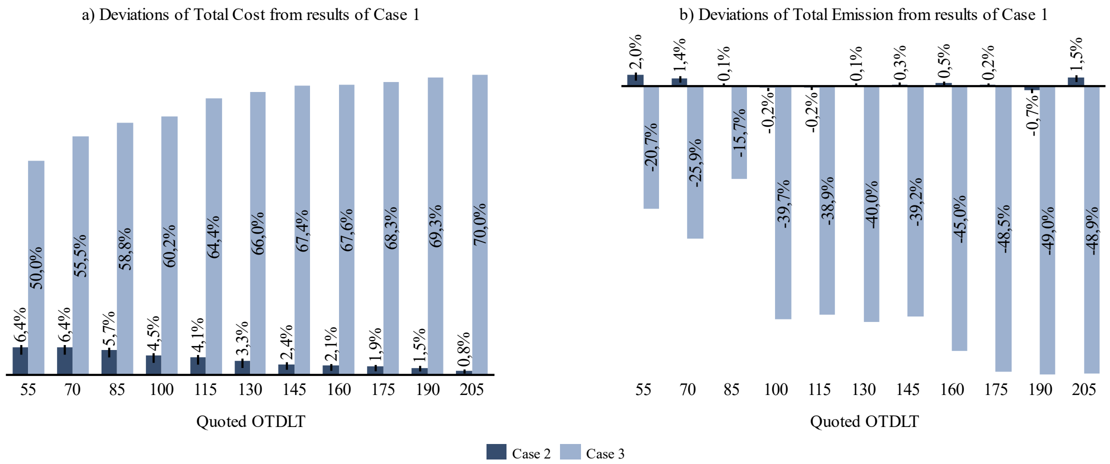

Figure 8.30: Percentual deviations in total cost and total emission results of cases 2 and 3 compared to results of Case 1

The differences caused by different emission policies in the supply chain network design are illustrated in Fig. 8.31. The design of the supply chain in cases 1 and 2 are similar. Only the amounts of goods procured, produced, handled, and stocked in different countries change. Nevertheless, no significant differences in location decisions are found based on the numerical example between Case 1 and Case 2.

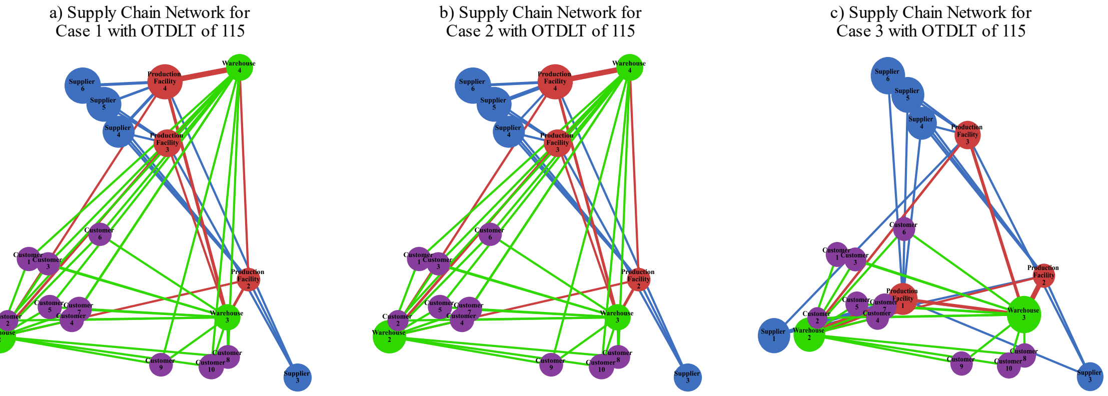

Figure 8.31: Supply chain network design for cases 1 to 3 with OTDLT of 115

For Case 3, the shape of the supply chain differs strongly from cases 1 and 2. Due to higher costs in high-emission countries caused by the uniform emission tax policy, a shift in location decisions is observed. Therefore, differences in the design of policies do not necessarily have much influence and do not necessarily provide an ecologically sustainable supply chain. Furthermore, such settings can lead to increasing withdrawal from countries with strict regulations. With equally designed emission policies that offer the incentive to avoid emissions, the shape of a supply chain can be altered more sustainably.

The design of the emission policy in each country has a varying influence on total cost, total emission, and supply chain design. As Fig. 8.32 shows, changes in the emission policy design in Country 1 have a rather small impact. Furthermore, if the imposed emission policy is strengthened, total emission and total cost slightly increase relative to the results of Case 2. As in the previous chapters, the imposed cap per period affects only the total cost and not the total emissions when the emission credit price is fixed. Emission credit price is the important factor under this emission policy. However, a small reduction in total emission is evident with lower emission prices. The reason is that the incentive to offshore supply chain activities is reduced because of the smaller emission costs under such circumstances.

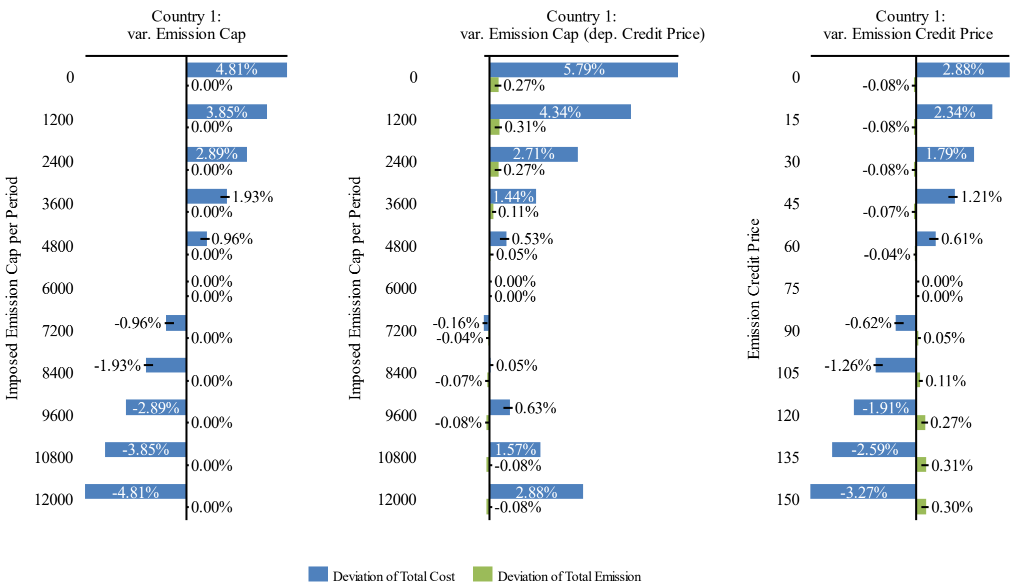

Figure 8.32: Percentual deviations in total cost and total emission results with policy variations in Country 1 in comparison to results of Case 2 with OTDLT of 115

More noteworthy changes are found with variations of the emission policy design in Country 2, as Fig. 8.33 illustrates. An emission tax below 30 (the tax rate assumed in Case 2) leads to lower total costs and total emissions. With increasing emission tax rates, supply chain activities are first offshored to Country 3, increasing the total emission. When the tax rate further increases, starting from a tax rate of 90, supply chain activities are shifted to Country 1; this results in lower total emission and higher total cost.

Production and handling activities are shifted from Country 2 to Country 1 with a high tax because of the cost advantages. Therefore, different designs of emission policies can offer different economic opportunities. In this example, the high-cost Country 1 benefits from the heavy taxation of emissions in Country 2, making locations in Country 1 advantageous for companies.

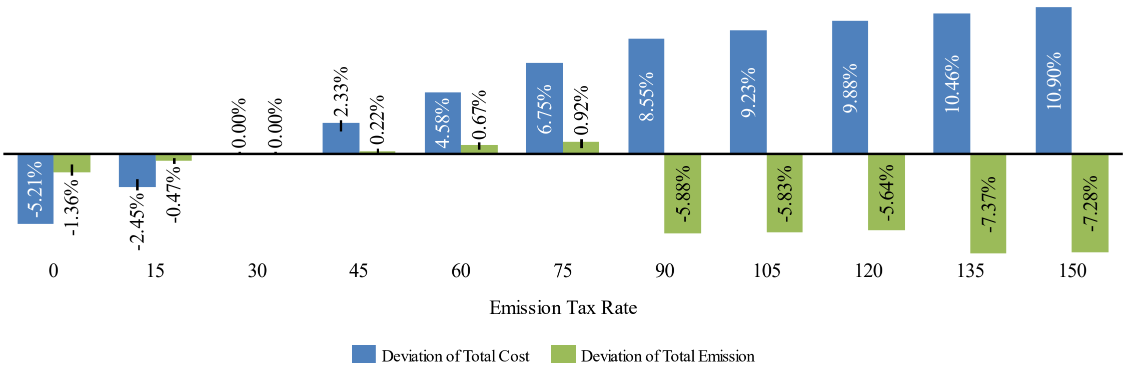

Figure 8.33: Percentual deviations in total cost and total emission results with policy variations in Country 2 in comparison to results of Case 2 with OTDLT of 115

Under the emission offset policy in Country 3, the results for total emission and total cost do not differ much from the results of Case 2 with quoted OTDLT of 115 time units, as Fig. 8.34 illustrates. In Case 2, the voluntary emission offset scheme is designed as a rather weak policy.

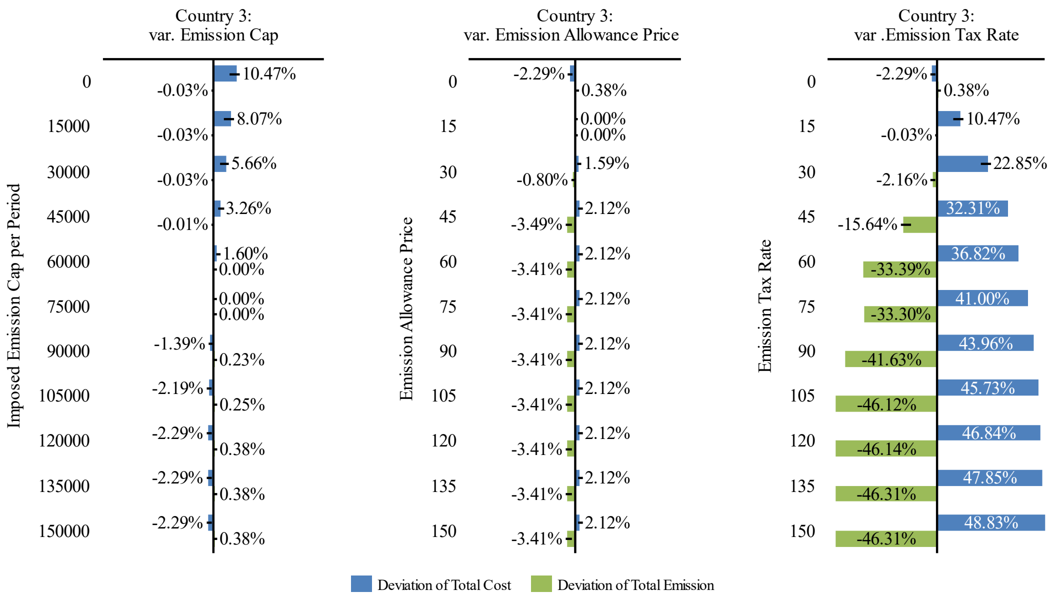

Figure 8.34: Percentual deviations in total cost and total emission results with policy variations in Country 3 in comparison to results of Case 2 with OTDLT of 115

A voluntary emission offset policy allows companies to design their policies according to their own preferences; hence, a weakly designed policy may be seen as "greenwashing." In Case 2, the emission offset policy has a high cap and a low emission allowance price, and the effects will be minor even if solely the cap is somewhat lower or the price higher. For this kind of policy, unlike the emission cap and trade policy, the parameters of emission cap and emission allowance price are both essential to generate satisfactory results for total emissions.

When Country 3 implements an emission tax policy, significant differences to the results of Case 2, with quoted OTDLT of 115, are evident. With an increasing tax rate, production and handling activities are shifted from Country 3 to countries 1 and 2 because the cost advantage of Country 3 is reduced. Therefore, total emissions can nearly be halved when the tax rate is high. However, due to the harsh taxation and the shift to high-cost countries, the total costs increase.

All results depend strongly on the presented assumption and the given numerical example. However, certain specific conclusions can be drawn:

- Longer quoted OTDLT offers companies more possibilities to offshore their supply chain activities to achieve cost advantages.
- The cost advantage of low-cost but high-emission countries can be increased by implementing weak or no emission policies in those countries.
- Differences in the stringency of emission policies of different countries can cause overall emissions to increase, because such differences can stimulate offshoring activities.
- When total cost is the only decision criterion for companies, offshoring is generally beneficial, if there are notable differences in the design of emission policies in various countries. Therefore, it seems suitable for companies to increase their quoted OTDLT.
- Policy changes in different countries can have a strong influence on the design of a supply chain. By implementing strict policies in (for example) low-cost and high-emission countries, the benefits of low costs can be cannibalized by a harsh emission policy that leads to additional emission costs.
- In nearly all cases, it seems advantageous to use distant suppliers to reduce procurement costs. Distant suppliers can be used to produce goods for stock and to lower procurement costs. A supplier mix of distant and nearby suppliers can guarantee responsiveness at a moderate cost.

- Location decisions about production facilities and warehouses depend strongly on the quoted OTDLT. When OTDLT is sufficiently high, companies can seek the advantages of different cost structures in various countries.
- A trade-off between inventory levels and the choice of logistic modes can be observed in a global setting. Furthermore, the choice of transportation modes is strongly determined by the level of relocation. In addition, with a high quoted OTDLT, it may be necessary to use faster logistic modes due to the longer transportation routes.

9 Final Conclusion

9.1 Summary of the Thesis

This thesis contributes to knowledge about the influence of OTDLT and different emission policies on the design of supply chains. Basic terminology was defined, and the existing literature on the subject was reviewed. Mathematical optimization models are then developed that enable the implementation of OTDLT and different emission policies alongside typical supply chain design decisions. Furthermore, the initial model was modified to make it possible to investigate the influence of OTDLT-sensitive consumers. A robust optimization approach was chosen to investigate demand uncertainties and uncertainties regarding the design of different emission policies. For an analysis of the influence of globally diverse emission policies, a further optimization model was used to represent country-specific emission policies and countries with different cost structures and emission avoidance standards. In this section, the research questions posed in section 1.2 are discussed.

RQ1 How does the trade-off between OTDLT and total cost influence the design of the supply chain, and how do different emission policies influence this trade-off?

A high proportion of existing supply chain design studies consider only certain types of lead time, as discussed in Chapter 4. To address RQ1, in Chapter 5 of this thesis, a supply chain design model was developed that includes all relevant types of OTDLT. The analysis of the model is twofold, using both a compromise programming approach and an ε-constraint approach to gain insights into the influence of OTDLT on supply chain design. The results presented in Chapter 5 indicate that OTDLT significantly influences location decisions. Furthermore, kept inventories and the use of different logistic modes are highly affected by OTDLT. Based on the provided numerical example and the assumptions made, total cost and total emission are strongly affected by OTDLT. Therefore, quotation of OTDLT can be an important decision that significantly affects the profitability of a company. Furthermore, it is important to consider OTDLT when designing a supply chain due to its significant influence on the selection of suppliers and facilities. The examined emission policies are all able to reduce total emissions. For the emission cap policy, too low an imposed cap can be prohibitive regarding certain OTDLT values and will thus limit a company's competitiveness. On the other hand, this policy does not lead to significant emission reductions with a too high imposed cap. Under the emission tax policy, total costs increase significantly, and companies may be harshly financially harmed. Nevertheless, this policy offers strong incentives to reduce their total emission. Similar incentives occur under the emission cap and trade policy, but total costs are less affected by this policy; however, its effectiveness depends strongly on the imposed cap. With an improperly imposed emission cap, prices for emission credits are too low, and the incentive to abate emissions is reduced. The almost voluntary emission offset policy can also reduce total emissions and has a far milder influence on total cost than the emission tax policy. The results of Chapter 5 indicate that supplier selection is mainly influenced by the various emission policies. Only the strict emission cap policy significantly affects other location decisions when the imposed cap is prohibitively low. In general, the influences of different emission policies depend vastly on their design.

RQ2 How do OTDLT-sensitive customers influence the design of a supply chain, and what influence do different emission policies have?

The influence of OTDLT-sensitive customers on supply chain design was examined in Chapter 6. With an increasing share of such customers, the design of the supply chain is strongly influenced. Furthermore, with a higher share of OTDLT-sensitive customers, total profit decreases, and total costs and total emissions increase. However, with a high share of sensitive customers, the shape of the supply chain is substantially changed. The necessary OTDLT to meet customers’ needs also affects location decisions. Emission policies have a strong influence on fulfilled demand and on the total profit of the supply chain. Furthermore, increases in product price are noted to outweigh the losses due to market-based emissions policies and could increase profitability. Therefore, product prices are essential for dealing with customer needs economically. Emission policies also have a significant influence on stock levels and the use of transportation modes. Furthermore, it was observed that the design of different emission policies largely determines their influence. Under an emission cap policy, too high an imposed cap almost removes the influence on supply chain design decisions. In contrast, under a low cap, the supply chain cannot meet customers’ expectations, and fulfilled demand is thus greatly reduced. The market-based emission policies, in contrast, offer more flexibility to deal with those expectations.

RQ3 How does OTDLT influence the supply chain design when it faces uncertainties in demand and the design of emission policies?

The applied robust programming approach enables to examine total cost variability and demand unfulfillment. When supply chains face uncertainties in demand and in the design of different emission policies, expected total cost tend to increase. Adjusting quoted OTDLT may be beneficial in order to better deal with these uncertainties. With increasing OTDLT, a decrease in expected total cost and total cost variability can be observed without emission policies. Under any emission policy at least a decrease in expected total cost can be observed. Furthermore, in the case of strict policies, it may be beneficial to not fully fulfill demand to achieve lower expected total cost and total cost variability. Market-based emission policies seem to offer better opportunities to deal with these kinds of uncertainties because demand can be already fulfilled at comparably low penalty costs. Command and control policies, like emission cap, restrict the decisions, and demand fulfillment can only be guaranteed with high expected total cost and sufficiently high quoted OTDLT Location decisions are highly dependent on the quoted OTDLT Furthermore, with uncertain design of emission policies, stocking levels are increased compared to the situation without emission policy. As the literature indicates, increased inventories can be interpreted as strategic stock, which is a suitable mitigation strategy to deal with emission policies generally as well as uncertainties in their design.[371]

RQ4 How does OTDLT influence the design of a supply chain, and what is the impact of country-specific emissions policies on supply chain design?

