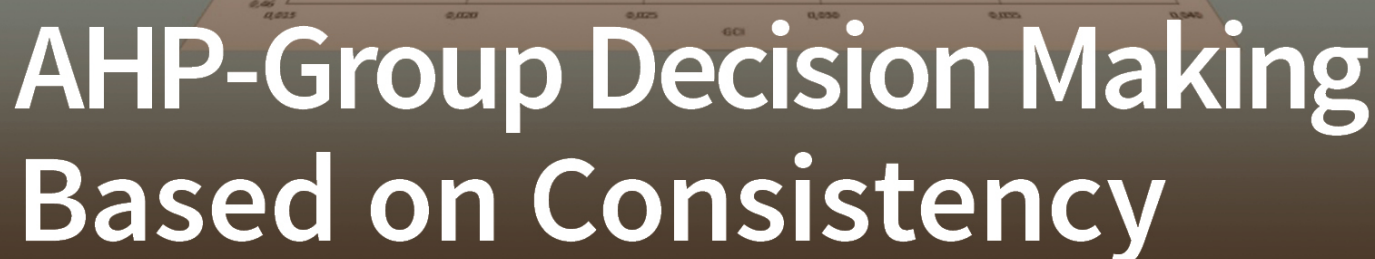


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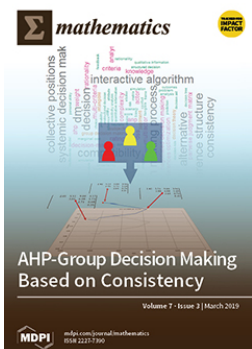


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### **The “Generator” of Int-Soft Filters on Residuated Lattices (/2227-7390/7/3/236)**

by **Huarong Zhang** (<https://sciprofiles.com/profile/616132>) and

**Minxia Luo** (<https://sciprofiles.com/profile/author/aE5KTIZuNWg0UXJPukdZamdCSEISdDJha2R4Z2FHZmM2NEJTdkd6d01ZST0=>).

*Mathematics* 2019, 7(3), 236; <https://doi.org/10.3390/math7030236> (<https://doi.org/10.3390/math7030236>) - 06 Mar 2019

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**Abstract** In this paper, we give the “generator” of int-soft filters and propose the notion of t-int-soft filters on residuated lattices. We study the properties of t-int-soft filters and obtain some commonalities (e.g., the extension property, quotient characteristics, and a triple of equivalent characteristics). [...] **Read more.**  
(This article belongs to the Special Issue **Fuzzy Sets, Fuzzy Logic and Their Applications (/journal/mathematics/special\_issues/Fuzzy\_Sets)**)

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### **On the Solvability of a Mixed Problem for a High-Order Partial Differential Equation with Fractional Derivatives with Respect to Time, with Laplace Operators with Spatial Variables and Nonlocal Boundary Conditions in Sobolev Classes (/2227-7390/7/3/235)**

by **Onur Alp İlhan** (<https://sciprofiles.com/profile/565053>),

**Shakirbay G. Kasimov** (<https://sciprofiles.com/profile/author/c2RjN3pWaFQ4bGRrWHRGckZyazdLUFBSaktiZDVjUjJCc2dEMEO1V0M0ST0=>),

**Shonazar Q. Otaev** (<https://sciprofiles.com/profile/author/OG04eIBrcEpGRIBjaXREbzlwZTVnVUtFbFh2UVg4TjBiSjl2Yk9WSIJtOD0=>) and

**Haci Mehmet Baskonus** (<https://sciprofiles.com/profile/117528>).

*Mathematics* 2019, 7(3), 235; <https://doi.org/10.3390/math7030235> (<https://doi.org/10.3390/math7030235>) - 05 Mar 2019

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**Abstract** In this paper, we study the solvability of a mixed problem for a high-order partial differential equation with fractional derivatives with respect to time, and with Laplace operators with spatial variables and nonlocal boundary conditions in Sobolev classes. **Full article (/2227-7390/7/3/235)**  
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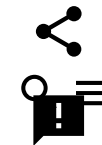
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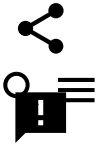
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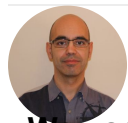
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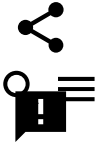
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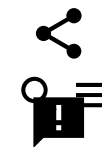
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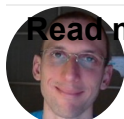
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**Interests:** differential geometry; geometric mechanics; mathematical physics

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**Interests:** concepts and implementation of programming languages; formal language definition, attribute grammars; compiler generators; domain specific languages; grammar-based systems; grammatical inference; meta-heuristics, single and multi-objective optimization

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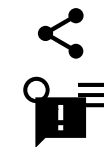
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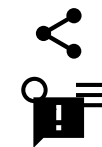
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**Interests:** functional data analysis; categorical data analysis; applied stochastic modelling and forecasting; data driven statistics in econometrics; chemometrics, biomechanics, engineering, and survival analysis