To examine the influence of country-specific emission policies, Chapter 8 provided a supply chain design model that considers different countries and quoted lead times. In the numerical example, differences in countries according to processing cost and emission avoidance standards are considered. With increasing OTDLTs, offshoring the supply chain activities and facilities is noted to be beneficial for lowering the total cost. Sourcing and production in low-cost countries, in particular, can lower the total cost substantially. However, in the previous chapters, longer quoted OTDLTs are associated with a decrease in total emission. In the global setting examined in Chapter 8, no such observation was made. With offshoring activities to low-cost and high-emission countries, total emissions remained high. To tackle the problem of increasing global emissions, governments

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[371] Cf. Sodhi, M. S.; Tang, C. S., 2012, p. 100.

worldwide consider implementing emission policies. As shown in Chapter 8, the total emission situation could worsen when diverse emission policy designs are implemented. The cost benefits of the high-emission countries in the presented numerical example can be increased through the various emission policies, and offshoring tendencies could be strengthened. The potential to lower emissions is shown by considering a global, equal emission tax. In this case, a significant reduction in total emissions is observed. Furthermore, the design of emission policies in different countries highly influences the design of the supply chain. In countries with high emission avoidance standards, stricter regulations can lead to higher total emissions because of the incentive to offshore certain activities. The greatest influence can arise from an emission policy imposed in a country with low emission avoidance standards. The implementation of a strict policy in other countries can prompt the relocation of production facilities and warehouses away from the countries that have higher standards. Furthermore, total emissions are highly affected by the policy in low emission standards countries. In addition, the voluntary nature of emission offset systems means that these are sometimes used for “greenwashing.” Only minor effects on total emissions are achieved with too high an imposed emission cap or too low an emission allowance price. Therefore, even if such a policy is in charge, the design strongly determines its effectiveness.

9.2 Limitations and Future Research

This study has several limitations. First, the difficulty of retrieving sufficient real-world data limits the model. The developed models solve pseudo-random generated data examples, which means that only preliminary results are obtained. Furthermore, the assumptions do not necessarily meet every industry’s requirements. Therefore, for some industries, the assumptions and model formulations might need to be altered. Industry-specific cases should be applied to gain deeper insights and to confirm the results.

The results indicate that total emission can be reduced the most by choosing less emission-intensive logistic modes, lowering stock levels, and contracting fewer emission-intensive suppliers. Nevertheless, changing the selected production or warehouse technology can lower the emissions generated by production and handling activities. In most cases, changing the technology requires large investments. When emission policies are tightened, these investments may become more economical if the emission price rises sharply. Therefore, future research should consider the possibilities for technology selection in strategic supply chain design models. This would enable investigating the potential for emission reduction in production and handling processes too.

Furthermore, the developed models neglect economies of scale. When higher capacity is assigned to a location, economies of scale arise and can affect the production cost (among other factors). In transportation, those effects can also arise. To improve the implementation of capacity, assignment of scale can be helpful. In addition, as studies have shown, economies of scale can positively impact emissions from transport activities.[372] Therefore, examining economies of scale in the green supply chain design context could be a further research opportunity.

Disruption risks have a high impact on supply chains. In the recent Suez Canal blockage by the cargo ship "Ever Given," supply chains globally were affected.[373] Supply lead time was critically affected. Therefore, in addition to the observed demand uncertainties and uncertainties in the design of emission policies, disruption risks strongly affect not only the supply chain design but also the achieved OTDLT. Supply chain design models that incorporate disruption risks and lead time uncertainties should thus be developed to create resilient supply chains.

Regarding the global supply chain, this study neglects global economic dynamics such as tax rates, tariffs, exchange rates, and local content regulations. Those dynamics may be useful to provide a broader view of global supply chain design to gain a deeper understanding of the influence of OTDLT and differently designed emission policies. Furthermore, it is assumed that these dynamics would influence offshoring decisions.

The presented solutions are limited to relatively small problems. The complexity of the models and the resulting computational burden mean that it remains challenging to solve such models in a reliable time. Further studies could focus on the development and application of powerful metaheuristics to offer the possibility to solve large-scale problems rapidly.

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[372] Cf. LINDSTAD, H.; ASBJØRNSLETT, B. E.; STRØMMAN, A. H., 2012, p. 396.
[373] Cf. RAMOS, K. G. ET AL., 2021, p. 145.

Appendix A: Results of Chapter 5.4

Results of Chapter 5.4: without emission Policy – varying weighting factor

										Production Facility 1		Production Facility 2		Production Facility 3		Production Facility 4		Warehouse 1		Warehouse 2		Warehouse 3		Warehouse 4		Average use of logistic modes			
ϖ	Total Cost	Max. OTDLT	Total Emission	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Supplier 5	Supplier 6	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Mode 1	Mode 2	Mode 3	Average stock
0	43538296.7	63.34	232580	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	251982.2	374114.7	796871.3	81129.13
0.1	18936048.7	63.34	64908	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	1	0	0	1	564772.3	355209.7	100665.3	50382.33
0.2	18905050.2	63.34	65117	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	0	1	0	1	559982.3	356048.7	104612.5	49657.46
0.3	18886853.1	63.34	65489	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	1	0	0	1	567560.4	350110.2	102965.3	49975.33
0.4	18412703.5	66.06	62953	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	528600.5	380412.8	111626.5	47087.00
0.5	18223017.5	67.62	61397	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	530021.1	392920.7	97701.0	46262.00
0.6	17221410.1	79.47	57298	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	554333.3	403260.1	63044.2	45263.67
0.7	15693995.4	108.54	54434	1	1	0	1	0	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	596600.4	371621.0	52429.4	38990.00
0.8	13605997.9	173.36	45221	1	1	0	1	0	1	1	0	0	0	1	0	0	1	1	0	1	0	1	0	0	1	768754.0	226212.4	25676.7	41560.17
0.9	11085683.1	316.33	36940	1	0	1	1	0	1	1	0	0	0	1	0	0	1	1	0	1	0	1	0	0	1	894217.7	105881.5	20542.3	16103.07
1	6566351.9	6143.00	29024.2	1	0	0	1	0	0	0	1	0	0	0	0	0	0	0	1	0	1	0	0	0	0	1020634.3	0.0	0.0	7505.00

Results of Chapter 5.4: Emission Cap Policy – varying weighting factor

										Production Facility 1		Production Facility 2		Production Facility 3		Production Facility 4		Warehouse 1		Warehouse 2		Warehouse 3		Warehouse 4		Average use of logistic modes			
ϖ	Total Cost	Max. OTDLT	Total Emission	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Supplier 5	Supplier 6	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Mode 1	Mode 2	Mode 3	Average stock
0	18790327.5	87.12	57000	1	1	1	1	1	1	1	0	1	0	1	0	0	1	1	0	1	0	0	1	0	1	398667.7	590273.0	31704.3	9756.70
0.1	18123347.6	87.47	57000	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	0	1	0	1	417479.8	551461.8	51693.6	10661.30
0.2	17735901.8	88.38	55012	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	0	1	0	1	446186.0	533242.3	41214.6	15235.06
0.3	17311681.4	90.21	52990	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	0	1	0	1	504598.9	481265.3	34780.9	20758.93
0.4	16686734.6	95.00	51734	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	499551.0	480071.6	41023.4	24250.53
0.5	16461600.6	97.53	50729	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	527643.9	462311.1	30685.3	26818.77
0.6	15813883.0	107.88	49766	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	577807.1	415022.3	27819.3	28406.67
0.7	14696065.9	135.64	49379	1	1	0	1	0	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	624666.5	366666.8	29312.7	28347.10
0.8	12395514.2	227.73	40734	1	1	0	1	0	1	1	0	0	0	1	0	0	1	1	0	1	0	1	0	0	1	837141.7	161636.8	21863.7	30564.57
0.9	10335900.9	392.39	34420	1	0	1	1	0	1	1	0	0	0	1	0	0	1	1	0	1	0	1	0	0	1	941092.7	63062.2	16478.0	9677.28
1	6566334.7	7292.00	29024.1	1	0	0	1	0	0	0	1	0	0	0	0	0	0	0	1	0	1	0	0	0	0	1020634.3	0.0	0.0	7505.00

Results of Chapter 5.4: Emission Tax Policy – varying weighting factor

											Production Facility 1		Production Facility 2		Production Facility 3		Production Facility 4		Warehouse 1		Warehouse 2		Warehouse 3		Warehouse 4		Average use of logistic modes			
ϖ	Total Cost	Max. OTDLT	Total Emission	Total Emission Cost	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Supplier 5	Supplier 6	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Mode 1	Mode 2	Mode 3	Average stock
0	59035660.6	63.34	220175	16513100	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	557201.8	377883.8	85556.5	81495.42
0.1	23706741.3	63.34	63415	4756160	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	0	1	0	1	557887.5	377195.6	85558.5	50875.40
0.2	23706749.3	63.34	63404	4755260	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	0	1	0	1	557739.5	377958.9	84946.5	51058.93
0.3	23676512.0	63.43	63248	4743630	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	0	1	0	1	534429.4	391981.1	94230.5	50922.47
0.4	22987317.6	66.45	61174	4588100	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	536737.6	408292.8	75611.1	48566.33
0.5	22532621.5	69.10	58888	4416600	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	545920.4	417991.0	56723.5	47137.67
0.6	21597002.6	77.81	55303	4147670	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	584785.2	403732.1	32130.6	42733.00
0.7	19827089.8	102.05	50157	3761770	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	606969.1	396261.5	17409.0	34420.00
0.8	17425840.2	156.73	42388	3179120	1	1	0	1	1	1	1	0	0	0	1	0	0	1	1	0	0	0	0	1	0	1	881733.3	120720.8	18192.3	28817.67
0.9	14053953.1	300.34	36687	2751540	1	1	0	1	0	1	1	0	0	0	1	0	0	1	1	0	1	0	1	0	0	1	1020634.3	0.0	0.0	15710.87
1	8743320.7	6905.00	29025	2176900	1	0	0	1	0	0	0	1	0	0	0	0	0	0	0	1	0	1	0	0	0	0	308618.3	0.0	0.0	7505.00

Results of Chapter 5.4: Emission Cap and Trade Policy – varying weighting factor

											Production Facility 1		Production Facility 2		Production Facility 3		Production Facility 4		Warehouse 1		Warehouse 2		Warehouse 3		Warehouse 4		Average use of logistic modes			
ϖ	Total Cost	Max. OTDLT	Total Emission	Total Emission Cost	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Supplier 5	Supplier 6	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Mode 1	Mode 2	Mode 3	Average stock
0	57775113.5	63.34	233379	14128300	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	557201.8	377883.8	85556.5	82603.17
0.1	20331742.5	63.34	63415	1381130	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	0	1	0	1	557596.8	377487.4	85557.7	50875.40
0.2	20331741.8	63.34	63409	1380620	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	0	1	0	1	534540.8	392359.4	93740.0	50978.80
0.3	19592636.9	66.55	61081	1206110	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	537493.0	407977.9	75177.6	48514.00
0.4	19109711.5	69.48	58709	1028130	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	547167.6	420836.6	52635.0	47021.00
0.5	17898220.5	81.44	54009	675670	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	593608.6	402277.0	24763.5	40601.33
0.6	16216773.3	106.15	49305	322810	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	600057.0	401970.8	18614.7	33026.33
0.7	14235609	151.51	42961	-152924	1	1	0	1	1	1	1	0	0	0	1	0	0	1	1	0	0	0	0	1	0	1	840855.0	159913.6	19866.7	29894.33
0.8	11732583.5	242.08	39224	-433195	1	1	0	1	0	1	1	0	0	0	1	0	0	1	1	0	1	0	1	0	0	1	949306.0	56035.3	15307.0	25605.70
0.9	9337680.59	412.18	33717	-846260	1	0	1	1	0	1	1	0	0	0	1	0	0	1	1	0	1	0	1	0	0	1	1020634.3	0.0	0.0	8376.71
1	5368161.31	6143.00	29024.1	-1198170	1	0	0	1	0	0	0	1	0	0	0	0	0	0	0	1	0	1	0	0	0	0	308618.3	0.0	0.0	7505.00

Results of Chapter 5.4: Emission Offset Policy – varying weighting factor

											Production Facility 1		Production Facility 2		Production Facility 3		Production Facility 4		Warehouse 1		Warehouse 2		Warehouse 3		Warehouse 4		Average use of logistic modes			
ϖ	Total Cost	Max. OTDLT	Total Emission	Total Emission Cost	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Supplier 5	Supplier 6	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Mode 1	Mode 2	Mode 3	Average stock
0	55265315.7	63.34	218052.0	12979000	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	539291.4	388885.5	92465.1	81474.33
0.1	20534552.8	63.34	64140.0	1556940	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	0	1	0	1	534481.0	395427.1	90730.0	46679.30
0.2	20527096.6	63.34	64041.0	1543410	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	0	1	0	1	534821.7	397416.7	88406.4	46210.07
0.3	20424129.3	63.70	63529.0	1503810	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	0	1	0	1	509243.7	428997.6	82394.3	45976.30
0.4	19336296.1	69.02	59715.0	1178919	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	505829.7	447943.6	66861.0	42144.00
0.5	18634707.8	75.16	56968.0	949755	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	522111.8	457758.9	40774.7	38193.00
0.6	17117044.4	93.40	51184.0	475490	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	585966.9	410921.2	23754.5	28103.33
0.7	15606242.4	119.90	47322.0	199500	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	772425.3	225394.0	22821.0	22328.60
0.8	12900771.1	204.23	41984.0	0	1	1	0	1	0	1	1	0	0	0	1	0	0	1	1	0	1	0	1	0	0	1	894217.7	105881.5	20542.3	27028.44
0.9	11085642.2	316.33	36940.0	0	1	0	1	1	0	1	1	0	0	0	1	0	0	1	1	0	1	0	1	0	0	1	1020634.3	0.0	0.0	16103.07
1	6566339.6	6117.00	29024.1	0	1	0	0	1	0	0	0	1	0	0	0	0	0	0	0	1	0	1	0	0	0	0	308618.3	0.0	0.0	7505.00

Results of Chapter 5.4: Emission Cap Policy – varying emission cap per period

Imposed Emission Cap	Total Cost	Max. OTDLT	Total Emission	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Supplier 5	Supplier 6	Production Facility 1 Cap-Opt. 1	Production Facility 1 Cap-Opt. 2	Production Facility 2 Cap-Opt. 1	Production Facility 2 Cap-Opt. 2	Production Facility 3 Cap-Opt. 1	Production Facility 3 Cap-Opt. 2	Production Facility 4 Cap-Opt. 1	Production Facility 4 Cap-Opt. 2	Warehouse 1 Cap-Opt. 1	Warehouse 1 Cap-Opt. 2	Warehouse 2 Cap-Opt. 1	Warehouse 2 Cap-Opt. 2	Warehouse 3 Cap-Opt. 1	Warehouse 3 Cap-Opt. 2	Warehouse 4 Cap-Opt. 1	Warehouse 4 Cap-Opt. 2	Average use of logistic modes Mode 1	Mode 2	Mode 3	Average stock
9000	9961363.89	824.01	27000	1	1	1	0	1	1	0	0	0	0	0	1	0	1	1	0	1	0	0	1	0	0	1020026.0	620.8	0.0	11062.93
10500	11065198.9	399.39	31500	1	0	1	1	1	1	0	0	0	0	0	1	0	1	1	0	1	0	1	0	0	1	929697.7	82342.8	8596.8	14297.17
12000	12875455.1	233.61	36000	1	1	1	1	1	1	1	0	0	0	1	0	0	1	1	0	0	0	0	1	0	1	758402.0	259973.7	2271.9	15511.03
13500	14135578.1	168.06	40500	1	1	1	1	1	1	1	0	0	0	1	0	0	1	1	0	0	0	0	1	0	1	573172.5	433819.7	13652.3	15037.30
15000	15298010.2	129.76	45000	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	575889.9	434024.3	10729.2	14074.80
16500	15818307	113.15	47614	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	560055.3	439245.2	21339.1	19406.90
18000	16215504.9	103.00	49399	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	545165.0	451749.9	23729.3	24857.30
19500	16565716.6	95.19	51292	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	524893.7	458511.2	37233.6	27861.90
21000	16790598.7	89.82	52486	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	524574.3	453326.3	42741.4	31411.47
22500	17052348.7	84.68	53965	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	517635.5	451884.5	51121.9	33822.00
24000	17319667.9	80.01	55506	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	514235.5	447537.2	58872.8	36075.00

Results of Chapter 5.4: Emission Cap and Trade Policy – varying emission cap per period

											Production Facility 1		Production Facility 2		Production Facility 3		Production Facility 4		Warehouse 1		Warehouse 2		Warehouse 3		Warehouse 4		Average use of logistic modes			
Imposed Emission Cap	Total Cost	Max. OTDLT	Total Emission	Total Emission Cost	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Supplier 5	Supplier 6	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Mode 1	Mode 2	Mode 3	Average stock
9000	19955555.9	73.85	56614	2221020	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	539960.3	418370.2	62308.6	45056.67
10500	19472758.3	75.27	56065	1842280	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	541212.1	419608.0	59813.5	44168.67
12000	19042891.9	76.21	55738	1480340	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	541522.6	421728.5	57392.7	43546.33
13500	18481561.7	78.62	54933	1082470	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	544033.0	421326.5	55274.7	42080.33
15000	17898220.5	81.44	54009	675670	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	547167.6	420836.6	52635.0	40601.33
16500	17183728.8	86.16	54118	346351	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	564406.9	405076.4	51155.1	42229.00
18000	16753922.5	87.37	53786	-16101	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	565646.6	405342.7	49648.4	41393.00
19500	16053211.5	92.45	52391	-458210	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	572182.5	406305.0	42162.7	38727.67
21000	15345344.8	98.05	51058	-895555	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	580408.9	402346.1	37886.6	36001.33
22500	14738576	102.49	50057	-1308230	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	585912.0	403968.3	30759.8	34270.00
24000	14035622.1	109.01	48716	-1746230	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	598053.8	399932.5	22654.4	32353.33

Results of Chapter 5.4: Emission Cap and Trade Policy (dep. emission credit price) – varying emission cap per period

											Production Facility 1		Production Facility 2		Production Facility 3		Production Facility 4		Warehouse 1		Warehouse 2		Warehouse 3		Warehouse 4		Average use of logistic modes			
Imposed Emission Cap	Total Cost	Max. OTDLT	Total Emission	Total Emission Cost	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Supplier 5	Supplier 6	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Mode 1	Mode 2	Mode 3	Average stock
9000	20855168.5	77.56	54769	3332360	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	546515.8	421256.1	52873.7	43577.33
10500	19849175.9	79.61	54351	2485090	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	548083.6	420449.0	52110.2	42449.67
12000	19035724.9	80.80	54111	1765854	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	548558.6	420029.9	52053.7	41509.67
13500	18384983.4	81.53	53998	1164170	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	551497.8	417959.6	51188.7	41264.67
15000	17898220.5	81.44	54009	675670	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	547167.6	420836.6	52635.0	40601.33
16500	17603376.2	80.34	54492	318209	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	551355.9	415110.6	54171.7	41558.33
18000	17240914.8	81.04	55985	104221	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	558751.8	402835.1	59059.1	44697.33
19500	17134307.9	79.79	56819	-69336	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	554920.4	405317.6	60410.8	45314.67
21000	17309990.7	76.28	58213	-143624	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	548320.3	403116.1	69205.7	46731.33
22500	17371962.8	75.17	58777	-163547	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	545316.9	402665.7	72659.8	47055.67
24000	18008969.7	68.90	60348	-87388	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	533524.9	397024.8	90092.5	45807.67

Results of Chapter 5.4: Emission Offset Policy – varying emission cap per period

											Production Facility 1		Production Facility 2		Production Facility 3		Production Facility 4		Warehouse 1		Warehouse 2		Warehouse 3		Warehouse 4		Average use of logistic modes			
Imposed Emission Cap	Total Cost	Max. OTDLT	Total Emission	Total Emission Cost	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Supplier 5	Supplier 6	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Mode 1	Mode 2	Mode 3	Average stock
9000	19957167.8	73.84	56645	2223410	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	543163.3	415146.5	62341.0	45200.00
10500	19578880.2	74.23	56461	1872071	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	540277.2	418778.1	61590.9	44824.33
12000	19242818.8	74.23	56483	1536210	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	536852.6	422013.8	61774.6	44171.33
13500	18923374.4	74.74	56678	1213270	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	520390.6	434111.6	66138.8	40265.00
15000	18634707.8	75.16	56968	949755	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	505829.7	447943.6	66861.0	38193.00
16500	18483445.3	74.54	57199	778440	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	509046.1	443407.5	68188.6	38420.33
18000	18367398.5	73.95	57761	648710	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	510088.0	441540.7	69011.1	38982.67
19500	18220957.7	74.12	57687	509880	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	507449.1	445542.6	67649.4	39190.33
21000	18106926.1	74.15	57677	397400	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	507490.5	445515.5	67638.7	39144.33
22500	17991499.9	74.12	57620	276690	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	507160.6	445793.7	67687.1	38999.00
24000	17878999.9	74.12	57620	164190	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	507160.6	445793.7	67687.1	38999.00

Results of Chapter 5.4: Emission Tax Policy – varying emission price

											Production Facility 1		Production Facility 2		Production Facility 3		Production Facility 4		Warehouse 1		Warehouse 2		Warehouse 3		Warehouse 4		Average use of logistic modes			
Emission Tax Rate	Total Cost	Max. OTDLT	Total Emission	Total Emission Cost	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Supplier 5	Supplier 6	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Mode 1	Mode 2	Mode 3	Average stock
0	18223126.9	67.62	61405	0	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	530503.3	392100.5	98037.5	46322.00
15	19053651.4	68.39	60327	904910	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	534505.3	397997.8	88136.8	46746.67
30	19929766.0	68.62	59901	1797000	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	535843.8	401185.9	83613.4	46754.00
45	20763796.1	69.10	59037	2656640	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	537257.7	405994.0	77399.1	46772.33
60	21648853.2	69.10	58951	3536910	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	538199.5	405652.4	76787.6	47220.33
75	22532621.5	69.10	58888	4416600	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	536737.6	408292.8	75611.1	47137.67
90	23415506.7	69.10	58842	5295800	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	536965.7	409165.8	74512.0	47192.67
105	24296707.1	69.10	58606	6153700	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	537687.6	409725.6	73233.3	47494.00
120	25188470.5	69.10	58649	7037900	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	538219.2	410101.8	72317.1	47696.00
135	26050658.8	69.10	58374	7880400	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	538386.6	409905.3	72339.7	47751.67
150	26916475.1	69.16	58309	8746400	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	538269.7	410549.5	71816.6	47839.33

Results of Chapter 5.4: Emission Cap and Trade Policy – varying emission price

											Production Facility 1		Production Facility 2		Production Facility 3		Production Facility 4		Warehouse 1		Warehouse 2		Warehouse 3		Warehouse 4		Average use of logistic modes			
Emission Credit Price	Total Cost	Max. OTDLT	Total Emission	Total Emission Cost	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Supplier 5	Supplier 6	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Mode 1	Mode 2	Mode 3	Average stock
0	18223019.4	67.62	61395	0	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	530185.9	392765.7	97690.5	46273.67
15	18303966.8	69.10	59709	220643	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	534309.4	406008.2	80320.1	46352.67
30	18371105.2	70.62	58734	412047	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	537076.3	408852.6	74707.3	45788.33
45	18230005	74.12	56647	524080	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	541823.9	415864.2	62956.0	44659.67
60	18104225.4	77.35	55410	624590	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	547101.8	416831.9	56714.5	43034.33
75	17898220.5	81.44	54009	675670	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	547167.6	420836.6	52635.0	40601.33
90	17666180.2	85.88	52699	692820	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	553846.4	421792.6	45008.0	38928.67
105	17370600.9	90.83	51090	639440	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	560910.5	422654.1	37069.7	36354.67
120	17150969.7	94.86	49896	587442	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	568317.8	420642.8	31675.8	34440.33
135	16670810.9	102.39	48179	429150	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	581368.2	421786.7	17483.9	31095.33
150	16297786.6	108.44	46978	296627	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	594222.8	411788.3	14624.6	28748.67

Results of Chapter 5.4 Emission Offset Policy – varying emission price

											Production Facility 1		Production Facility 2		Production Facility 3		Production Facility 4		Production Facility 1		Production Facility 2		Production Facility 3		Production Facility 4		Average use of logistic modes			
Emission Allowance Price	Total Cost	Max. OTDLT	Total Emission	Total Emission Cost	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Supplier 5	Supplier 6	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Mode 1	Mode 2	Mode 3	Average stock
0	18223019.4	67.62	61395	0	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	530185.9	392765.7	97690.5	46273.67
15	18362630.3	68.90	60346	264138	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	528620.3	403196.0	88829.2	44870.00
30	18559700.2	69.48	59883	502783	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	525021.8	412922.9	82697.1	43737.33
45	18687167.9	70.66	59294	707675	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	518823.0	421716.9	80108.6	42183.67
60	18665961.7	72.91	57840	844200	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	517102.1	431370.1	72169.9	40505.00
75	18634707.8	75.16	56968	949755	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	505829.7	447943.6	66861.0	38193.00
90	18694952.3	76.35	56591	1069049	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	500635.0	456463.9	63549.8	36717.67
105	18603817.4	78.86	55636	1120800	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	499735.2	460085.6	60824.8	34800.00
120	18509853.8	81.16	54580	1149600	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	497736.9	466229.9	56675.1	33153.00
135	18544695.2	82.17	54146	1234700	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	498213.1	467654.0	54774.0	32360.00
150	18369764.5	85.12	53159	1223800	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	497780.7	473793.0	49061.9	30592.00

Appendix B: Results of Chapter 5.5

Results of Chapter 5.5 without Emission Policy – varying quoted OTDLT

									Production Facility 1		Production Facility 2		Production Facility 3		Production Facility 4		Production Facility 1		Production Facility 2		Production Facility 3		Production Facility 4		Average use of logistic modes			
Quoted OTDLT	Total Cost	Total Emission	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Supplier 5	Supplier 6	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Mode 1	Mode 2	Mode 3	Average stock
64	18785415.1	64578	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	1	0	0	1	567050.4	354755.6	98833.8	49634.33
79	17253484.0	57513	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	552890.4	402944.9	64804.1	45409.33
94	16401152.9	52851	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	572023.8	402039.0	46576.8	36921.00
109	15673598.4	54325	1	1	0	1	0	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	596562.4	372270.5	51812.2	38633.00
124	15070550.5	51143	1	1	0	1	0	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	614337.3	372118.2	34198.4	32943.67
139	14593128.1	49032	1	1	0	1	0	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	634111.9	357177.0	29359.7	28548.43
154	14157069.9	47571	1	1	0	1	0	1	1	0	0	0	1	0	0	1	1	0	1	0	1	0	0	1	733648.0	258998.5	27985.5	45470.65
169	13720497.2	45713	1	1	0	1	0	1	1	0	0	0	1	0	0	1	1	0	1	0	1	0	0	1	761218.7	233184.7	26238.8	42356.07
184	13338625.0	44237	1	1	0	1	0	1	1	0	0	0	1	0	0	1	1	0	1	0	1	0	0	1	783764.7	211595.9	25284.0	39193.63
199	12986324.0	42792	1	1	0	1	0	1	1	0	0	0	1	0	0	1	1	0	1	0	1	0	0	1	804534.7	192538.7	23563.0	35853.37
214	12662822.1	41606	1	1	0	1	0	1	1	0	0	0	1	0	0	1	1	0	1	0	1	0	0	1	825664.0	172673.8	22307.2	33047.40

Results of Chapter 5.5: Emission Cap Policy – varying quoted OTDLT

									Production Facility 1		Production Facility 2		Production Facility 3		Production Facility 4		Production Facility 1		Production Facility 2		Production Facility 3		Production Facility 4		Average use of logistic modes			
Quoted OTDLT	Total Cost	Total Emission	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Supplier 5	Supplier 6	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Mode 1	Mode 2	Mode 3	Average stock
64																												
79																												
94	16808402.6	52057	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	486806.2	489128.7	44710.5	22548.73
109	15762339.3	49585	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	584001.1	409097.7	27541.9	28560.53
124	15181624.0	51064	1	1	0	1	0	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	587386.7	401978.4	31281.0	27348.23
139	14593128.1	49032	1	1	0	1	0	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	634111.9	357177.0	29359.7	28548.43
154	14185126.1	47492	1	1	0	1	0	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	656381.7	337877.8	26385.0	24344.57
169	13721828.6	45648	1	1	0	1	0	1	1	0	0	0	1	0	0	1	1	0	1	0	1	0	0	1	752986.0	241433.5	26219.7	41348.37
184	13338625.0	44237	1	1	0	1	0	1	1	0	0	0	1	0	0	1	1	0	1	0	1	0	0	1	783764.7	211595.9	25284.0	39193.63
199	12986324.0	42792	1	1	0	1	0	1	1	0	0	0	1	0	0	1	1	0	1	0	1	0	0	1	804534.7	192538.7	23563.0	35853.37
214	12662822.1	41606	1	1	0	1	0	1	1	0	0	0	1	0	0	1	1	0	1	0	1	0	0	1	825664.0	172673.8	22307.2	33047.40

Results of Chapter 5.5: Emission Tax Policy – varying quoted OTDLT

										Production Facility 1		Production Facility 2		Production Facility 3		Production Facility 4		Production Facility 1		Production Facility 2		Production Facility 3		Production Facility 4		Average use of logistic modes			
Quoted OTDLT	Total Cost	Total Emission	Total Emission Cost	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Supplier 5	Supplier 6	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Mode 1	Mode 2	Mode 3	Average stock
64	23535093.1	62559	4691960	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	0	1	0	1	558416.8	381743.3	80483.2	50559.33
79	21484778.7	54802	4110120	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	544325.5	421122.7	55193.0	41846.00
94	20335188.1	52017	3901340	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	572425.0	407426.4	40782.3	37522.33
109	19435669.0	48738	3655370	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	596854.1	401093.2	22693.7	32011.67
124	18747800.3	46540	3490400	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	618080.7	384251.8	18304.2	26580.50
139	18089888.1	44371	3327870	1	1	0	1	1	1	1	0	0	0	1	0	0	1	1	0	0	0	0	1	0	1	586722.8	414015.7	19901.3	33456.00
154	17521198.9	42688	3201630	1	1	0	1	1	1	1	0	0	0	1	0	0	1	1	0	0	0	0	1	0	1	602743.7	399748.9	18148.7	29304.33
169	17025643.6	41215	3091130	1	1	0	1	1	1	1	0	0	0	1	0	0	1	1	0	0	0	0	1	0	1	626132.2	378836.4	15669.8	25836.47
184	16577174.9	40087	3006490	1	1	0	1	1	1	1	0	0	0	1	0	0	1	1	0	0	0	0	1	0	1	652237.3	352847.0	15551.2	21962.87
199	16168407.7	41998	3149930	1	1	0	1	0	1	1	0	0	0	1	0	0	1	1	0	1	0	1	0	0	1	794565.3	204590.6	21480.8	32952.43
214	15758311.3	40889	3066620	1	1	0	1	0	1	1	0	0	0	1	0	0	1	1	0	1	0	1	0	0	1	815514.0	184600.4	20523.5	30203.40

Results of Chapter 5.5: Emission Cap and Trade Policy – varying quoted OTDLT

										Production Facility 1		Production Facility 2		Production Facility 3		Production Facility 4		Production Facility 1		Production Facility 2		Production Facility 3		Production Facility 4		Average use of logistic modes			
Quoted OTDLT	Total Cost	Total Emission	Total Emission Cost	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Supplier 5	Supplier 6	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Mode 1	Mode 2	Mode 3	Average stock
64	20160093.1	62559	1316980	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	0	1	0	1	558416.8	381743.3	80483.2	50559.33
79	18109778.7	54802	735090	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	544325.5	421122.7	55193.0	41846.00
94	16960188.1	52017	526300	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	572425.0	407426.4	40782.3	37522.33
109	16060669.0	48738	280343	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	596854.1	401093.2	22693.7	32011.67
124	15372800.3	46540	115470	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	618080.7	384251.8	18304.2	26580.50
139	14714888.1	44371	-47143	1	1	0	1	1	1	1	0	0	0	1	0	0	1	1	0	0	0	0	1	0	1	586722.8	414015.7	19901.3	33456.00
154	14146198.9	42688	-173360	1	1	0	1	1	1	1	0	0	0	1	0	0	1	1	0	0	0	0	1	0	1	602743.7	399748.9	18148.7	29304.33
169	13650643.6	41215	-283866	1	1	0	1	1	1	1	0	0	0	1	0	0	1	1	0	0	0	0	1	0	1	626132.2	378836.4	15669.8	25836.47
184	13202174.9	40087	-368547	1	1	0	1	1	1	1	0	0	0	1	0	0	1	1	0	0	0	0	1	0	1	652237.3	352847.0	15551.2	21962.87
199	12793407.7	41998	-225090	1	1	0	1	0	1	1	0	0	0	1	0	0	1	1	0	1	0	1	0	0	1	794565.3	204590.6	21480.8	32952.43
214	12383311.3	40889	-308380	1	1	0	1	0	1	1	0	0	0	1	0	0	1	1	0	1	0	1	0	0	1	815514.0	184600.5	20523.5	30203.40

Results of Chapter 5.5: Emission Offset Policy – varying quoted OTDLT

										Production Facility 1		Production Facility 2		Production Facility 3		Production Facility 4		Production Facility 1		Production Facility 2		Production Facility 3		Production Facility 4		Average use of logistic modes			
Quoted OTDLT	Total Cost	Total Emission	Total Emission Cost	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Supplier 5	Supplier 6	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Mode 1	Mode 2	Mode 3	Average stock
64	20353467.4	63175	1476550	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	0	1	0	1	534966.0	400141.4	85529.9	45785.33
79	18259998.0	55530	829174	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	508252.8	451110.6	61279.2	35788.00
94	17075900.8	51045	465530	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	524849.9	455389.8	40397.9	27919.33
109	16146003.6	48982	334300	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	570685.6	423524.9	26424.0	26305.33
124	15431247.7	47041	166760	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	592140.4	406073.6	22434.9	20843.47
139	14871857.3	45892	75505	1	0	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	609768.3	392083.8	18786.5	17402.60
154	14367785.1	46913	143450	1	1	0	1	0	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	626388.8	370622.3	23619.3	19605.00
169	13916574.9	41891	0	1	1	0	1	1	1	1	0	0	0	1	0	0	1	1	0	0	0	0	1	0	1	616123.3	384790.6	19722.5	23978.33
184	13489724.0	43694	84570	1	1	0	1	0	1	1	0	0	0	1	0	0	1	1	0	1	0	1	0	0	1	721259.0	274294.7	25088.8	26488.83
199	13043952.6	42350	585	1	1	0	1	0	1	1	0	0	0	1	0	0	1	1	0	1	0	1	0	0	1	748049.0	249284.8	23317.7	25284.73
214	12672412.0	41487	0	1	1	0	1	0	1	1	0	0	0	1	0	0	1	1	0	1	0	1	0	0	1	800314.3	197931.2	22396.0	29547.97

Results of Chapter 5.5: Emission Cap Policy – varying emission cap per period

									Production Facility 1		Production Facility 2		Production Facility 3		Production Facility 4		Production Facility 1		Production Facility 2		Production Facility 3		Production Facility 4		Average use of logistic modes			
Imposed Emission Cap	Total Cost	Total Emission	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Supplier 5	Supplier 6	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Mode 1	Mode 2	Mode 3	Average stock
9000																												
10500																												
12000																												
13500																												
15000																												
16500	15766886.0	47484	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	565655.6	434082.8	20897.6	19878.97
18000	15586654.8	48664	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	586179.0	409026.1	25443.6	26303.13
19500	15563592.8	48722	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	602966.4	391554.9	26117.9	29040.00
21000	15522315.5	52699	1	1	0	1	0	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	575455.0	407979.4	37210.7	31504.57
22500	15459072.8	52967	1	1	0	1	0	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	594810.3	382679.7	43154.8	35440.33
24000	15457057.9	52934	1	1	0	1	0	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	599111.2	378848.7	42685.4	36650.33