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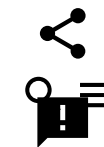


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**Interests:** association rules; evolutionary fuzzy systems; explainable artificial intelligence; bioinformatics; data mining software



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**Interests:** boolean networks; discrete mathematics; computational mathematics

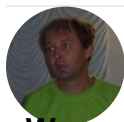
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Special Issue in **Mathematics: Boolean Networks Models in Science and Engineering II**

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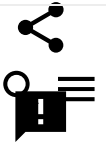
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Department of Mathematics, Bar-Ilan University, Ramat-Gan 52900, Israel

**Interests:** Specht problem; Dixmier conjecture; PI-algebra; Jacobian Conjecture interlocking structures; finitely generated skew field; small

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**Interests:** electromagnetic fields; numerical methods; optimization



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**Interests:** analysis of networks; cooperative game theory; restricted cooperation

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**Interests:** computer science; e-Health

**Prof. Dr. David Edmund Allen**

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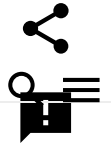
**Interests:** finance; investments; financial econometrics; financial economics; time-series

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**Interests:** finite semigroups; profinite structures; symbolic dynamics



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**Interests:** mathematical finance; stochastic modeling; fractional Brownian motion

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**Interests:** mathematical physics equations; nonlinear boundary value problems; weak solutions; mathematical theory of radiative-conductive heat exchange problems, numerical analysis; homogenization; projection methods

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**Interests:** computational analysis; approximation theory; probability; theory of moments

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**Interests:** boundary element methods; Green's functions; solid mechanics; fracture mechanics; heat conduction; analysis of nonhomogeneous materials; analysis of non-ideal interfaces in multi-layered materials; bioheat transfer in human eye; multi-field analysis; and non-classical boundary value problems

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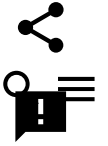
Department of Statistics and Operational Research, Faculty of Sciences, School of Mathematics, Aristotle University of Thessaloniki, 54124

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**Interests:** complex systems; networks; statistical mechanics; dynamical systems; chaos

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**Interests:** Efficiency; Productivity; Data Envelopment Analysis

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Department of Quantitative Economics, University of Oviedo, Avda. Cristo, s/n. 33006 Oviedo, Spain

**Interests:** fuzzy decision making; fuzzy sets; multicriteria decision-making; fuzzy multi-criteria programming; possibilistic multi-criteria programming; economic-business applications

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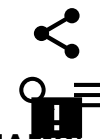
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Special Issue in **Foundations: Iterative Methods with Applications in Mathematical Sciences** ([/journal/foundations/special\\_issues/IMAMS](https://journal/foundations/special_issues/IMAMS))



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**Interests:** mathematical modeling of ecological systems; population dynamics; management of renewable resources **Accept** ([/accept\\_cookies](#))

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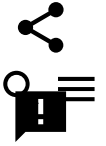
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**Interests:** composite materials; sandwich composites; damage modelling; impact simulation; structural health monitoring

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**Interests:** electromagnetics; numerical and analytical methods; magnetic materials; physics

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**Interests:** Foundations of Fuzzy Logic and Fuzzy Control; Fuzzy Connectives; Aggregation Functions; Functional Equations and Inequalities related to Fuzzy Logic

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**Interests:** finler spaces and areal metrics; variational problems applied to Gravitation and Relativity; applications of the theory of loop groups to surfaces theory; differential geometry applied to image processing; fuzzy theory applied to image processing

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**Prof. Dr. Dumitru Baleanu**

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Special Issue in ***Mathematics: Advances in Differential and Difference Equations with Applications 2019***

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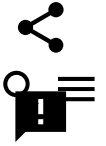


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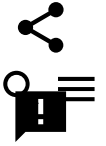
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---

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**Interests:** mathematical statistics; statistical inference; asymptotic theory; characterizations; exponential families



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**Interests:** control theory; control systems; controller design; fuzzy logic

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**Interests:** mathematical and computational biology; RNA structure prediction; viral dynamics; scientific computing; numerical analysis

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**Prof. Dr. Xavier Barber**

**Website** ([https://www.umh.es/contenido/Universidad/:persona\\_4585/datos\\_en.html](https://www.umh.es/contenido/Universidad/:persona_4585/datos_en.html)) **SciProfiles** (<https://sciprofiles.com/profile/1247273>)

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**Interests:** Bayesian statistics; spatio-temporal models; environmental processes; longitudinal models



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**Interests:** optimization theory; game theory; mathematics for economics; variational methods for economics

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Special Issue in **Mathematics: Optimization Theory, Variational Methods for Applied Mathematics**

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**Prof. Dr. Giovanni Barone Adesi**

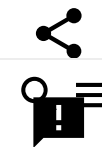
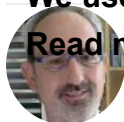
**Website** (<https://search.usi.ch/en/people/5be736fa2b7c09db295e1b3747f643b9/barone-adesi-giovanni>)

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**Interests:** financial derivatives; risk management

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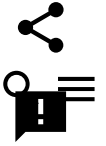


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**Interests:** dynamical systems; bifurcations; mathematical neuroscience; cardiac dynamics



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Department of Theoretical and Mathematical Physics, Institute of Mathematics and Computer Sciences, Ural Federal University, 620000 Ekaterinburg, Russia

**Interests:** stochastic dynamics; chaos; bifurcations; control

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**Interests:** financial mathematics; option pricing; DEA (data envelopment analysis) models; performance evaluation of mutual funds; credit risk

**Special Issues, Collections and Topics in MDPI journals**

Special Issue in **Mathematics: Financial Mathematics** ([/journal/mathematics/special\\_issues/Financial\\_Mathematics\\_2017](/journal/mathematics/special_issues/Financial_Mathematics_2017))

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**Interests:** discrete mathematics; network analysis; algorithms; optimization; graph theory



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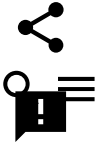


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**Interests:** computational mathematics; image analysis; multicriteria decision making; algorithms and applications

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Département de mathématiques, Université Paris-Saclay, 91000 Évry, France

**Interests:** Number theory; Arithmetic geometry; coding theory; Modular forms; Special functions; Special values of Zetas and L-functions; q-series and partition theory

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**Prof. Dr. Valeriu Beiu**

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**Interests:** artificial neural network; computer architecture; computer security and reliability; electrical engineering; electronic engineering



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**Interests:** fixed point theory; geometry of banach spaces

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**Interests:** numerical analysis; mathematical modelling; mathematical biology; reaction–diffusion systems



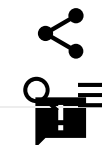
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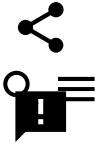


Engineering Department, University of Ferrara, Via Saragat, 1, 44122 Ferrara, Italy

**Interests:** computational models for solid mechanics; fracture; damage; nonlocal elasticity

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**Interests:** applied mathematics; numerical analysis; fixed point theory; inverse problems; functional analysis

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**Interests:** theory of partitions; q-series; theta functions and quadratic forms



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**Interests:** elasticity theory; almost-periodic functions; biomathematics (models of glucose-insulin kinetics; models of intracellular biochemical signal transduction and metabolism; models of stem cells action; functional mathematical indexes for food quality)

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**Website** ([https://www.upit.ro/\\_document/29923/bizon\\_11nov\\_2018\\_cv\\_eng\\_website\\_fecc.pdf](https://www.upit.ro/_document/29923/bizon_11nov_2018_cv_eng_website_fecc.pdf))

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**Interests:** power electronics; renewable energy; fuel cell; hybrid power systems; control; optimization

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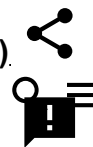
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**Interests:** multiobjective optimization and its applications; process control; energy management systems

**Prof. Dr. Lucio Boccardo**

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**Interests:** mathematical analysis; applied mathematics



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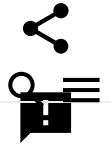
**Prof. Dr. Gennady Bocharov**

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**Interests:** multiscale and hybrid modelling in biology; mathematical and computational immunology; dynamics of infections in humans and experimental animals; mathematical systems theory



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**Interests:** numerical and applied mathematics; linear and nonlinear inverse ill-posed problems; regularization methods; numerical methods for inverse Sturm-Liouville problems; applications in atmospheric physics

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**Dr. Leonid V. Bogachev**

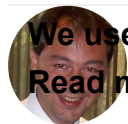
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**Interests:** Hamiltonian systems; Sturm–Liouville equations; boundary value problems; difference equations; variational analysis; control theory; optimization; dynamical systems; oscillation; fractional differentiation equations; positivity; matrix analysis; eigenvalue problems; computational mathematics; time scales



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**Interests:** nonparametric statistics; risk quantification; micro econometrics; data analysis

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**Interests:** applied and computational statistics; molecular modeling; genetic analysis; statistical modeling in medicine; integrated health informatics system; medical diagnostic research; statistical inference; medical imaging analysis; assisted decision systems; research ethics; social media and health information; evidence-based medicine

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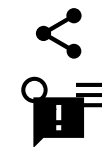
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**Interests:** Thermodynamics and Statistical Mechanics; Statistical Thermodynamics; Nonlinear Dynamics, Stochastic Processes; Lattice gas automata; Dynamics; Nonlinear Models, Statistical Mechanics; Convection

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**Interests:** complex networks; complex systems; computational social science; information ecosystems; urban computing

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**Interests:** mathematical ecology; theoretical ecology; evolution; adaptive dynamics; epidemiology; population dynamics; food webs; community assembly



---

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**Interests:** complex networks, webs, webs

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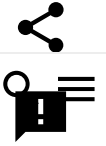
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**Interests:** functional equations and inequalities; Ulam's type stability; fixed point theory