Results of Chapter 5.5: Emission Cap and Trade Policy – varying emission cap per period

										Production Facility 1		Production Facility 2		Production Facility 3		Production Facility 4		Production Facility 1		Production Facility 2		Production Facility 3		Production Facility 4		Average use of logistic modes			
Imposed Emission Cap	Total Cost	Total Emission	Total Emission Cost	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Supplier 5	Supplier 6	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Mode 1	Mode 2	Mode 3	Average stock
9000	17161312.7	47925	1569380	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	604681.9	394537.9	21415.1	30087.00
10500	16823812.7	47925	1231880	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	604681.9	394537.9	21415.1	30087.00
12000	16486312.7	47925	894377	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	604681.9	394537.9	21415.1	30087.00
13500	16148812.7	47925	556877	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	604681.9	394537.9	21415.1	30087.00
15000	15811312.7	47925	219377	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	604681.9	394537.9	21415.1	30087.00
16500	15473812.7	47925	-118123	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	604681.9	394537.9	21415.1	30087.00
18000	15136312.7	47925	-455624	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	604681.9	394537.9	21415.1	30087.00
19500	14798812.7	47925	-793124	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	604681.9	394537.9	21415.1	30087.00
21000	14461312.7	47925	-1130620	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	604681.9	394537.9	21415.1	30087.00
22500	14123812.7	47925	-1468120	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	604681.9	394537.9	21415.1	30087.00
24000	13786312.7	47925	-1805620	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	604681.9	394537.9	21415.1	30087.00

Results of Chapter 5.5: Emission Cap and Trade Policy (dep. emission credit price) – varying emission cap per period

										Production Facility 1		Production Facility 2		Production Facility 3		Production Facility 4		Warehouse 1		Warehouse 2		Warehouse 3		Warehouse 4		Average use of logistic modes			
Imposed Emission Cap	Total Cost	Total Emission	Total Emission Cost	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Supplier 5	Supplier 6	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Mode 1	Mode 2	Mode 3	Average stock
9000	18079343.9	46195	2303520	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	604178.3	403487.3	12986.6	26538.13
10500	17372641.3	46391	1619460	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	604436.1	402146.5	14058.7	26530.80
12000	16753096.3	47809	1151360	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	606029.1	394444.7	20175.1	30470.00
13500	16231936.6	47871	635670	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	605297.6	394318.3	21022.3	30337.67
15000	15811312.7	47925	219377	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	604681.9	394537.9	21415.1	30087.00
16500	15491332.9	47953	-98619	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	604726.2	394153.6	21763.7	29991.67
18000	15272106.2	48022	-313834	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	604066.4	393874.0	22705.4	29722.33
19500	15152402	48375	-417667	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	603323.9	394198.2	23121.4	29484.67
21000	15130895.6	48449	-436525	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	602293.6	394293.8	24050.3	29195.33
22500	15179662.2	52435	-282458.3	1	1	0	1	0	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	602118.2	381128.0	37397.0	38000.00
24000	15313514.4	52744	-144415.5	1	1	0	1	0	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	602255.3	377392.2	40993.3	37437.67

Results of Chapter 5.5: Emission Offset Policy – varying emission cap per period

										Production Facility 1		Production Facility 2		Production Facility 3		Production Facility 4		Warehouse 1		Warehouse 2		Warehouse 3		Warehouse 4		Average use of logistic modes			
Imposed Emission Cap	Total Cost	Total Emission	Total Emission Cost	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Supplier 5	Supplier 6	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Mode 1	Mode 2	Mode 3	Average stock
9000	17161312.7	47925	1569380	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	604681.9	394537.9	21415.1	30087.00
10500	16823812.7	47925	1231880	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	604681.9	394537.9	21415.1	30087.00
12000	16486312.7	47925	894377	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	604681.9	394537.9	21415.1	30087.00
13500	16150841.3	47956	559220	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	599834.4	398624.1	22181.2	28759.00
15000	15883575.2	48161	269490	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	577554.5	417876.2	25211.6	24487.33
16500	15709449.5	48615	117950	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	578821.9	415599.0	26213.4	24365.27
18000	15586654.8	48664	0	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	586179.0	409026.1	25443.6	26303.13
19500	15563592.8	48722	0	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	602966.4	391554.9	26117.9	29040.00
21000	15519106.6	52692	17280	1	1	0	1	0	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	577351.3	405747.5	37545.1	32167.87
22500	15459072.8	52967	0	1	1	0	1	0	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	594810.3	382679.7	43154.8	35440.33
24000	15457057.9	52934	0	1	1	0	1	0	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	599111.2	378848.7	42685.4	36650.33

Results of Chapter 5.5: Emission Tax Policy – varying emission tax rate

										Production Facility 1		Production Facility 2		Production Facility 3		Production Facility 4		Warehouse 1		Warehouse 2		Warehouse 3		Warehouse 4		Average use of logistic modes			
Emission Tax Rate	Total Cost	Total Emission	Total Emission Cost	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Supplier 5	Supplier 6	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Mode 1	Mode 2	Mode 3	Average stock
0	15457057.9	52934	0	1	1	0	1	0	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	599111.2	378848.7	42685.4	36650.33
15	16248524.3	52518	787770	1	1	0	1	0	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	601421.0	381189.0	38033.6	37824.33
30	17020895.6	48449	1453470	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	602293.6	394293.8	24050.3	29195.33
45	17746818.1	48059	2162710	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	603812.1	393859.3	22973.2	29579.33
60	18467106.6	47979	2878720	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	604151.4	394397.1	22099.5	29840.67
75	19186312.7	47925	3594350	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	604681.9	394537.8	21415.1	30087.00
90	19904460.0	47829	4304600	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	605513.6	394647.0	20475.4	30395.00
105	20621058.3	47650	5003300	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	607160.9	393806.8	19670.5	30754.67
120	21319343.9	46195	5543600	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	604178.3	403487.3	12986.6	26538.13
135	22012142.5	46160	6231600	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	605125.3	402556.9	12951.4	26890.47
150	22704253.9	46121	6918300	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	606721.3	401231.9	12677.7	27021.80

Results of Chapter 5.5: Emission Cap and Trade Policy – varying emission credit price

										Production Facility 1		Production Facility 2		Production Facility 3		Production Facility 4		Warehouse 1		Warehouse 2		Warehouse 3		Warehouse 4		Average use of logistic modes			
Emission Credit Price	Total Cost	Total Emission	Total Emission Cost	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Supplier 5	Supplier 6	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Mode 1	Mode 2	Mode 3	Average stock
0	15457057.9	52934	0	1	1	0	1	0	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	599111.2	378848.7	42685.4	36650.33
15	15573524.3	52518	112766	1	1	0	1	0	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	601421.0	381189.0	38033.6	37824.33
30	15670895.6	48449	103471	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	602293.6	394293.8	24050.3	29195.33
45	15721818.1	48059	137707	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	603812.1	393859.3	22973.2	29579.33
60	15767106.6	47979	178739	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	604151.4	394397.1	22099.5	29840.67
75	15811312.7	47925	219377	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	604681.9	394537.9	21415.1	30087.00
90	15854460.0	47829	254603	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	605513.6	394647.1	20475.4	30395.00
105	15896058.3	47650	278312	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	607160.9	393806.8	19670.5	30754.67
120	15919343.9	46195	143488	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	604178.3	403487.3	12986.6	26538.13
135	15937142.5	46160	156645	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	605125.3	402556.9	12951.4	26890.47
150	15954253.9	46121	168199	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	606721.3	401231.9	12677.7	27021.80

Results of Chapter 5.5: Emission Offset Policy – varying emission allowance price

										Production Facility 1		Production Facility 2		Production Facility 3		Production Facility 4		Warehouse 1		Warehouse 2		Warehouse 3		Warehouse 4		Average use of logistic modes			
Emission Allowance Price	Total Cost	Total Emission	Total Emission Cost	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Supplier 5	Supplier 6	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Mode 1	Mode 2	Mode 3	Average stock
0	15457057.9	52934	0	1	1	0	1	0	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	599111.2	378848.7	42685.4	36650.33
15	15604134.0	52633	141872	1	1	0	1	0	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	596673.3	384343.5	39624.6	36345.67
30	15710809.1	48576	132282	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	590050.3	404464.3	26134.8	26310.33
45	15773891.5	48238	170935	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	585656.0	409462.2	25528.4	25474.00
60	15829488.7	48155	217250	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	578955.8	416461.8	25219.2	24672.00
75	15883575.2	48161	269490	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	577554.5	417876.2	25211.6	24487.33
90	15936486.9	48167	312280	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	574575.9	420989.5	25069.7	23870.07
105	15975920.7	47034.0	213570	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	569890.5	430378.8	20366.9	20215.63
120	16006026.8	46955.0	234610	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	567012.6	434033.8	19600.1	19821.73
135	16035222.3	46934.0	261030	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	565837.6	435551.8	19244.6	19679.60
150	16063849.0	46888	283230	1	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	564307.2	437726.5	18611.4	19414.83

Appendix C: Results of Chapter 6

Results of Chapter 6: without Emission Policy – varying share of OTDLT-sensitive Customers

										Production Facility 1		Production Facility 2		Production Facility 3		Warehouse 1		Warehouse 2		Warehouse 3		Average use of logistic modes			
Share of OTDLT-sensitive Customers	Total Profit	Total Cost	Total Revenue	Total Emission	Fulfilled Demand	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Mode 1	Mode 2	Mode 3	Average stock
100	33108168.3	4356831.7	37465000	16390	202511	1	0	1	0	0	0	0	1	0	0	0	0	0	0	0	1	607532.0	0.0	0.0	0.00
90	29530038.5	4188961.5	33719000	14973	182266	1	0	1	0	0	0	0	1	0	0	0	0	0	0	0	1	546798.7	0.0	0.0	0.00
80	26419666.5	3553233.5	29972900	14373	162014	0	1	1	0	0	0	0	1	0	0	0	0	0	0	0	1	486041.3	0.0	0.0	0.00
70	23180014.9	7204985.1	30385000	29242	164240	1	0	1	0	0	0	0	1	0	0	1	0	1	0	1	0	428541.7	25864.1	38314.0	25417.20
60	21349143.0	8401157.0	29750300	36062	160816	1	1	1	0	0	0	0	1	0	0	1	0	1	0	1	0	394095.5	34678.0	53673.0	34636.67
50	19762185.2	8249314.8	28011500	35346	151415	1	0	1	0	0	0	0	1	0	0	1	0	1	0	1	0	365592.5	34087.0	54566.0	34664.33
40	18385013.6	8868986.4	27254000	38743	147315	1	1	1	0	0	0	0	1	0	0	1	0	1	0	1	0	342862.7	37517.0	61566.0	38566.33
30	17055556.9	8629143.1	25684700	37620	138836	1	0	1	0	0	0	0	1	0	0	1	0	1	0	1	0	317933.7	37343.0	61231.0	38374.67
20	16254172.7	13127927.3	29382100	55918	158823	1	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	268751.0	118704.7	89010.6	38210.33
10	16045286.0	13055214.0	29100500	55449	157297	1	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	267067.7	116389.7	88437.2	38069.33
0	15866595.6	12978704.4	28845300	54931	155916	1	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	265766.4	114395.7	87589.2	37946.67

Results of Chapter 6: Emission Cap Policy – varying share of OTDLT-sensitive Customers

										Production Facility 1		Production Facility 2		Production Facility 3		Warehouse 1		Warehouse 2		Warehouse 3		Average use of logistic modes			
Share of OTDLT-sensitive Customers	Total Profit	Total Cost	Total Revenue	Total Emission	Fulfilled Demand	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Mode 1	Mode 2	Mode 3	Average stock
100	33108168.3	4356831.7	37465000	16390	202511	1	0	1	0	0	0	0	1	0	0	0	0	0	0	0	1	607532.0	0.0	0.0	0.00
90	29530038.5	4188961.5	33719000	14973	182266	1	0	1	0	0	0	0	1	0	0	0	0	0	0	0	1	546798.7	0.0	0.0	0.00
80	26419666.5	3553233.5	29972900	14373	162014	0	1	1	0	0	0	0	1	0	0	0	0	0	0	0	1	486041.3	0.0	0.0	0.00
70	23180014.9	7204985.1	30385000	29242	164240	1	0	1	0	0	0	0	1	0	0	1	0	1	0	1	0	428541.7	25864.1	38314.0	25417.20
60	21226660.6	7546639.4	28773300	30866	155531	1	0	1	0	0	0	0	1	0	0	1	0	1	0	1	0	393619.0	28567.0	44408.0	28736.00
50	19429958.6	7659141.4	27089100	31200	146426	1	0	1	0	0	0	0	1	0	0	1	0	1	0	1	0	361405.0	32332.0	45541.0	30799.33
40	17824337.8	7259262.2	25083600	31322	135584	0	1	1	0	0	0	0	1	0	0	1	0	1	0	1	0	326844.5	32448.0	47458.0	31551.20
30	16302527.3	7325872.7	23628400	31285	127723	0	1	1	0	0	0	0	1	0	0	1	0	1	0	1	0	299966.0	36141.0	47062.0	33089.83
20	14971629.4	7390970.6	22362600	31464	120878	0	1	1	0	0	0	0	1	0	0	1	0	1	0	1	0	275493.2	40901.0	46240.0	35023.00
10	14352631.5	10261068.5	24613700	36512	133044	1	1	1	1	0	0	0	1	1	0	1	0	1	0	1	0	254963.7	86276.5	57891.2	35436.67
0	14176075.1	10246124.9	24422200	36484	132009	1	1	1	1	0	0	0	1	1	0	1	0	1	0	1	0	252813.4	85148.0	58066.0	35290.00

Results of Chapter 6: Emission Tax Policy – varying share of OTDLT-sensitive Customers

											Production Facility 1		Production Facility 2		Production Facility 3		Warehouse 1		Warehouse 2		Warehouse 3		Average use of logistic modes			
Share of OTDLT-sensitive Custom-ers	Total Profit	Total Cost	Total Revenue	Total Emission	Total Emission Cost	Fulfilled Demand	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Mode 1	Mode 2	Mode 3	Average stock
100	31878942.4	5586057.6	37465000	16390	1229220	202511	1	0	1	0	0	0	0	1	0	0	0	0	0	0	0	1	607532.0	0.0	0.0	0.00
90	28407090.4	5311909.6	33719000	14973	1122950	182266	1	0	1	0	0	0	0	1	0	0	0	0	0	0	0	1	546798.7	0.0	0.0	0.00
80	25341721.3	4631178.7	29972900	14373	1077940	162014	0	1	1	0	0	0	0	1	0	0	0	0	0	0	0	1	486041.3	0.0	0.0	0.00
70	22057590.8	4169109.2	26226700	12696	952220	141764	0	1	1	0	0	0	0	1	0	0	0	0	0	0	1	0	425291.3	0.0	0.0	0.00
60	19082713.5	7404986.5	26487700	21939	1645390	143177	0	1	1	0	0	0	0	1	0	0	1	0	1	0	1	0	382024.3	23357.9	24148.4	19625.83
50	17165670.8	10515529.2	27681200	33531	2514850	149630	1	0	1	0	0	0	0	1	0	0	1	0	1	0	1	0	362469.4	35585.0	50838.0	34069.67
40	15602500.2	10778799.8	26381300	34357	2576790	142602	1	0	1	0	0	0	0	1	0	0	1	0	1	0	1	0	334286.4	39891.0	53630.0	36995.67
30	14254911.5	11248788.5	25503700	36687	2751520	137854	1	0	1	0	0	0	0	1	0	0	1	0	1	0	1	0	316120.9	38090.0	59354.0	38047.33
20	13097048.7	10196451.3	23293500	33840	2537920	125910	0	1	1	0	0	0	0	1	0	0	1	0	1	0	1	0	284774.8	39101.0	53853.0	36700.33
10	12255908.6	12389091.4	24645000	40423	3031710	133212	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	269967.1	68114.2	61557.5	36930.33
0	12122930.5	12483069.5	24606000	40863	3064620	133003	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	268891.9	67815.9	62302.7	36963.33

Results of Chapter 6: Emission Cap and Trade Policy – varying share of OTDLT-sensitive Customers

											Production Facility 1		Production Facility 2		Production Facility 3		Warehouse 1		Warehouse 2		Warehouse 3		Average use of logistic modes			
Share of OTDLT-sensitive Custom-ers	Total Profit	Total Cost	Total Revenue	Total Emission	Total Emission Cost	Fulfilled Demand	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Mode 1	Mode 2	Mode 3	Average stock
100	34016442.4	3448557.6	37465000	16390	-908280	202511	1	0	1	0	0	0	0	1	0	0	0	0	0	0	0	1	607532.0	0.0	0.0	0.00
90	30544590.4	3174409.6	33719000	14973	-1014550	182266	1	0	1	0	0	0	0	1	0	0	0	0	0	0	0	1	546798.7	0.0	0.0	0.00
80	27479221.3	2493678.7	29972900	14373	-1059560	162014	0	1	1	0	0	0	0	1	0	0	0	0	0	0	0	1	486041.3	0.0	0.0	0.00
70	24195090.8	2031609.2	26226700	12696	-1185280	141764	0	1	1	0	0	0	0	1	0	0	0	0	0	0	1	0	425291.3	0.0	0.0	0.00
60	21220213.5	5267486.5	26487700	21939	-492110	143177	0	1	1	0	0	0	0	1	0	0	1	0	1	0	1	0	382024.3	23357.9	24148.4	19625.83
50	19303170.8	8378029.2	27681200	33531	377324	149630	1	0	1	0	0	0	0	1	0	0	1	0	1	0	1	0	362469.4	35585.0	50838.0	34069.67
40	17740000.2	8641299.8	26381300	34357	439304.6	142602	1	0	1	0	0	0	0	1	0	0	1	0	1	0	1	0	334286.4	39891.0	53630.0	36995.67
30	16392411.5	9111288.5	25503700	36687	613983	137854	1	0	1	0	0	0	0	1	0	0	1	0	1	0	1	0	316120.9	38090.0	59354.0	38047.33
20	15234548.7	8058951.3	23293500	33840	400466	125910	0	1	1	0	0	0	0	1	0	0	1	0	1	0	1	0	284774.8	39101.0	53853.0	36700.33
10	14393408.6	10251591.4	24645000	40423	894195	133212	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	269967.1	68114.2	61557.5	36930.33
0	14260437.1	10345562.9	24606000	40863	927164	133003	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	268891.9	67815.9	62302.7	36963.33