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**Interests:** noncommutative geometry; corings and comodules; Hopf algebras; category theory; algebraic structures

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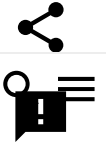
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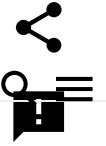
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**Interests:** group decision making; consensus; fuzzy logic; linguistic modeling

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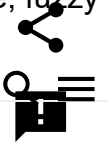
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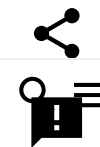
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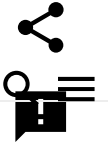
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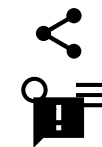
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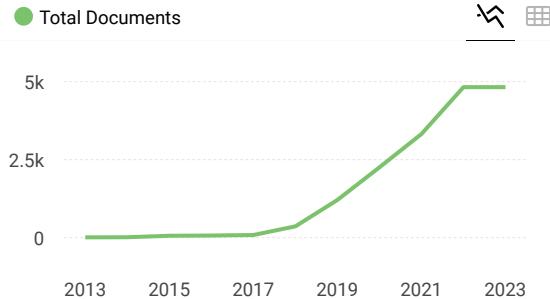
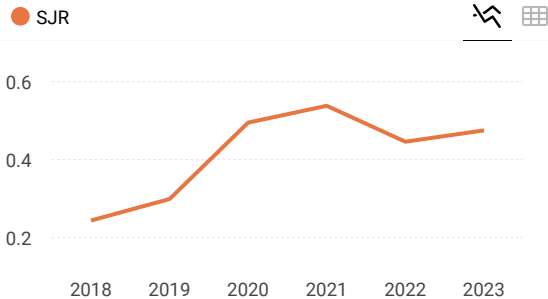
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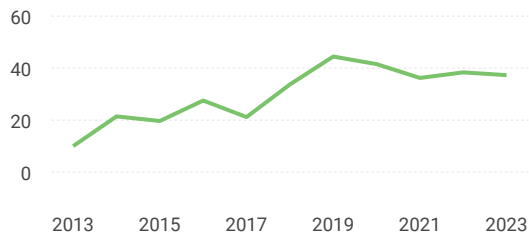
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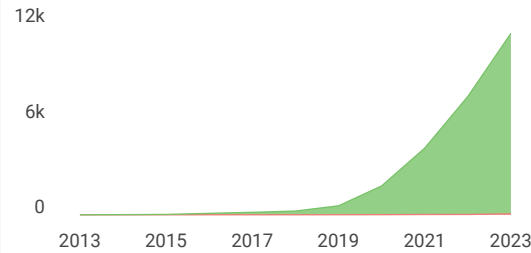
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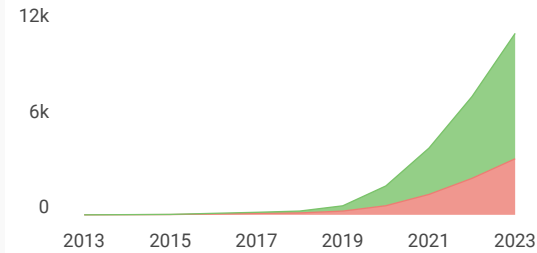
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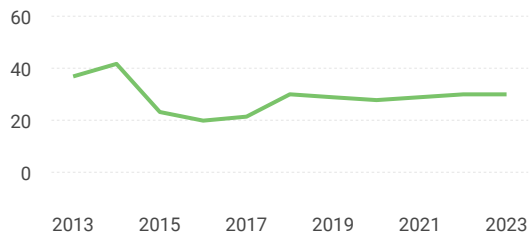
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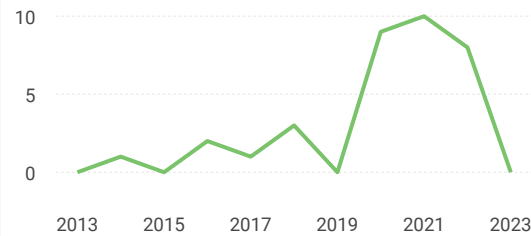
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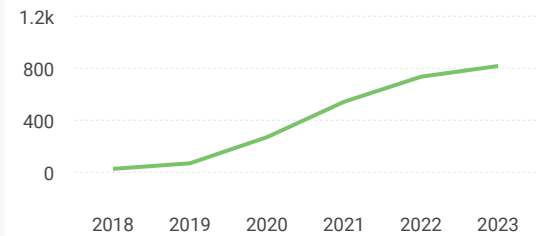
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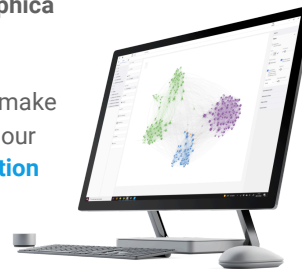
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**Abstract:** Nowadays, many countries have implemented carbon pricing policies. Hence, the industry adapts to this policy while striving for its main goal of maximizing financial benefits. Here, we study a single manufacturer–retailer inventory decision considering carbon emission cost and item deterioration for an imperfect production system. This study examines two models considering two cases of quality inspection. The first is when the buyer performs the quality inspection, and the second is when the quality inspection becomes the vendor’s responsibility so that no defective products are passed to the buyer. Carbon emission costs are incorporated under a carbon tax policy, and we consider the carbon footprint from transporting and warehousing the items. The objective is to jointly optimize the delivery quantity and number of deliveries per production cycle that minimize the total cost and reduce the total carbon emissions. This study provides solution procedures to solve the models, as well as two numerical examples.

**Keywords:** supply chain inventory; imperfect quality; inspection; carbon emission; deteriorating items

## 1. Introduction

Supply chain coordination has a favorable effect on inventory replenishment decisions. Supply chain coordination can be realized through information sharing and joint decision-making. Coordination brings many advantages such as lower inventory-related costs and quality improvement [1]. This study considers supply chain management coordination and examines its effect on both economic and environmental performance. This study proposes supply chain inventory models that consider carbon emission costs and the existence of defective items under different inspection coordination mechanisms. Further, the models also consider the effect of item deterioration. In real life, many inventory items deteriorate over time due to spoilage, physical depletion, or obsolescence.

Due to increasing pressure from legislation, customers, and other organizations, business and industry are striving for more eco-friendly operation. The production, distribution, consumption, and other post-consumption processes of a product are sources of carbon emission. Therefore, the concept of a low-carbon supply chain has gained massive interest among researchers and industry practitioners [2,3]. The objective is to control and reduce CO<sub>2</sub> emissions (the major part of greenhouse gas emission) from the supply chain. Recently, Kazemi et al. [4] considered the effect of carbon emissions on several economic order quantity (EOQ) models. Sarkar et al. [5] considered warehouse emissions in the EOQ model with a rework for the defective items. The model also considered partial

backorder and multi-trade-credit-period. Taleizadeh et al. [6] proposed economic production quantity (EPQ) models that considered carbon emissions. Recently, Sarkar et al. [7,8] and Daryanto and Wee [9] incorporated a carbon tax in a supply chain total cost model. Wahab et al. [10], Jauhari et al. [11], Sarkar et al. [12], Jauhari [13], Gautam and Khanna [14], and Tiwari et al. [15] incorporated both carbon emissions and imperfect quality in a low-carbon supply chain model. The quality inspection is performed by the buyer, and the defective products are sent back to the vendor or sold into the secondary market at a discounted price.

Table 1 illustrates the research gap by comparing this paper with the existing literature. This study focuses on supply chain inventory models for a system that contains imperfect quality items. The decisions of the supply chain dealing with the defective items in the imperfect production processes affect carbon emissions, because defective item processing also adds to the total emissions. Moreover, the loss due to imperfect quality and deterioration also forces the manufacturer to produce more products to satisfy customer demand per period, resulting in the increase in carbon emission from production, holding, and distribution. The objectives of these studies are to simultaneously minimize the total cost and reduce carbon emissions. This paper also contributes to low-carbon supply chain models by considering two cases of quality inspection. In the first case, the buyer performs the quality inspection, and in the second case, the quality inspection becomes the vendor's responsibility. The first model extends the studies of Wahab et al. [10], Jauhari et al. [11], Sarkar et al. [12], Jauhari [13], and Gautam and Khanna [14] to consider the effect of deterioration. In addition to the fixed and variable inspection costs, the model also extends Tiwari et al.'s [15] model by introducing weight and distance-dependent transportation cost and emission variables. The second model extends the first model by introducing an inspection option to prevent defective products from being shipped to the buyer. This model reduces the expected total costs and emission costs of the supply chain.