Results of Chapter 6: Emission Offset Policy – varying share of OTDLT-sensitive Customers

Share of OTDLT-sensitive Custom-ers	Total Profit	Total Cost	Total Revenue	Total Emission	Total Emission Cost	Fulfilled Demand	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Production Facility 1 Cap-Opt. 1	Production Facility 1 Cap-Opt. 2	Production Facility 2 Cap-Opt. 1	Production Facility 2 Cap-Opt. 2	Production Facility 3 Cap-Opt. 1	Production Facility 3 Cap-Opt. 2	Warehouse 1 Cap-Opt. 1	Warehouse 1 Cap-Opt. 2	Warehouse 2 Cap-Opt. 1	Warehouse 2 Cap-Opt. 2	Warehouse 3 Cap-Opt. 1	Warehouse 3 Cap-Opt. 2	Average use of logistic modes: Mode 1	Mode 2	Mode 3	Average stock
100	33108168.3	4356831.7	37465000	16390	0	202511	1	0	1	0	0	0	0	1	0	0	0	0	0	0	0	1	607532.0	0.0	0.0	0.00
90	29530038.5	4188961.5	33719000	14973	0	182266	1	0	1	0	0	0	0	1	0	0	0	0	0	0	0	1	546798.7	0.0	0.0	0.00
80	26419666.5	3553233.5	29972900	14373	0	162014	0	1	1	0	0	0	0	1	0	0	0	0	0	0	0	1	486041.3	0.0	0.0	0.00
70	23179532.0	4883768.0	28063300	22414	0	151691	0	1	1	0	0	0	0	1	0	0	1	0	0	0	1	0	421341.7	12239.4	21492.9	13120.83
60	21018414.7	7644185.3	28662600	30199	196380	154932	1	0	1	0	0	0	0	1	0	0	1	0	1	0	1	0	392582.0	29340.0	42874.0	28536.43
50	19264280.8	8482419.2	27746700	33986	448674	149985	1	0	1	0	0	0	0	1	0	0	1	0	1	0	1	0	363064.7	35340.0	51549.0	34187.67
40	17734225.6	8648074.4	26382300	34381	446292	142607	1	0	1	0	0	0	0	1	0	0	1	0	1	0	1	0	334285.9	39884.4	53653.4	36995.67
30	16373959.2	9129740.8	25503700	36726	633877	137854	1	0	1	0	0	0	0	1	0	0	1	0	1	0	1	0	316120.9	38090.0	59354.0	38047.33
20	15165328.2	8128771.8	23294100	33863	470814	125913	0	1	1	0	0	0	0	1	0	0	1	0	1	0	1	0	284774.0	39096.5	53869.5	36700.33
10	14393408.6	10251591.4	24645000	40423	894195	133212	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	269967.1	68114.2	61557.5	36930.33
0	14260437.1	10345562.9	24606000	40863	927164	133003	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	268891.9	67815.9	62302.7	36963.33

Results of Chapter 6: without Emission Policy – varying product price

										Production Facility 1		Production Facility 2		Production Facility 3		Warehouse 1		Warehouse 2		Warehouse 3		Average use of logistic modes			
Product Price	Total Profit	Total Cost	Total Revenue	Total Emission	Fulfilled Demand	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Mode 1	Mode 2	Mode 3	Average stock
80	1809228.4	5258511.6	7067740	23484	88347	0	1	1	0	0	0	1	0	0	0	1	0	0	0	1	0	192288.9	35494.8	37257.1	26989.00
95	3494711.1	7513288.9	11008000	33302	115873	0	1	1	0	0	0	0	1	0	0	1	0	1	0	1	0	251869.7	41331.3	54417.7	36008.33
110	5309969.1	8490830.9	13800800	38858	125462	0	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	272569.6	43688.3	60129.0	37087.00
125	7219917.2	9447582.8	16667500	41436	133340	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	272053.8	63983.8	63979.7	36982.67
140	9231857.4	9553142.6	18785000	42118	134179	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	273648.6	63740.8	65146.7	37262.33
155	11262492.5	11430407.5	22692900	49774	146405	1	1	1	0	1	0	1	0	1	0	1	0	1	0	1	0	283552.1	84396.8	71268.0	37946.33
170	13529089.7	12941810.3	26470900	54660	155711	1	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	265953.1	114064.7	87117.8	37946.33
185	15866595.6	12978704.4	28845300	54931	155916	1	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	265766.4	114395.7	87589.2	37946.67
200	18210344.3	13059555.7	31269900	55788	156348	1	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	265554.7	115128.5	88363.2	37946.33
215	20557692.0	13101208.0	33658900	56072	156550	1	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	265504.7	117704.2	86442.5	37946.33
230	22905943.6	13100656.4	36006600	56072	156550	1	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	265504.7	117704.2	86442.5	37946.33

Results of Chapter 6: Emission Cap Policy – varying product price

										Production Facility 1		Production Facility 2		Production Facility 3		Warehouse 1		Warehouse 2		Warehouse 3		Average use of logistic modes			
Product Price	Total Profit	Total Cost	Total Revenue	Total Emission	Fulfilled Demand	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Mode 1	Mode 2	Mode 3	Average stock
80	1809228.4	5258511.6	7067740	23484	88347	0	1	1	0	0	0	1	0	0	0	1	0	0	0	1	0	192288.9	35494.8	37257.1	26989.00
95	3330021.4	7002878.6	10332900	28871	108768	0	1	1	0	0	0	0	1	0	0	1	0	1	0	1	0	238435.7	43514.3	44352.7	33640.33
110	4968667.6	7174142.4	12142810	29646	110389	0	1	1	0	0	0	0	1	0	0	1	0	1	0	1	0	241530.7	43032.3	46603.7	34180.33
125	6689902.7	8657697.3	15347600	33966	122780	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	249949.7	69907.5	48483.3	33543.00
140	8539194.4	8820305.6	17359500	34503	123997	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	251573.0	70827.2	49589.8	33897.33
155	10401274.9	8853225.1	19254500	35035	124223	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	252011.9	70929.2	49726.5	33902.00
170	12265799.2	8898100.8	21163900	35594	124494	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	252093.0	71530.8	49857.7	33917.67
185	14176075.1	10246124.9	24422200	36484	132009	1	1	1	1	0	0	0	1	1	0	1	0	1	0	1	0	252813.4	85148.0	58066.0	35290.00
200	16157074.8	10260525.2	26417600	36484	132089	1	1	1	1	0	0	0	1	1	0	1	0	1	0	1	0	252014.4	86462.2	57791.4	35290.00
215	18138580.7	10268119.3	28406700	36484	132124	1	1	1	1	0	0	0	1	1	0	1	0	1	0	1	0	250867.7	87860.2	57645.4	35290.00
230	20122375.3	10361624.7	30484000	36484	132539	1	1	1	1	0	0	0	1	1	0	1	0	1	0	1	0	249852.7	89617.0	58148.3	35290.00

Results of Chapter 6: Emission Tax Policy – varying product price

											Production Facility 1		Production Facility 2		Production Facility 3		Warehouse 1		Warehouse 2		Warehouse 3		Average use of logistic modes			
Product Price	Total Profit	Total Cost	Total Revenue	Total Emission	Total Emission Cost	Fulfilled Demand	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Mode 1	Mode 2	Mode 3	Average stock
80	167439.6	6352700.4	6520140	19538	1465360	81501	0	1	1	0	0	0	1	0	0	0	1	0	0	0	1	0	179298.0	36963.8	28242.2	24728.00
95	1403132.6	6638757.4	8041890	21216	1591170	84652	0	1	1	0	0	0	1	0	0	0	1	0	0	0	1	0	185316.1	36215.8	32423.2	25778.33
110	2862851.2	9208358.8	12071210	29065	2179880	109738	0	1	1	0	0	0	0	1	0	0	1	0	1	0	1	0	240345.7	43214.3	45654.7	33963.33
125	4523201.7	9407318.3	13930520	29871	2240330	111444	0	1	1	0	0	0	0	1	0	0	1	0	1	0	1	0	243654.4	42940.3	47736.7	34532.00
140	6217779.5	10072220.5	16290000	33323	2499240	116357	0	1	1	0	0	0	0	1	0	0	1	0	1	0	1	0	252793.6	41514.3	54765.7	36170.33
155	8134675.3	12368624.7	20503300	40313	3023420	132279	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	267733.9	67719.1	61386.2	36776.00
170	10127889.0	12482611.0	22610500	40863	3064620	133003	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	268891.9	67815.9	62302.7	36963.33
185	12122930.5	12483069.5	24606000	40863	3064620	133003	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	268891.9	67815.9	62302.7	36963.33
200	14221811.9	15983088.1	30204900	49274	3695640	151024	1	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	272635.7	106356.5	74079.2	37946.33
215	16501948.2	16378451.8	32880400	51125	3834340	152929	1	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	267954.4	113574.7	77261.2	37946.33
230	18805689.4	16682810.6	35488500	52560	3942040	154298	1	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	266627.4	115491.2	80774.3	37946.33

Results of Chapter 6: Emission Cap and Trade Policy – varying product price

											Production Facility 1		Production Facility 2		Production Facility 3		Warehouse 1		Warehouse 2		Warehouse 3		Average use of logistic modes			
Product Price	Total Profit	Total Cost	Total Revenue	Total Emission	Total Emission Cost	Fulfilled Demand	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Mode 1	Mode 2	Mode 3	Average stock
80	2304939.6	4215200.4	6520140	19538	-672143	81501	0	1	1	0	0	0	1	0	0	0	1	0	0	0	1	0	179298.0	36963.8	28242.2	24728.00
95	3540632.6	4501257.4	8041890	21216	-546329	84652	0	1	1	0	0	0	1	0	0	0	1	0	0	0	1	0	185316.1	36215.8	32423.2	25778.33
110	5000351.2	7070858.8	12071210	29065	42384	109738	0	1	1	0	0	0	0	1	0	0	1	0	1	0	1	0	240345.7	43214.3	45654.7	33963.33
125	6660700.9	7269819.1	13930520	29871	102794	111444	0	1	1	0	0	0	0	1	0	0	1	0	1	0	1	0	243654.4	42940.3	47736.7	34532.00
140	8355279.8	7934720.2	16290000	33323	361694	116357	0	1	1	0	0	0	0	1	0	0	1	0	1	0	1	0	252793.6	41514.3	54765.7	36170.00
155	10272174.8	10231125.2	20503300	40313	885942	132279	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	267733.9	67719.1	61386.2	36776.00
170	12265389.0	10345111.0	22610500	40863	927164	133003	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	268891.9	67815.9	62302.7	36963.33
185	14260437.1	10345562.9	24606000	40863	927164	133003	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	268891.9	67815.9	62302.7	36963.33
200	16359311.9	13845588.1	30204900	49274	1558080	151024	1	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	272635.7	106356.5	74079.2	37946.33
215	18639448.2	14240951.8	32880400	51125	1696840	152929	1	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	267954.4	113574.7	77261.2	37946.33
230	20943174.3	14544325.7	35487500	52560	1804460	154298	1	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	266625.7	115491.2	80773.3	37946.33

Results of Chapter 6: Emission Offset Policy – varying product price

											Production Facility 1		Production Facility 2		Production Facility 3		Warehouse 1		Warehouse 2		Warehouse 3		Average use of logistic modes			
Product Price	Total Profit	Total Cost	Total Revenue	Total Emission	Total Emission Cost	Fulfilled Demand	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Mode 1	Mode 2	Mode 3	Average stock
80	1751123.0	5180917.0	6932040	22489	14269	86651	0	1	1	0	0	0	1	0	0	0	1	0	0	0	1	0	189151.7	35814.8	34987.2	26444.67
95	3123711.5	7465688.5	10589400	30534	311810	111467	0	1	1	0	0	0	0	1	0	0	1	0	1	0	1	0	243506.7	42642.3	48253.7	34540.00
110	4814629.3	7660880.7	12475510	31617	324650	113414	0	1	1	0	0	0	0	1	0	0	1	0	1	0	1	0	247225.0	42201.3	50816.7	35189.00
125	6544056.2	7974663.8	14518720	33253	423280	116150	0	1	1	0	0	0	0	1	0	0	1	0	1	0	1	0	252404.4	41581.3	54464.7	36100.67
140	8335097.9	8627602.1	16962700	35394	517050	121163	0	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	264513.5	45232.3	53743.0	35653.33
155	10272175.3	10231124.7	20503300	40313	885944	132279	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	267733.9	67719.1	61386.2	36776.00
170	12265389.0	10345111.0	22610500	40863	927164	133003	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	268891.9	67815.9	62302.7	36963.33
185	14260437.1	10345562.9	24606000	40863	927164	133003	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	268891.9	67815.9	62302.7	36963.33
200	16359311.9	13845588.1	30204900	49274	1558080	151024	1	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	272635.7	106356.5	74079.2	37946.33
215	18639448.2	14240951.8	32880400	51125	1696840	152929	1	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	267954.4	113574.7	77261.2	37946.33
230	20943189.4	14545310.6	35488500	52560	1804470	154298	1	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	266627.4	115491.2	80774.3	37946.33

Results of Chapter 6: Emission Cap Policy – varying emission cap per period

										Production Facility 1		Production Facility 2		Production Facility 3		Warehouse 1		Warehouse 2		Warehouse 3		Average use of logistic modes			
Imposed Emission Cap	Total Profit	Total Cost	Total Revenue	Total Emission	Fulfilled Demand	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Mode 1	Mode 2	Mode 3	Average stock
5000	7607069.5	5843530.5	13450600	14684	72706	0	1	1	1	0	0	1	0	0	0	0	0	1	0	1	0	146841.9	51154.2	20124.1	20443.63
6500	9409830.1	6630469.9	16040300	19424	86705	0	1	1	1	0	0	1	0	0	0	1	0	1	0	1	0	195466.1	37683.8	26966.2	24836.60
8000	10946697.7	7738302.3	18685000	23206	101000	0	1	1	1	0	0	1	0	1	0	1	0	1	0	1	0	213468.0	61690.1	27843.1	27434.00
9500	12240944.1	8156755.9	20397700	27053	110258	0	1	1	1	0	0	1	0	1	0	1	0	1	0	1	0	224781.8	73685.5	32305.3	30124.57
11000	13311954.9	9712245.1	23024200	33000	124453	1	1	1	1	0	0	0	1	1	0	1	0	1	0	1	0	243166.7	85752.2	44440.5	33246.00
12500	14176075.1	10246124.9	24422200	36484	132009	1	1	1	1	0	0	0	1	1	0	1	0	1	0	1	0	252813.4	85148.0	58066.0	35290.00
14000	14801251.9	9397748.1	24199000	39417	130803	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	262040.4	71799.2	58569.8	35704.33
15500	15200436.1	9623163.9	24823600	41669	134179	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	265868.9	74055.2	62614.2	36698.33
17000	15396182.1	11300517.9	26696700	45484	144304	1	1	1	1	0	0	0	1	1	0	1	0	1	0	1	0	259745.8	96534.0	76633.8	37920.00
18500	15605251.3	11308148.7	26913400	48835	145474	1	1	1	0	1	0	1	0	1	0	1	0	1	0	1	0	283461.2	82969.5	69992.3	37946.33
20000	15696498.9	12335101.1	28031600	50137	151518	1	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	274023.1	105220.0	75311.3	37946.33

Results of Chapter 6: Emission Cap and Trade Policy – varying emission cap per period

											Production Facility 1		Production Facility 2		Production Facility 3		Warehouse 1		Warehouse 2		Warehouse 3		Average use of logistic modes			
Imposed Emission Cap	Total Profit	Total Cost	Total Revenue	Total Emission	Total Emission Cost	Fulfilled Demand	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Mode 1	Mode 2	Mode 3	Average stock
5000	13247937.1	11358062.9	24606000	40863	1939660	133003	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	268891.9	67815.9	62302.7	36963.33
6500	13585437.1	11020562.9	24606000	40863	1602160	133003	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	268891.9	67815.9	62302.7	36963.33
8000	13922937.1	10683062.9	24606000	40863	1264660	133003	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	268891.9	67815.9	62302.7	36963.33
9500	14260437.1	10345562.9	24606000	40863	927164	133003	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	268891.9	67815.9	62302.7	36963.33
11000	14597937.1	10008062.9	24606000	40863	589664	133003	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	268891.9	67815.9	62302.7	36963.33
12500	14935437.1	9670562.9	24606000	40863	252163	133003	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	268891.9	67815.9	62302.7	36963.33
14000	15272937.1	9333062.9	24606000	40863	-85337	133003	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	268891.9	67815.9	62302.7	36963.33
15500	15610437.1	8995562.9	24606000	40863	-422841	133003	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	268891.9	67815.9	62302.7	36963.33
17000	15947937.1	8658062.9	24606000	40863	-760341	133003	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	268891.9	67815.9	62302.7	36963.33
18500	16285437.1	8320562.9	24606000	40863	-1097840	133003	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	268891.9	67815.9	62302.7	36963.33
20000	16622937.1	7983062.9	24606000	40863	-1435340	133003	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	268891.9	67815.9	62302.7	36963.33

Results of Chapter 6: Emission Cap and Trade Policy (dep. emission credit price) – varying emission cap per period

											Production Facility 1		Production Facility 2		Production Facility 3		Warehouse 1		Warehouse 2		Warehouse 3		Average use of logistic modes			
Imposed Emission Cap	Total Profit	Total Cost	Total Revenue	Total Emission	Total Emission Cost	Fulfilled Demand	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Mode 1	Mode 2	Mode 3	Average stock
5000	12550306.1	12055193.9	24605500	40814	2633020	133003	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	268535.2	68436.9	62038.7	36905.00
6500	13201139.2	11403960.8	24605100	40819	1982640	133003	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	268958.8	67974.9	62074.8	36911.00
8000	13771176.7	10834823.3	24606000	40863	1416430	133003	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	268891.9	67815.9	62302.7	36963.33
9500	14260437.1	10345562.9	24606000	40863	927164	133003	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	268891.9	67815.9	62302.7	36963.33
11000	14674585.2	10149314.8	24823900	41865	585134	134179	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	271123.2	67456.4	63958.2	37355.33
12500	15011004.8	9812395.2	24823400	41887	250053	134179	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	271128.4	67325.6	64083.7	37381.33
14000	15313255.7	12913744.3	28227000	51002	432080	152574	1	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	271804.4	108662.3	77255.3	37946.33
15500	15574822.1	12874377.9	28449200	52271	225080	153775	1	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	268758.1	110627.1	81940.5	37945.00
17000	15768091.9	12862408.1	28630500	53455	73649	154755	1	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	267682.1	110813.7	85770.0	37946.33
18500	15886709.6	12794390.4	28681100	53817	-35336.2	155029	1	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	266158.4	112996.8	85930.9	37946.33
20000	15928832.2	12878467.8	28807300	54660	-64077	155711	1	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	265953.1	114064.7	87117.8	37946.33