**Table 1.** Gap analysis with existing literature.

| Authors                      | Imperfect Quality   |                    | Deteriorating Item | Variable Transportation Cost | Carbon Emission |
|------------------------------|---------------------|--------------------|--------------------|------------------------------|-----------------|
|                              | Vendor's Inspection | Buyer's Inspection |                    |                              |                 |
| Huang (2002)                 |                     | ✓                  |                    |                              |                 |
| Goyal et al. (2003)          |                     | ✓                  |                    |                              |                 |
| Wee et al. (2006)            |                     | ✓                  | ✓                  |                              |                 |
| Wahab et al. (2011)          |                     | ✓                  |                    |                              | ✓               |
| Benjaafar et al. (2013)      |                     |                    |                    |                              | ✓               |
| Lee and Kim (2014)           |                     | ✓                  | ✓                  |                              |                 |
| Bazan et al. (2014)          | ✓                   |                    |                    |                              |                 |
| Bozorgi et al. (2014)        |                     |                    |                    |                              | ✓               |
| Jauhari et al. (2014)        |                     | ✓                  |                    |                              | ✓               |
| Bozorgi (2016)               |                     |                    |                    |                              | ✓               |
| Ghosh et al. (2016)          |                     |                    |                    |                              | ✓               |
| Sarkar et al. (2016b)        |                     | ✓                  |                    | ✓                            | ✓               |
| Yu and Hsu (2017)            |                     | ✓                  |                    |                              |                 |
| Sarkar et al. (2017)         | ✓                   |                    |                    | ✓                            |                 |
| Toptal and Çetinkaya (2017)  |                     |                    |                    |                              | ✓               |
| Bouchery et al. (2017)       |                     |                    |                    |                              | ✓               |
| Dwicalyani et al. (2017)     |                     |                    |                    |                              | ✓               |
| Wangsa (2017)                |                     |                    |                    |                              | ✓               |
| Li et al. (2017)             |                     |                    |                    |                              | ✓               |
| Anvar et al. (2018)          |                     |                    |                    |                              | ✓               |
| Hariga et al. (2018)         |                     |                    |                    |                              | ✓               |
| Ji et al. (2018)             |                     |                    |                    |                              | ✓               |
| Wang and Ye (2018)           |                     |                    |                    |                              | ✓               |
| Gosh et al. (2018)           |                     |                    |                    |                              | ✓               |
| Ma et al. (2018)             |                     |                    |                    |                              | ✓               |
| Darom et al. (2018)          |                     |                    |                    |                              | ✓               |
| Jauhari (2018)               |                     | ✓                  |                    |                              | ✓               |
| Gautam and Khanna (2018)     |                     | ✓                  |                    |                              | ✓               |
| Wangsa and Wee (2018)        |                     |                    |                    | ✓                            |                 |
| Tiwari et al. (2018)         |                     | ✓                  | ✓                  |                              | ✓               |
| Kundu and Chakrabarti (2019) |                     |                    |                    |                              | ✓               |
| This paper                   | ✓                   | ✓                  | ✓                  | ✓                            | ✓               |

This study incorporates carbon emissions, item deterioration, and defective percentage to guide the supply chain managers to make the inventory decisions on the delivery size and the number of

deliveries per cycle. This introduction section is followed by reviews of previous related studies in Section 2. Then, Section 3 defines the problem, assumptions, and notations in this study. Section 4 presents two mathematical models. Section 5 provides two numerical examples and the sensitivity analysis to find some insights from the proposed models. In the end, Section 6 summarizes the findings and discusses some opportunities for further research.

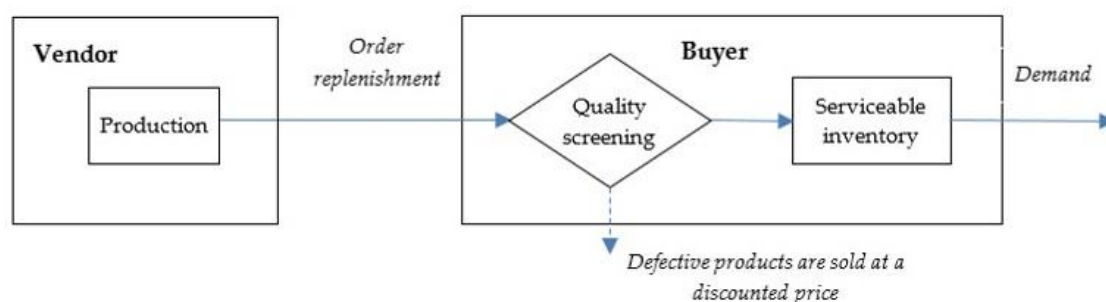
## 2. Literature Review

This study incorporates both economic and emission costs in a two-echelon supply chain production–inventory model assuming that defective products exist in each delivered lot. This section presents the existing literature that supports this study.

### 2.1. Imperfect Quality Inventory Model

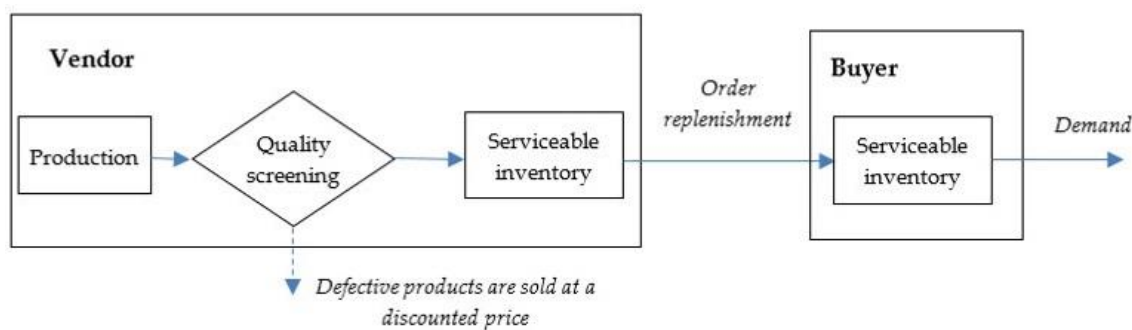
In many industries, production systems are imperfect, producing a certain percentage of defective products. Rosenblatt and Lee [16] and Porteus [17] studied the relationship between the optimal lot size and quality performance. Rosenblatt and Lee [16] studied the optimal production cycle through considering the proportion of defective items, while Porteus [17] related the model to the opportunity for quality improvement and setup cost reduction through investment. Salameh and Jaber [18] incorporated defective items into the EPQ model and considered the screening time and cost. Many other researchers have continued the research on the EOQ and EPQ models with imperfect quality. Those researchers assume that at the end of the screening period, or the end of the cycle, the defective products will be sold at a lower price.