Results of Chapter 6: Emission Offset Policy – varying emission cap per period

											Production Facility 1		Production Facility 2		Production Facility 3		Warehouse 1		Warehouse 2		Warehouse 3		Average use of logistic modes			
Imposed Emission Cap	Total Profit	Total Cost	Total Revenue	Total Emission	Total Emission Cost	Fulfilled Demand	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Mode 1	Mode 2	Mode 3	Average stock
5000	13247937.1	11358062.9	24606000	40863	1939660	133003	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	268891.9	67815.9	62302.7	36963.33
6500	13585435.0	11020565.0	24606000	40863	1602160	133003	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	268891.9	67815.9	62302.7	36963.33
8000	13922937.1	10683062.9	24606000	40863	1264660	133003	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	268891.9	67815.9	62302.7	36963.33
9500	14260437.1	10345562.9	24606000	40863	927164	133003	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	268891.9	67815.9	62302.7	36963.33
11000	14596820.6	10123179.4	24720000	41363	627220	133620	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	270063.6	67636.9	63159.7	37168.67
12500	14851084.6	9972915.4	24824000	41865	408613	134179	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	271117.9	67463.9	63956.7	37355.00
14000	15075665.8	9748234.2	24823900	41886	185160	134179	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	270606.7	67986.6	63942.5	37213.00
15500	15209956.4	9615143.6	24825100	41898	31958	134186	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	268991.6	69780.4	63787.2	36923.00
17000	15412025.9	12201874.1	27613900	47808	143436	149260	1	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	276765.4	98767.3	72250.3	37946.33
18500	15605251.3	11308148.7	26913400	48835	0	145474	1	1	1	0	1	0	1	0	1	0	1	0	1	0	1	0	283461.2	82969.5	69992.3	37946.33
20000	15696498.9	12335101.1	28031600	50137	0	151518	1	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	274023.1	105220.0	75311.3	37946.33

Results of Chapter 6: Emission Tax Policy – varying emission tax rate

											Production Facility 1		Production Facility 2		Production Facility 3		Warehouse 1		Warehouse 2		Warehouse 3		Average use of logistic modes			
Emission Tax Rate	Total Profit	Total Cost	Total Revenue	Total Emission	Total Emission Cost	Fulfilled Demand	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Mode 1	Mode 2	Mode 3	Average stock
0	15866600.0	12978700.0	28845300	54931	0	155916	1	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	265766.4	114395.7	87589.2	37946.33
15	15045247.4	13707752.6	28753000	54297	814460	155417	1	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	266008.1	113602.2	86644.2	37946.33
30	14238091.9	14392408.1	28630500	53455	1603650	154755	1	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	267682.1	110813.7	85770.0	37946.33
45	13450801.1	14867898.9	28318700	51473	2316270	153070	1	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	269340.7	112205.2	77664.3	37946.33
60	12747859.7	12076040.3	24823900	41881	2512910	134179	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	271009.9	67475.8	64051.3	37375.33
75	12122930.5	12483069.5	24606000	40863	3064620	133003	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	268891.9	67815.9	62302.7	36963.33
90	11510142.8	13095357.2	24605500	40836	3675230	133003	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	268855.7	67980.4	62174.2	36934.00
105	10897863.5	13707636.5	24605500	40814	4285500	133003	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	268535.2	68436.9	62038.7	36905.00
120	10291444.6	13945455.4	24236900	39130	4695600	131011	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	265369.2	68327.5	59337.2	36319.00
135	9724278.6	13796221.4	23520500	36178	4884100	127138	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	259102.4	68343.0	53967.8	35250.33
150	9187751.7	13798948.3	22986700	34343	5151300	124253	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	254551.6	67866.2	50339.2	34532.00

Results of Chapter 6: Emission Cap and Trade Policy – varying emission credit price

											Production Facility 1		Production Facility 2		Production Facility 3		Warehouse 1		Warehouse 2		Warehouse 3		Average use of logistic modes			
Emission Credit Price	Total Profit	Total Cost	Total Revenue	Total Emission	Total Emission Cost	Fulfilled Demand	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Mode 1	Mode 2	Mode 3	Average stock
0	15866595.6	12978704.4	28845300	54931	0	155916	1	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	265766.4	114395.7	87589.2	37946.67
15	15472747.4	13280252.6	28753000	54297	386958	155417	1	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	266008.1	113602.2	86644.2	37946.33
30	15093091.9	13537408.1	28630500	53455	748646	154755	1	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	267682.1	110813.7	85770.0	37946.33
45	14733301.1	13585398.9	28318700	51473	1033770	153070	1	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	269340.7	112205.2	77664.3	37946.33
60	14457858.1	10366041.9	24823900	41881	802900	134179	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	271009.9	67475.8	64051.3	37375.33
75	14260437.1	10345562.9	24606000	40863	927164	133003	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	268891.9	67815.9	62302.7	36963.33
90	14075142.8	10530357.2	24605500	40836	1110239	133003	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	268855.7	67980.4	62174.2	36934.00
105	13890363.5	10715136.5	24605500	40814	1292980	133003	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	268535.2	68436.9	62038.7	36905.00
120	13711444.6	10525455.4	24236900	39130	1275531	131011	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	265369.2	68327.5	59337.2	36319.00
135	13571778.6	9948721.4	23520500	36178	1036590	127138	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	259102.4	68343.0	53967.8	35250.33
150	13462752.5	9523947.5	22986700	34343	876360	124253	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	254551.6	67866.2	50339.2	34532.00

Results of Chapter 6: Emission Offset Policy – varying emission allowance price

											Production Facility 1		Production Facility 2		Production Facility 3		Warehouse 1		Warehouse 2		Warehouse 3		Average use of logistic modes			
Emission Allow. Price	Total Profit	Total Cost	Total Revenue	Total Emission	Total Emission Cost	Fulfilled Demand	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Mode 1	Mode 2	Mode 3	Average stock
0	15866600.0	12978700.0	28845300	54931	0	155916	1	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	265766.4	114395.7	87589.2	37946.33
15	15472747.4	13280252.6	28753000	54297	386958	155417	1	1	1	0	1	0	1	0	1	0	1	0	1	0	1	0	266008.1	113602.2	86644.2	37946.33
30	15093091.9	13537408.1	28630500	53455	748646	154755	1	1	1	0	1	0	1	0	1	0	1	0	1	0	1	0	267682.1	110813.7	85770.0	37946.33
45	14733301.1	13585398.9	28318700	51473	1033770	153070	1	1	1	0	1	0	1	0	1	0	1	0	1	0	1	0	269340.7	112205.2	77664.3	37946.33
60	14457859.7	10366040.3	24823900	41881	802900	134179	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	271009.9	67475.8	64051.3	37375.33
75	14260437.1	10345562.9	24606000	40863	927164	133003	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	268891.9	67815.9	62302.7	36963.33
90	14075142.8	10530357.2	24605500	40836	1110239	133003	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	268855.7	67980.4	62174.2	36934.00
105	13890355.4	10715144.6	24605500	40814	1292970	133003	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	268535.2	68436.9	62036.7	36904.67
120	13711444.6	10525455.4	24236900	39130	1275531	131011	1	1	1	0	0	0	1	0	1	0	1	0	1	0	1	0	265369.2	68327.5	59337.2	36319.00
135	13567296.0	10184904.0	23752200	37183	1172260	128393	1	1	1	1	0	0	1	0	1	0	1	0	1	0	1	0	261413.0	67934.0	55830.8	35668.67
150	13440377.4	10176522.6	23616900	36644	1221560	127662	1	1	1	1	0	0	1	0	1	0	1	0	1	0	1	0	260969.7	66949.2	55065.2	35668.67

Appendix D: Results of Chapter 7

Results of Chapter 7: without Emission Policy – varying quoted OTDLT

									Production Facility 1		Production Facility 2		Production Facility 3		Warehouse 1		Warehouse 2		Warehouse 3		Average use of logistic modes			
Quoted OTDLT	Expected Total Cost	Total Cost Variability	Unfulfilled Demand	Total Emission	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Mode 1	Mode 2	Mode 3	Average stock
55	14639304.9	1005548.5	0.00	41540	0	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	237941.4	194219.0	144279.1	6463.26
69	13336463.7	711830.7	4617.07	42945	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	242394.7	176860.9	143332.2	10968.33
83	13024817.4	773365.9	1533.26	41854	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	236210.2	208688.3	126943.1	7944.22
97	12548753.2	944965.4	47.31	39141	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	243979.8	230833.2	101485.3	4096.77
111	12195521.6	871694.8	0.00	36805	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	255631.5	247414.6	73394.4	2494.30
125	11900821.1	837090.5	0.00	35944	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	272239.1	243681.3	60519.0	756.43
139	11531707.4	891979.3	0.00	36925	0	1	1	1	1	0	0	0	1	0	1	0	1	0	0	0	259201.2	236017.2	81217.1	2232.37
153	11298058.0	844511.7	0.00	35398	0	1	1	1	1	0	0	0	1	0	1	0	1	0	0	0	272013.2	239545.9	64880.2	1543.35
167	11103191.3	807922.0	0.00	34005	0	1	1	1	1	0	0	0	1	0	1	0	1	0	0	0	273052.9	254340.4	49046.2	198.01
181	10941733.1	775541.0	0.00	33716	0	1	1	1	1	0	0	0	1	0	1	0	1	0	0	0	300990.4	232518.3	42930.4	1228.70
195	10795868.3	759386.4	0.00	33858	0	1	1	1	1	0	0	0	1	0	1	0	0	0	1	0	280097.9	247065.1	49275.0	60.57

Results of Chapter 7: Emission Cap Policy – varying quoted OTDLT

									Production Facility 1		Production Facility 2		Production Facility 3		Warehouse 1		Warehouse 2		Warehouse 3		Average use of logistic modes			
Quoted OTDLT	Expected Total Cost	Total Cost Variability	Unfulfilled Demand	Total Emission	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Mode 1	Mode 2	Mode 3	Average stock
55	14434019.0	410548.6	9165.86	37531	0	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	234989.2	218556.2	98565.1	9136.17
69	14285334.5	501399.6	4421.91	36373	0	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	251362.4	241872.3	71926.3	6824.65
83	12565270.2	430876.7	9675.77	36941	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	234683.2	217114.1	95615.9	8109.77
97	12501824.7	433944.1	5952.49	36364	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	245294.9	226459.9	86831.1	6767.36
111	12214307.6	556016.3	3620.89	35732	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	265699.0	233988.8	66615.4	4987.25
125	11921592.1	673387.8	2288.90	34364	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	274504.0	248661.8	46407.6	3539.56
139	11698026.9	758748.6	1175.34	33913	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	286331.0	245473.0	41109.0	2148.62
153	11524581.4	801247.7	384.77	33255	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	296291.5	249671.3	29424.2	784.06
167	11105018.3	724947.4	1415.86	33305	0	1	1	1	1	0	0	0	1	0	1	0	1	0	0	0	286026.3	240204.5	46765.3	1719.65
181	10943732.9	778796.3	608.29	32581	0	1	1	1	1	0	0	0	1	0	1	0	1	0	0	0	289705.0	247798.8	37109.2	908.02
195	10815108.6	793694.7	124.27	32841	0	1	1	1	1	0	0	0	1	0	1	0	1	0	0	0	289704.0	251588.3	34773.1	528.90

Results of Chapter 7: Emission Tax Policy – varying quoted OTDLT

										Production Facility 1		Production Facility 2		Production Facility 3		Warehouse 1		Warehouse 2		Warehouse 3		Average use of logistic modes			
Quoted OTDLT	Expected Total Cost	Total Cost Variability	Unfulfilled Demand	Total Emission	Total Emission Cost	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Mode 1	Mode 2	Mode 3	Average stock
55	18251398.1	921255.3	1463.13	40085	3426120	0	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	252461.4	217831.5	101757.4	11566.06
69	17551020.2	1063788.8	222.35	37178	3229200	0	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	261777.0	244786.0	69209.0	9245.53
83	16463680.8	730390.8	3149.50	39554	3352170	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	252157.8	217708.5	97125.5	12398.17
97	15939664.4	883912.7	1539.71	37087	3196140	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	262099.5	234020.8	75701.9	8931.10
111	15489135.1	1018417.6	407.56	35818	3108790	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	274593.7	241319.0	59300.8	6198.66
125	15121775.0	1024149.3	0.00	34594	3014230	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	280947.5	246584.5	48904.4	3846.25
139	14815135.8	968889.3	0.00	33217	2906210	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	297050.5	249453.6	29933.8	3777.73
153	14579803.4	916043.9	0.00	32603	2871770	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	309114.0	241321.2	26000.7	2176.99
167	14180881.6	1009285.3	0.00	33316	2900310	0	1	1	1	1	0	0	0	1	0	1	0	1	0	0	0	288724.3	246495.0	41221.7	2933.27
181	13957977.6	971709.8	0.00	31695	2780630	0	1	1	1	1	0	0	0	1	0	1	0	1	0	0	0	308479.0	242079.5	25879.9	3983.58
195	13772432.9	924689.5	0.00	31560	2766780	0	1	1	1	1	0	0	0	1	0	1	0	1	0	0	0	305661.0	247484.3	23293.6	1382.83

Results of Chapter 7: Emission Cap and Trade Policy – varying quoted OTDLT

										Production Facility 1		Production Facility 2		Production Facility 3		Warehouse 1		Warehouse 2		Warehouse 3		Average use of logistic modes			
Quoted OTDLT	Expected Total Cost	Total Cost Variability	Unfulfilled Demand	Total Emission	Total Emission Cost	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Mode 1	Mode 2	Mode 3	Average stock
55	15491398.1	929806.7	1463.13	39920	671906	0	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	250370.8	217814.5	103864.6	10994.60
69	14791020.2	1072340.1	222.35	36948	462410	0	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	256047.6	251450.2	68275.7	7285.29
83	13703680.8	738942.1	3149.50	38735	550610	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	259015.7	211617.2	96357.8	14085.30
97	13179664.4	892464.1	1539.71	36990	434072	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	266609.5	233167.2	72042.7	9438.25
111	12729135.1	1026969.0	407.56	35146	296946	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	279383.4	243706.5	52126.1	7963.36
125	12361775.0	1032700.7	0.00	34306	243174	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	284968.5	253571.0	37899.1	5756.41
139	12055135.8	977440.7	0.00	33165	161747	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	295087.0	252428.1	28925.4	2793.25
153	11819803.4	924595.3	0.00	32369	102614	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	313339.0	241975.1	21122.5	3128.96
167	11420881.6	1017836.6	0.00	32934	129949	0	1	1	1	1	0	0	0	1	0	1	0	1	0	0	0	296039.0	242703.3	37693.8	4005.77
181	11197977.6	980261.2	0.00	31897	54313	0	1	1	1	1	0	0	0	1	0	1	0	1	0	0	0	297368.5	248881.5	30189.2	2547.32
195	11012432.9	933240.9	0.00	31244	5044	0	1	1	1	1	0	0	0	1	0	1	0	1	0	0	0	315863.0	241331.8	19246.4	2156.01

Results of Chapter 7: Emission Offset Policy – varying quoted OTDLT

										Production Facility 1		Production Facility 2		Production Facility 3		Warehouse 1		Warehouse 2		Warehouse 3		Average use of logistic modes			
Quoted OTDLT	Expected Total Cost	Total Cost Variability	Unfulfilled Demand	Total Emission	Total Emission Cost	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Mode 1	Mode 2	Mode 3	Average stock
55	15491398.1	933556.2	1463.13	39590	670835	0	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	251780.7	204701.6	115567.7	12074.77
69	14791020.2	1072890.0	222.35	37370	502701	0	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	260911.5	247883.5	66974.8	6450.23
83	13703680.8	749243.0	3149.50	39283	608313	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	250586.4	215612.8	100790.5	11973.02
97	13179664.4	897914.5	1539.71	37647	517712	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	262431.1	229320.1	80066.8	7572.04
111	12729135.1	1029295.4	407.56	35561	396008	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	276359.0	239409.1	59449.7	5990.83
125	12361775.0	1034189.6	0.00	34542	324841	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	274830.5	252409.5	49198.1	3111.59
139	12056686.0	979801.7	0.00	33319	256488	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	295744.5	246382.5	34314.1	2942.20
153	11850058.5	914746.9	0.00	32630	219997	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	308571.5	247308.1	20562.4	1433.01
167	11423383.1	1023035.3	0.00	32823	227212	0	1	1	1	1	0	0	0	1	0	1	0	1	0	0	0	288757.9	249379.4	38298.8	3091.43
181	11212760.1	981778.6	0.00	32638	195084	0	1	1	1	1	0	0	0	1	0	1	0	1	0	0	0	290746.0	250117.9	35577.6	1389.73
195	11058231.3	921640.3	0.00	31900	170557	0	1	1	1	1	0	0	0	1	0	1	0	1	0	0	0	309893.0	240149.1	26398.8	1419.96

Results of Chapter 7: without Emission Policy – varying solution robustness parameter