Other researchers bring the effect of imperfect quality items into the integrated vendor–buyer or multi-echelon inventory model. Huang [19] considered imperfect quality and assumed that the vendor provides a product warranty for the defective items. The buyer conducts a 100% inspection, and at the end, the vendor treats the faulty items. Goyal et al. [20] extended the previous model with a single production and multiple deliveries containing defective products. They assumed that the buyer sells the defective items at a discounted price. Figure 1 illustrates the scenario. Wee et al. [21] considered imperfect quality, shortage backorder, and item deterioration in an integrated production–inventory model. Lee and Kim [22] also developed an integrated production–inventory model of imperfect quality deteriorating items.



**Figure 1.** Illustration of an integrated inventory model for imperfect quality items where defective products are sold at a discounted price.

Bazan et al. [23] studied the effect of imperfect quality in different vendor–buyer inventory models. In their study, the vendor performs the inspection and considers one of three possible decisions regarding the defective items: (1) scrap off, (2) salvage at a discounted price, and (3) rework. Figure 2 illustrates the scenario when the vendor performs the inspection. Sarkar et al. [24] studied the integrated inventory model with two-stage inspection by the vendor considering the rework process and variable transportation cost. Yu and Hsu [25] developed a production–inventory model in which the defective items are returned to the vendor immediately for rework.



**Figure 2.** Illustration of an integrated inventory model for imperfect quality items with vendor's inspection.

## 2.2. Low-Carbon Supply Chain Management

Research on low-carbon supply chain management has increased rapidly in recent years and has been marked by a surge in the amount of literature in this area. Much of this research revealed that supply chain collaboration and the adjustment on operational decisions could reduce carbon emissions without significantly increasing their costs. Wahab et al. [10] studied the optimal shipment size and number of shipments for a two-echelon supply chain with carbon emission cost from transporting the inventory. The emissions are affected by the distance traveled, vehicle fuel efficiency, and the actual shipment weight. Benjaafar et al. [26] modified the traditional supply chain model by associating the carbon footprint from placing an order to the supplier, production setup, production process, and inventory holding. Fahimnia et al. [27] studied the impact of carbon pricing on a closed-loop supply chain through a case study.

Bozorgi et al. [28] considered carbon emissions from transporting and storing cold items that require temperature-controlled trucks and freezers. Bozorgi [29] extended the previous model considering multi-product cold items under limited capacity. Hariga et al. [30] incorporated carbon emissions from transporting and storing the cold items in a three-echelon supply chain. Ghosh et al. [31] considered carbon emissions from production, inventory holding, and transportation in a vendor–buyer supply chain under a single setup and multiple deliveries policy. Toptal and Çetinkaya [32] studied the effect of supply chain coordination and carbon emissions on vendor–buyer order quantity under lot-for-lot delivery. Bouchery et al. [33] examined different supply chain coordination configurations considering carbon emissions under limited vehicle capacity. Dwicahyani et al. [34] incorporated carbon emission costs, energy cost, and waste disposal for a two-echelon supply chain with remanufacturing. Li et al. [35] considered joint carbon tax and cap-and-trade policies for a two-echelon supply chain production–distribution model with transportation outsourcing. Wangsa [36] incorporated the government's penalties and incentive policies to reduce carbon emissions.

Anvar et al. [37] considered emissions from transportation and inventory-holding activities in a one-supplier multi-retailer supply chain. Hariga et al. [38] considered carbon tax and carbon cap policies for a two-echelon supply chain with vendor-managed consignment inventory partnership. The model incorporated emissions from the ordering process, production setup, and holding the inventory. Ji et al. [39] considered a carbon reduction investment from the supplier to get higher customer demand. Wang and Ye [40] compared the effect of considering carbon emissions on just-in-time and economic order quantity decisions for two-echelon supply chain inventory models. Ghosh et al. [41] considered a carbon tax regulation to minimize the total expected cost of a supply chain under stochastic demand and shortage backorder. Ma et al. [42] considered the effect of the carbon tax scheme between suppliers and buyer for production, procurement, and pricing decisions. Darom et al. [43] developed a manufacturer–retailer inventory model considering disruption risks and recovery with safety stock and the effect of carbon emission costs. The model considered carbon emissions from the transportation activities for a better recovery plan. Huang et al. [44] studied inventory and

pricing decisions considering carbon emission, production disruption, and controllable deterioration using preservation technology. Recently, Daryanto et al. [45] proposed a low-carbon three-echelon supply chain inventory model considering item deterioration. Kundu and Chakrabarti [46] developed a low-carbon supply chain inventory model taking into account the effect of inflation and the time-value of money. Other researchers incorporated carbon emissions in supplier selection and order allocation [47–49].