									Production Facility 1		Production Facility 2		Production Facility 3		Warehouse 1		Warehouse 2		Warehouse 3		Average use of logistic modes			
λ	Expected Total Cost	Total Cost Variability	Unfulfilled Demand	Total Emission	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Mode 1	Mode 2	Mode 3	Average stock
0	11561341.2	1260360.1	0.0	37404	0	1	1	1	1	0	0	0	1	0	1	0	1	0	0	0	263540.9	217932.0	94964.7	2133.50
0.2	11561341.2	1260359.3	0.0	37404	0	1	1	1	1	0	0	0	1	0	1	0	1	0	0	0	263540.9	217932.0	94964.7	2133.50
0.4	11561341.2	1260359.3	0.0	37404	0	1	1	1	1	0	0	0	1	0	1	0	1	0	0	0	263540.9	217932.0	94964.7	2133.50
0.6	11561341.2	1260359.3	0.0	37404	0	1	1	1	1	0	0	0	1	0	1	0	1	0	0	0	263540.9	217932.0	94964.7	2133.50
0.8	11670620.6	1102114.0	0.0	35085	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	276190.7	246704.1	53544.7	500.47
1	11900821.1	837090.5	0.0	35893	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	268797.6	245476.7	62165.6	2716.77
1.2	11900821.1	837090.5	0.0	35940	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	269453.5	247747.2	59239.4	2516.21
1.4	11900821.1	837090.5	0.0	36011	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	265651.0	245469.2	65319.3	2731.30
1.6	11900821.1	837090.5	0.0	36063	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	262844.0	250602.4	62988.9	1233.93
1.8	11900821.1	837090.5	0.0	35885	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	269343.4	246190.0	60906.8	2743.24
2	11900821.1	837090.5	0.0	35818	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	272224.6	239061.5	65153.2	2110.35

Results of Chapter 7: Emission Cap Policy – varying solution robustness parameter

									Production Facility 1		Production Facility 2		Production Facility 3		Warehouse 1		Warehouse 2		Warehouse 3		Average use of logistic modes			
λ	Expected Total Cost	Total Cost Variability	Unfulfilled Demand	Total Emission	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Mode 1	Mode 2	Mode 3	Average stock
0	12763959.5	1161886.5	0.00	33960	0	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	305823.5	251107.8	19507.2	752.26
0.2	12763959.5	1161886.0	0.00	33960	0	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	305823.5	251107.8	19507.2	752.26
0.4	12763959.5	1161886.0	0.00	33960	0	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	305823.5	251107.8	19507.2	752.26
0.6	12763959.5	1161886.0	0.00	33960	0	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	305823.5	251107.8	19507.2	752.26
0.8	12763959.5	1161886.0	0.00	33960	0	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	305823.5	251107.8	19507.2	752.26
1	12919969.4	983284.1	0.00	34473	0	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	300574.3	252576.0	23290.0	846.08
1.2	12919969.4	983284.1	0.00	34391	0	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	294053.0	254974.3	27411.0	935.30
1.4	12919969.4	983284.1	0.00	34509	0	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	291202.5	255985.3	29250.5	835.10
1.6	12919969.4	983284.1	0.00	34278	0	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	297456.7	254007.6	24972.7	892.07
1.8	12919969.4	983284.1	0.00	34393	0	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	304876.5	244771.9	26792.9	1034.72
2	12919969.4	983284.1	0.00	34641	0	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	286511.9	261134.0	28794.2	752.26

Results of Chapter 7: Emission Tax Policy – varying solution robustness parameter

										Production Facility 1		Production Facility 2		Production Facility 3		Warehouse 1		Warehouse 2		Warehouse 3		Average use of logistic modes			
λ	Expected Total Cost	Total Cost Variability	Unfulfilled Demand	Total Emission	Total Emission Cost	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Mode 1	Mode 2	Mode 3	Average stock
0	14639050.6	1571238.2	0.0	32745	2875730	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	294039.5	250180.0	32220.2	2346.02
0.2	14639050.6	1571237.6	0.0	32745	2875730	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	294039.5	250180.0	32220.2	2346.02
0.4	14639050.6	1571237.6	0.0	32745	2875730	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	294039.5	250180.0	32220.2	2346.02
0.6	14639050.6	1571237.6	0.0	32745	2875730	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	294039.5	250180.0	32220.2	2346.02
0.8	14639050.6	1571237.6	0.0	32745	2875730	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	294039.5	250180.0	32220.2	2346.02
1	15121775.0	1024149.3	0.0	34048	2972700	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	288189.1	245393.7	42856.7	6081.47
1.2	15121775.0	1024149.3	0.0	33966	2960960	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	295077.1	241506.4	39855.5	6696.65
1.4	15121775.0	1024149.3	0.0	33742	2934910	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	290356.1	244886.0	41195.2	7043.16
1.6	15121775.0	1024149.3	0.0	33999	2966470	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	282898.7	254173.0	39366.8	5915.27
1.8	15121775.0	1024149.3	0.0	34197	2984210	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	279498.2	250428.5	46509.7	5443.19
2	15121775.0	1024149.3	0.0	33995	2962790	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	288550.8	238672.1	49216.7	5803.37

Results of Chapter 7: Emission Cap and Trade Policy – varying solution robustness parameter

										Production Facility 1		Production Facility 2		Production Facility 3		Warehouse 1		Warehouse 2		Warehouse 3		Average use of logistic modes			
λ	Expected Total Cost	Total Cost Variability	Unfulfilled Demand	Total Emission	Total Emission Cost	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Mode 1	Mode 2	Mode 3	Average stock
0	11895705.8	1560913.5	0.0	32745	132385	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	294039.5	250180.0	32220.2	2346.02
0.2	11895705.8	1560913.1	0.0	32745	132385	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	294039.5	250180.0	32220.2	2346.02
0.4	11895705.8	1560913.1	0.0	32745	132385	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	294039.5	250180.0	32220.2	2346.02
0.6	11895705.8	1560913.1	0.0	32745	132385	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	294039.5	250180.0	32220.2	2346.02
0.8	11895705.8	1560913.1	0.0	32745	132385	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	294039.5	250180.0	32220.2	2346.02
1	12361775.0	1032700.7	0.0	33721	183727	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	291577.3	244325.8	40536.0	6540.92
1.2	12361775.0	1032700.7	0.0	33769	189304	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	293336.0	241050.5	42053.4	6676.84
1.4	12361775.0	1032700.7	0.0	34080	232071	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	289759.7	245045.0	41634.4	5843.40
1.6	12361775.0	1032700.7	0.0	34208	238148	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	276177.4	256306.8	43954.9	5352.66
1.8	12361775.0	1032700.7	0.0	34183	240622	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	275151.9	256958.3	44328.3	4612.13
2	12361775.0	1032700.7	0.0	33843	201216	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	279163.5	254394.4	42879.5	5496.21

Results of Chapter 7: Emission Offset Policy – varying solution robustness parameter

										Production Facility 1		Production Facility 2		Production Facility 3		Warehouse 1		Warehouse 2		Warehouse 3		Average use of logistic modes			
λ	Expected Total Cost	Total Cost Variability	Unfulfilled Demand	Total Emission	Total Emission Cost	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Mode 1	Mode 2	Mode 3	Average stock
0	12044957.8	1393249.9	0.0	33328	295320	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	291056.8	247863.0	37516.9	2347.19
0.2	12044957.8	1393249.5	0.0	33328	295320	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	291056.8	247863.0	37516.9	2347.19
0.4	12044957.8	1393249.5	0.0	33328	295320	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	291056.8	247863.0	37516.9	2347.19
0.6	12044957.8	1393249.5	0.0	33328	295320	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	291056.8	247863.0	37516.9	2347.19
0.8	12044957.8	1393249.5	0.0	33328	295320	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	291056.8	247863.0	37516.9	2347.19
1	12361775.0	1034189.6	0.0	34086	324965	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	287389.9	244762.6	44288.2	4975.42
1.2	12361775.0	1034189.6	0.0	34263	295746	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	279982.0	248772.7	47686.0	4319.46
1.4	12361775.0	1034189.6	0.0	34550	323804	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	262982.2	263266.3	50191.0	3356.30
1.6	12361775.0	1034189.6	0.0	34264	333675	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	280982.5	251500.6	43955.6	3750.33
1.8	12361775.0	1034189.6	0.0	34354	300995	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	276056.3	252222.5	48160.5	3643.31
2	12361775.0	1034189.6	0.0	34267	317275	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	276529.6	255331.7	44577.1	5302.28

Results of Chapter 7: without Emission Policy – varying model robustness parameter

									Production Facility 1		Production Facility 2		Production Facility 3		Warehouse 1		Warehouse 2		Warehouse 3		Average use of logistic modes			
ω	Expected Total Cost	Total Cost Variability	Unfulfilled Demand	Total Emission	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Mode 1	Mode 2	Mode 3	Average stock
0	0.0	0.0	192146.28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0	0.00
100	11484398.0	0.0	10917.97	36815	0	1	1	1	1	0	0	0	1	0	1	0	1	0	0	0	239009.1	207995.1	96684.2	4769.47
200	11900821.1	837090.5	0.00	35944	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	272239.1	243681.3	60519.0	1735.97
300	11900821.1	837090.5	0.00	35998	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	272471.5	244382.4	59583.1	1570.90
400	11900821.1	837090.5	0.00	36018	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	267381.0	244241.9	64813.8	941.16
500	11900821.1	837090.5	0.00	36356	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	258853.9	256285.8	61300.5	1396.02
600	11900821.1	837090.5	0.00	35920	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	272215.0	246460.9	57760.3	2148.66
700	11900821.1	837090.5	0.00	36289	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	262249.0	247666.9	66525.4	1057.13
800	11900821.1	837090.5	0.00	36108	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	265470.4	251977.5	58988.4	2373.70
900	11900821.1	837090.5	0.00	36296	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	269141.2	245520.3	61777.5	2279.81
1000	11900821.1	837090.5	0.00	35963	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	272961.8	242077.1	61398.9	2309.64

Results of Chapter 7: Emission Cap Policy – varying model robustness parameter

									Production Facility 1		Production Facility 2		Production Facility 3		Warehouse 1		Warehouse 2		Warehouse 3		Average use of logistic modes			
ω	Expected Total Cost	Total Cost Variability	Unfulfilled Demand	Total Emission	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Mode 1	Mode 2	Mode 3	Average stock
0	0.0	0.0	192146.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0	0.00
100	11412028.2	0.0	11857.1	36167	0	1	1	1	1	0	0	0	1	0	1	0	1	0	0	0	230658.7	222410.5	88786.1	2565.15
200	11921592.1	673387.8	2288.9	34364	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	274504.0	248661.8	46407.6	3539.56
300	11921592.1	684454.7	2244.7	34442	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	273641.5	246541.3	49523.7	4047.79
400	11921592.1	693322.6	2219.3	34989	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	277166.0	238999.6	53613.2	2792.96
500	11921592.1	700849.4	2202.5	34431	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	281675.5	236958.3	51198.2	3917.70
600	12884019.7	949660.3	83.7	31294	0	1	1	1	1	0	1	0	0	0	1	0	1	0	0	0	253749.2	273281.9	49158.5	941.52
700	12884019.7	959617.5	68.4	31086	0	1	1	1	1	0	1	0	0	0	1	0	1	0	0	0	261878.9	264824.5	49529.7	1561.37
800	12884019.7	959617.5	68.4	30896	0	1	1	1	1	0	1	0	0	0	1	0	1	0	0	0	265050.1	263418.8	47763.7	1647.20
900	12919969.4	983284.1	0.0	34167	0	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	308080.0	248450.8	19903.9	917.77
1000	12919969.4	983284.1	0.0	33983	0	1	1	1	1	0	1	0	1	0	1	0	1	0	1	0	307291.0	249436.3	19710.8	942.03

Results of Chapter 7: Emission Tax Policy – varying model robustness parameter

										Production Facility 1		Production Facility 2		Production Facility 3		Warehouse 1		Warehouse 2		Warehouse 3		Average use of logistic modes			
ω	Expected Total Cost	Total Cost Variability	Unfulfilled Demand	Total Emission	Total Emission Cost	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Mode 1	Mode 2	Mode 3	Average stock
0	0.0	0.0	192146.28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0	0.00
100	12793701.3	0.0	25726.96	28929	2534010	0	1	1	1	1	0	0	0	1	0	1	0	1	0	0	0	245497.7	218919.2	34841.3	2355.42
200	15121775.0	1024149.3	0.00	34594	3014230	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	280947.5	246584.5	48904.4	3846.25
300	15121775.0	1024149.3	0.00	33857	2955990	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	288634.0	246451.4	41352.9	5926.29
400	15121775.0	1024149.3	0.00	34010	2967140	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	286209.0	250984.1	39247.8	5508.55
500	15121775.0	1024149.3	0.00	34243	2984020	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	289674.5	245948.8	40813.7	5049.88
600	15121775.0	1024149.3	0.00	34162	2976890	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	288347.0	243108.9	44983.7	5007.65
700	15121775.0	1024149.3	0.00	34081	2971250	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	285972.0	248020.4	42444.7	5514.63
800	15121775.0	1024149.3	0.00	34417	3000790	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	293296.0	237094.9	46046.4	4665.25
900	15121775.0	1024149.3	0.00	34191	2974840	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	288817.5	247062.5	40561.2	6312.54
1000	15121775.0	1024149.3	0.00	34175	2977070	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	290702.5	241540.3	44196.7	5012.29

Results of Chapter 7: Emission Cap and Trade Policy – varying model robustness parameter

										Production Facility 1		Production Facility 2		Production Facility 3		Warehouse 1		Warehouse 2		Warehouse 3		Average use of logistic modes			
ω	Expected Total Cost	Total Cost Variability	Unfulfilled Demand	Total Emission	Total Emission Cost	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Mode 1	Mode 2	Mode 3	Average stock
0	0.0	0.0	191379.78	3643	-2422720	1	1	1	0	1	0	0	0	0	0	1	0	0	0	0	0	202720.0	16161.6	2249.7	255.50
100	10033701.3	0.0	25799.31	28839	-216159	0	1	1	1	1	0	0	0	1	0	1	0	1	0	0	0	285561.4	231299.6	35432.1	2345.19
200	12361775.0	1032700.7	0.00	34306	243174	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	308256.0	258295.6	37340.1	5756.41
300	12361775.0	1032700.7	0.00	34172	240751	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	300601.0	262964.6	40325.1	4835.73
400	12361775.0	1032700.7	0.00	34168	237408	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	305104.0	259371.6	39413.3	4949.87
500	12361775.0	1032700.7	0.00	34341	245715	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	310512.0	250765.6	42614.2	4562.81
600	12361775.0	1032700.7	0.00	34169	236852	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	268057.6	280552.0	55280.6	4107.70
700	12361775.0	1032700.7	0.00	34180	238597	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	264326.3	288452.0	51113.1	4642.18
800	12361775.0	1032700.7	0.00	34580	270528	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	268556.6	282007.0	53329.1	3826.81
900	12361775.0	1032700.7	0.00	34047	227781	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	269475.6	284133.0	50282.8	4763.57
1000	12361775.0	1032700.7	0.00	34031	229893	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	273025.6	280045.0	50818.9	4832.51

Results of Chapter 7: Emission Offset Policy – varying model robustness parameter

										Production Facility 1		Production Facility 2		Production Facility 3		Warehouse 1		Warehouse 2		Warehouse 3		Average use of logistic modes			
ω	Expected Total Cost	Total Cost Variability	Unfulfilled Demand	Total Emission	Total Emission Cost	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Cap-Opt. 1	Cap-Opt. 2	Mode 1	Mode 2	Mode 3	Average stock
0	0.0	0.0	192146.28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0	0.00
100	10436524.2	10432.2	22915.98	30708	5397	0	1	1	1	1	0	0	0	1	0	1	0	1	0	0	0	240477.0	216864.2	50350.4	1883.69
200	12361775.0	1034189.6	0.00	34542	324841	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	274830.5	252409.5	49198.1	3111.59
300	12361775.0	1034189.6	0.00	34568	315609	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	286517.0	243180.6	46740.6	4176.40
400	12361775.0	1034189.6	0.00	34557	316230	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	283961.0	248760.5	43719.6	3737.51
500	12361775.0	1034189.6	0.00	34774	318780	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	284796.5	244032.5	47609.9	3396.75
600	12361775.0	1034189.6	0.00	34354	340750	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	286903.5	243691.7	45839.3	3976.74
700	12361775.0	1034189.6	0.00	34583	331050	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	279966.6	248474.5	47996.0	3604.80
800	12361775.0	1034189.6	0.00	34573	310925	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	280975.0	248218.8	47246.4	3864.42
900	12361775.0	1034189.6	0.00	34492	347690	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	289154.0	239711.1	47573.9	4018.40
1000	12361775.0	1034189.6	0.00	34496	326273	0	1	1	1	1	0	0	0	1	0	1	0	1	0	1	0	288806.5	242877.7	44756.4	4422.43

Appendix E: Results of Chapter 8

Results of Chapter 8 – Case 1

		Total Emission			Average use of logistic modes			Average Stock		
Quoted OTDLT	Total Cost	Country 1	Country 2	Country 3	Mode 1	Mode 2	Mode 3	Country 1	Country 2	Country 3
55	36517567.7	32035	50472	185136	564113.3	522025.9	226875.1	19696.00	10008.33	7244.13
70	32513728.7	28088	49727	190856	568401.1	473899.1	270716.3	8246.83	14086.33	13549.33
85	30282360.2	21802	48006	196739	560305.6	553066.0	199641.7	5938.20	13125.33	15186.67
100	28749600.4	10463	46854	229332	616248.2	514226.6	182534.1	3529.97	12674.00	27044.33
115	26936163.0	7540	46233	234268	603784.8	550248.5	158971.8	254.41	11291.67	30009.00
130	25844557.6	6190	43088	230046	636698.5	578731.8	97587.3	0.00	6825.33	32954.33
145	24992139.4	6101	50655	214900	502362.3	700154.0	110500.2	55.30	1081.13	6152.27
160	24322582.2	5545	49631	211091	546105.1	714255.7	52650.5	0.00	0.00	7288.67
175	23675444.0	5504	45319	221352	539214.8	697431.0	76374.7	0.00	0.00	7288.67
190	23121231.8	5386	44639	217506	577081.2	693838.0	42094.5	0.00	0.00	7288.67
205	22643122.6	0	54918	212121	518322.0	683954.3	110735.2	0.00	1531.73	5756.80

Results of Chapter 8 – Case 2

		Total Emission			Total Emission Cost			Average use of logistic modes			Average Stock		
Quoted OTDLT	Total Cost	Country1	Country2	Country3	Country 1	Country 2	Country 3	Mode 1	Mode 2	Mode 3	Country 1	Country 2	Country 3
55	38851256.8	25264	44534	203141	544778	1336020	320115	665601.8	480176.3	167235.8	19494.87	18951.00	14403.67
70	34586446.2	21795	40781	209855	284655	1223436	378150	661183.2	462858.0	188964.2	12732.00	19473.67	20379.67
85	32011515.4	19627	46034	201095	122055	1381020	120735	577695.3	547050.5	188262.8	7127.43	14299.67	14310.00
100	30033522.6	8199	45314	232423	-735113	1359420	548415	609963.9	527074.3	175963.6	3418.76	11890.33	26023.00
115	28044390.5	6463	44606	236379	-865305	1338180	560100	600456.9	569479.8	143077.8	800.60	9992.67	29245.33
130	26689678.6	5885	43282	230362	-908648	1298460	390600	607569.8	613558.7	91877.3	0.00	4882.23	28797.67
145	25586626.3	5811	49035	217513	-914198	1471050	0	499291.7	712829.5	100896.7	55.30	729.51	5998.73
160	24828791.9	5207	47036	215441	-959505	1411080	0	547056.8	707593.8	58362.5	0.00	0.00	7288.67
175	24118775.0	5265	43350	224155	-955110	1300500	45870	540249.6	697561.0	75199.6	0.00	0.00	6198.00
190	23471116.5	0	50936	214742	-1350000	1528080	0	560494.3	646461.9	106064.9	0.00	2198.83	4800.57
205	22815568.2	0	48058	223017	-1350000	1441740	54000	513430.1	683848.3	115732.4	0.00	1459.07	4534.53

Results of Chapter 8 – Case 3

		Total Emission			Total Emission Cost			Average use of logistic modes			Average Stock		
Quoted OTDLT	Total Cost	Country1	Country2	Country3	Country 1	Country 2	Country 3	Mode 1	Mode 2	Mode 3	Country 1	Country 2	Country 3
55	54765688.8	41512	56229	114370	3113385	4217175	8577750	646227.0	514083.0	152707.2	25090.10	21545.00	4046.63
70	50568432.9	42415	51758	104976	3181110	3881850	7873200	645987.1	536021.8	131012.6	27391.35	21317.67	0.00
85	48082829.8	27030	52453	145251	2027273	3933975	10893825	616329.3	571672.9	125012.4	6652.87	15133.33	11854.67
100	46070552.0	35380	73595	63960	2653508	5519625	4797000	610214.1	523744.6	179071.7	10588.67	33037.67	0.00
115	44293504.7	35714	61415	78936	2678580	4606125	5920200	543234.6	612140.8	157632.4	4913.50	19336.00	0.00
130	42895348.9	34705	58144	74740	2602838	4360800	5605500	584788.7	656920.2	71305.6	535.00	23235.33	0.00
145	41825753.5	34821	57916	72529	2611538	4343700	5439675	586537.1	670639.8	55834.4	215.68	24151.67	0.00
160	40769762.1	35765	82159	28610	2682383	6161925	2145720	500788.5	698091.5	114135.7	96.49	16316.33	0.00
175	39846919.1	35109	79413	25781	2633175	5955975	1933598	536438.4	704865.7	71710.8	0.00	16412.67	0.00
190	39150552.7	34190	78034	24252	2564250	5852550	1818908	562547.1	709657.3	40801.3	0.00	14997.00	0.00
205	38494966.4	34817	79718	21939	2611275	5978850	1645410	549981.0	713565.5	49472.7	0.00	15625.00	0.00

Results of Chapter 8: Country 1 – varying emission cap per period

		Total Emission			Total Emission Cost			Total Use			Average Stock		
Imposed Emission Cap	Total Cost	Country1	Country2	Country3	Country 1	Country 2	Country 3	Mode 1	Mode 2	Mode 3	Country 1	Country 2	Country 3
0	29394390.5	6463	44606	236379	484695	1338180	560100	600456.9	569479.8	143077.8	800.60	9992.67	29245.33
1200	29124390.5	6463	44606	236379	214695	1338180	560100	600456.9	569479.8	143077.8	800.60	9992.67	29245.33
2400	28854390.5	6463	44606	236379	-55305	1338180	560100	600456.9	569479.8	143077.8	800.60	9992.67	29245.33
3600	28584390.5	6463	44606	236379	-325305	1338180	560100	600456.9	569479.8	143077.8	800.60	9992.67	29245.33
4800	28314390.5	6463	44606	236379	-595305	1338180	560100	600456.9	569479.8	143077.8	800.60	9992.67	29245.33
6000	28044390.5	6463	44606	236379	-865305	1338180	560100	600456.9	569479.8	143077.8	800.60	9992.67	29245.33
7200	27774390.5	6463	44606	236379	-1135305	1338180	560100	600456.9	569479.8	143077.8	800.60	9992.67	29245.33
8400	27504390.5	6463	44606	236379	-1405305	1338180	560100	600456.9	569479.8	143077.8	800.60	9992.67	29245.33
9600	27234390.5	6463	44606	236379	-1675305	1338180	560100	600456.9	569479.8	143077.8	800.60	9992.67	29245.33
10800	26964390.5	6463	44606	236379	-1945305	1338180	560100	600456.9	569479.8	143077.8	800.60	9992.67	29245.33
12000	26694390.5	6463	44606	236379	-2215305	1338180	560100	600456.9	569479.8	143077.8	800.60	9992.67	29245.33

Results of Chapter 8: Country 1 – varying emission cap per period (dep. emission credit price)

		Total Emission			Total Emission Cost			Total Use			Average Stock		
Imposed Emission Cap	Total Cost	Country1	Country2	Country3	Country 1	Country 2	Country 3	Mode 1	Mode 2	Mode 3	Country 1	Country 2	Country 3
0	29667506.3	5346	44610	238274	801855	1338300	597390	602772.9	576332.0	133913.3	17.53	11144.00	29339.00
1200	29261211.6	5300	44575	238450	229487	1337250	595860	601653.3	576081.0	135283.8	0.00	11213.33	29172.00
2400	28803506.3	5346	44610	238274	-222516	1338300	597390	602772.9	576332.0	133913.3	17.53	11144.00	29339.00
3600	28448334.5	5948	44556	237271	-509439	1336680	582765	603171.5	571825.5	138031.5	133.08	10986.33	29320.67
4800	28193752.0	6294	44601	236704	-729549	1338030	566385	601249.6	570503.6	141261.0	148.26	10722.33	29222.00
6000	28044390.5	6463	44606	236379	-865305	1338180	560100	600456.9	569479.8	143077.8	800.60	9992.67	29245.33
7200	27999797.5	6713	44504	236118	-893202	1335120	556680	600171.8	568559.6	144284.2	1563.73	9145.33	29406.33
8400	28058370.2	7030	44579	235630	-817632	1337370	548010	599467.3	566200.3	147355.8	1563.73	9051.00	29410.33
9600	28221448.2	7194	44644	235371	-648174	1339320	544125	598880.4	558764.0	155379.6	1563.73	9146.67	29314.67
10800	28485237.8	7811	44522	234893	-368832	1335660	528480	595498.2	557318.0	160201.0	1563.73	9146.67	28721.33
12000	28852395.5	7993	44599	234634	0	1337970	524595	594384.8	557685.6	160949.0	1563.73	8976.33	28690.00

Results of Chapter 8: Country 1 – varying emission credit price

		Total Emission			Total Emission Cost			Total Use			Average Stock		
Emission Credit Price	Total Cost	Country1	Country2	Country3	Country 1	Country 2	Country 3	Mode 1	Mode 2	Mode 3	Country 1	Country 2	Country 3
0	28852395.5	7993	44599	234634	0	1337970	524595	594384.8	557685.6	160949.0	1563.73	8976.33	28690.00
15	28701237.8	7811	44522	234893	-152832	1335660	528480	595498.2	557318.0	160201.0	1563.73	9146.67	28721.33
30	28545448.2	7194	44644	235371	-324174	1339320	544125	598880.4	558764.0	155379.6	1563.73	9146.67	29314.67
45	28382370.2	7030	44579	235630	-493632	1337370	548010	599467.3	566200.3	147355.8	1563.73	9051.00	29410.33
60	28215797.5	6713	44504	236118	-677202	1335120	556680	600171.8	568559.6	144284.2	1563.73	9145.33	29406.33
75	28044390.5	6463	44606	236379	-865305	1338180	560100	600456.9	569479.8	143077.8	800.60	9992.67	29245.33
90	27869752.0	6294	44601	236704	-1053549	1338030	566385	601249.6	570503.6	141261.0	148.26	10722.33	29222.00
105	27692334.5	5948	44556	237271	-1265439	1336680	582765	603171.5	571825.5	138031.5	133.08	10986.33	29320.67
120	27507506.3	5346	44610	238274	-1518516	1338300	597390	602772.9	576332.0	133913.3	17.53	11144.00	29339.00
135	27317211.6	5300	44575	238450	-1714514	1337250	595860	601653.3	576081.0	135283.8	0.00	11213.33	29172.00
150	27126593.9	5276	44668	238379	-1908675	1340040	597675	602660.6	575098.1	135271.9	0.00	11380.33	29147.33

Results of Chapter 8: Country 2 – varying emission tax rate

		Total Emission			Total Emission Cost			Total Use			Average Stock		
Emission Tax Rate	Total Cost	Country1	Country2	Country3	Country 1	Country 2	Country 3	Mode 1	Mode 2	Mode 3	Country 1	Country 2	Country 3
0	26582866.9	6558	53631	223343	-858128	0	368055	584608.7	578701.5	149699.2	280.80	9991.00	27250.33
15	27357051.6	6612	47687	231805	-854138	715305	477645	585376.8	580687.0	146961.3	1178.90	9534.00	26763.67
30	28044390.5	6463	44606	236379	-865305	1338180	560100	600456.9	569479.8	143077.8	800.60	9992.67	29245.33
45	28697133.6	6454	42941	238671	-865958	1932345	606780	603652.6	570062.0	139299.8	886.27	9656.33	30469.00
60	29328330.1	6401	41020	241944	-869895	2461200	670305	611985.8	565986.6	135048.2	567.33	10639.33	31376.33
75	29938437.1	6282	40376	243432	-878880	3028200	681240	611361.1	567085.0	134563.8	711.89	10299.00	31579.00
90	30442551.0	17968	12905	239664	-2385	1161441	649005	616158.1	571402.8	125436.8	0.00	14608.67	26851.33
105	30632071.1	18038	12312	240332	2820	1292792	661080	616178.2	574974.0	121866.7	0.00	15433.33	26257.00
120	30815040.1	18028	11982	241212	2123	1437828	670695	616097.5	575837.0	121068.3	0.00	14820.67	27080.67
135	30977129.4	20307	8409	237561	172995	1135269	599250	625707.3	564461.3	122852.2	0.00	13611.00	27087.33
150	31101711.3	20323	8197	238000	174248	1229520	607770	626965.0	565301.6	120746.3	0.00	13701.00	27086.00

Results of Chapter 8: Country 3 – varying emission cap per period

		Total Emission			Total Emission Cost			Total Use			Average Stock		
Imposed Emission Cap	Total Cost	Country1	Country2	Country3	Country 1	Country 2	Country 3	Mode 1	Mode 2	Mode 3	Country 1	Country 2	Country 3
0	30981601.4	6389	44067	236907	-870810	1322010	3553605	615759.9	559118.0	138145.3	0.00	12065.00	31588.33
15000	30306601.4	6389	44067	236907	-870810	1322010	2878605	615759.9	559118.0	138145.3	0.00	12065.00	31588.33
30000	29631601.4	6389	44067	236907	-870810	1322010	2203605	615759.9	559118.0	138145.3	0.00	12065.00	31588.33
45000	28958586.2	6385	43870	237164	-871163	1316100	1532460	614898.6	558399.9	139713.7	800.60	11122.67	31321.67
60000	28494390.5	6463	44606	236379	-865305	1338180	1010100	600456.9	569479.8	143077.8	800.60	9992.67	29245.33
75000	28044390.5	6463	44606	236379	-865305	1338180	560100	600456.9	569479.8	143077.8	800.60	9992.67	29245.33
90000	27655307.4	6476	43771	237864	-864315	1313130	219750	605249.6	567486.6	140284.5	485.20	10625.33	30409.33
105000	27430749.8	6399	43526	238247	-870098	1305780	0	605577.1	569245.5	138167.2	526.80	10575.33	30390.00
120000	27401425.4	6231	42283	240031	-882645	1268490	0	615625.8	561885.6	135497.8	0.00	11637.00	31971.00
135000	27401425.4	6231	42283	240031	-882645	1268490	0	615625.8	561885.6	135497.8	0.00	11637.00	31971.00
150000	27401425.4	6231	42283	240031	-882645	1268490	0	615625.8	561885.6	135497.8	0.00	11637.00	31971.00

Results of Chapter 8: Country 3 – varying emission allowance price

		Total Emission			Total Emission Cost			Total Use			Average Stock		
Emission Allowance Price	Total Cost	Country1	Country2	Country3	Country 1	Country 2	Country 3	Mode 1	Mode 2	Mode 3	Country 1	Country 2	Country 3
0	27401425.4	6231	42283	240031	-882645	1268490	0	615625.8	561885.6	135497.8	0.00	11637.00	31971.00
15	28044390.5	6463	44606	236379	-865305	1338180	560100	600456.9	569479.8	143077.8	800.60	9992.67	29245.33
30	28490136.5	7005	49607	228537	-824655	1488210	738360	570623.1	581018.8	161371.6	1358.10	9387.33	23549.33
45	28638040.3	7122	63043	207241	-815873	1891290	20565	528794.7	610684.8	173539.2	2946.17	7457.87	16381.67
60	28638690.2	7160	63062	207433	-812970	1891860	0	525189.0	607560.5	180268.6	2866.87	7454.33	15853.33
75	28638690.2	7160	63062	207433	-812970	1891860	0	525189.0	607560.5	180268.6	2866.87	7454.33	15853.33
90	28638690.2	7160	63062	207433	-812970	1891860	0	525189.0	607560.5	180268.6	2866.87	7454.33	15853.33
105	28638690.2	7160	63062	207433	-812970	1891860	0	525189.0	607560.5	180268.6	2866.87	7454.33	15853.33
120	28638690.2	7160	63062	207433	-812970	1891860	0	525189.0	607560.5	180268.6	2866.87	7454.33	15853.33
135	28638690.2	7160	63062	207433	-812970	1891860	0	525189.0	607560.5	180268.6	2866.87	7454.33	15853.33
150	28638690.2	7160	63062	207433	-812970	1891860	0	525189.0	607560.5	180268.6	2866.87	7454.33	15853.33

Results of Chapter 8: Country 3 – varying emission tax rate

		Total Emission			Total Emission Cost			Total Use			Average Stock		
Emission Tax Rate	Total Cost	Country1	Country2	Country3	Country 1	Country 2	Country 3	Mode 1	Mode 2	Mode 3	Country 1	Country 2	Country 3
0	27401425.4	6231	42283	240031	-882645	1268490	0	615625.8	561885.6	135497.8	0.00	11637.00	31971.00
15	30981601.4	6389	44067	236907	-870810	1322010	3553605	615759.9	559118.0	138145.3	0.00	12065.00	31588.33
30	34451134.4	6967	52922	221358	-827475	1587660	6640740	604211.5	565766.4	143041.3	1856.02	10921.00	29317.67
45	37105173.2	10335	76747	155411	-574898	2302410	6993495	607003.9	601060.7	104942.5	2036.63	8438.27	23299.00
60	38371037.3	25739	86937	78787	580395	2608110	4727220	557127.6	545579.5	210302.1	4495.50	21658.67	0.00
75	39542455.1	25709	88749	77269	578168	2662470	5795175	554684.0	541623.9	216708.6	4495.50	21579.33	0.00
90	40371720.7	29759	94897	43139	881903	2846910	3882501	599679.0	585455.6	127882.9	5378.37	32942.00	0.00
105	40869432.0	39532	94297	21046	1614900	2828910	2209809	454857.2	737943.8	120207.6	7656.67	8756.00	0.00
120	41180523.5	39941	94746	20143	1645575	2842380	2417208	450570.5	742055.5	120391.5	7907.47	8505.20	0.00
135	41464647.8	40850	95079	18393	1713750	2852370	2483015	445697.5	741209.3	126104.7	8047.37	8365.30	0.00
150	41737211.6	40986	95398	17955	1723950	2861940	2693220	444206.0	742188.8	126625.7	8047.37	8365.30	0.00

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Eidesstattliche Erklärung

Hiermit erkläre ich gemäß § 6 Abs. 2 Nr. 2 der Promotionsordnung der wirtschaftswissenschaftlichen Fakultät der Universität Würzburg vom 19.10.1998, mit drei Satzungsänderungen, dass ich diese Dissertation eigenständig, d.h. insbesondere selbständig und ohne Hilfe eines kommerziellen Promotionsberaters angefertigt habe, und dass ich außer den im Schrifttumsverzeichnis angegebenen Hilfsmitteln keine weiteren benutzt habe und alle Stellen, die aus dem Schrifttum ganz oder annähernd entnommen sind, als solche kenntlich gemacht und einzeln nach ihrer Herkunft unter Bezeichnung der Ausgabe (Auflage und Jahr des Erscheinens), des Bandes und ggf. der Seite des benutzten Werkes nachgewiesen habe.

Ort, Datum, Unterschrift

Lebenslauf

Benjamin Siller
geboren am 28.09.1988 in Kemnath

Schulabschluss

09/1999 – 06/2008	**Luisenburg-Gymnasium Wunsiedel** Abschluss: Abitur

Hochschulstudium

10/2008 – 09/2011	**Studium der Wirtschaftswissenschaften mit dem Abschluss Bachelor of Science** Friedrich-Schiller-Universität Jena
10/2011 – 09/2014	**Studium Business Management mit dem Abschluss Master of Science** Julius-Maximilians-Universität Würzburg

Berufserfahrung

12/2021 – heute	**PricewaterhouseCoopers GmbH WPG** Associate
11/2014 – 11/2021	**Julius-Maximilians-Universität Würzburg, Lehrstuhl für BWL und Industriebetriebslehre** Wissenschaftlicher Mitarbeiter
04/2013 – 09/2013	**Lufthansa Technik Logistik Services GmbH** Praktikant
08/2010 – 10/2010	**Schott Jenaer Glas GmbH** Praktikant

Würzburg, 11.12.2022 Benjamin Siller