### 3. Problem Definition, Assumption, and Notations

#### 3.1. Problem Definition

This study considers a manufacturer–retailer supply chain that produces one type of item sold solely through one channel. The retailer orders  $n$  deliveries of equal lot size ( $Q$ ) per cycle. The manufacturer implements single-setup multiple-deliveries (SSMD). Hence, it produces  $nQ$  units of item per production cycle. This study develops two models considering two cases of quality inspection. (1) In the first, the buyer performs a complete quality inspection process. (2) In the second, the vendor performs the quality inspection so that no defective products are passed to the buyer. The defective items are sold at a discounted price with no additional cost in both scenarios. Both the vendor and the buyer consider the carbon emission costs in their decision to comply with the carbon tax regulation. Model 1 is an extension of Tiwari et al.'s [15] model by introducing weight and distance-dependent transportation costs in addition to the fixed and variable inspection costs. Later, the second model extends the first model by studying another inspection option to reduce the expected total costs and emissions.

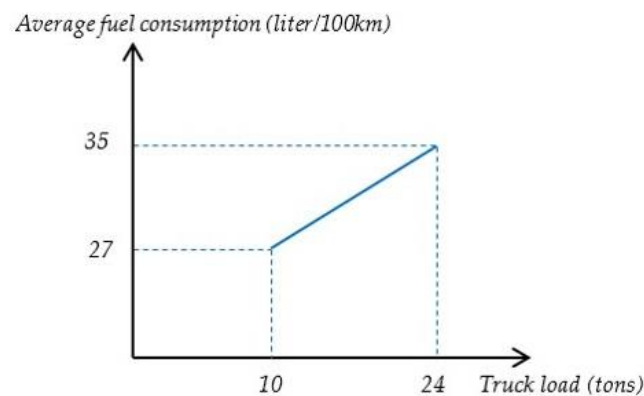
#### 3.2. Assumption and Notation

This study explores real-life problems of cost minimization and carbon emission reduction under certain assumptions of a controlled situation. The assumptions are listed below, while the notations are presented in Table 2.

1. The retailer's demand rate and the manufacturer's production rate are known and constant.
2. The manufacturer implements a single-setup multiple-deliveries (SSMD) policy. Based on the retailer's order, the manufacturer produces  $nQ$  units of item per production cycle to reduce the setup time and cost. Then, it delivers the item in an equal lot sizes and constant time intervals [50].
3. The replenishment is instantaneous.
4. The items deteriorate in the manufacturer and retailer's inventory. The deterioration rate for both the manufacturer and retailer are equal and constant.
5. The defective percentage,  $u$ , has a uniform distribution where  $0 \leq \alpha < \beta < 1$ .
6. Good products are always available during the quality inspection as  $x > D$ .
7. The retailer (in Model 1) and the manufacturer (in Model 2) perform a 100% quality inspection to ensure an excellent service.
8. The fixed inspection cost per cycle is constant, whether performed by the buyer or the manufacturer.
9. Carbon emissions come from the fuel and electricity consumption during transporting and holding the inventory.
10. Shortage is not considered.
11. The additional fuel consumption is a linear function of truckloads. Figure 3 illustrates the linear fuel consumption model, which is similar to that of Hariga et al. [30] with an example of the dataset from Volvo Corporation [51].

Table 2. List of notations.

| Symbol                    | Definition                                                                                             |
|---------------------------|--------------------------------------------------------------------------------------------------------|
| $D$                       | demand rate (unit/year);                                                                               |
| $P$                       | production rate (unit/year);                                                                           |
| $R$                       | production quantity; $R = PT_1$ ;                                                                      |
| $\theta$                  | deterioration rate; ( $0 \leq \theta < 1$ );                                                           |
| $u$                       | the probability of defective products per delivery lot size;                                           |
| $x$                       | quality screening rate (unit/year);                                                                    |
| $i_c$                     | fixed quality inspection cost (\$/cycle);                                                              |
| $u_c$                     | unit inspection cost (\$/unit);                                                                        |
| $c$                       | retailer's ordering cost (\$/order);                                                                   |
| $h_d$                     | retailer's holding cost (\$/unit/year);                                                                |
| $d_d$                     | retailer's deteriorating cost (\$/unit);                                                               |
| $s$                       | manufacturer's setup cost (\$/order);                                                                  |
| $h_p$                     | manufacturer's holding cost (\$/unit/year);                                                            |
| $d_p$                     | manufacturer's deteriorating cost (\$/unit);                                                           |
| $t_f$                     | manufacturer's fixed transportation cost per delivery (\$/delivery);                                   |
| $t_v$                     | fuel price for manufacturer's variable transportation cost (\$/liter);                                 |
| $d$                       | distance traveled from vendor to buyer (km);                                                           |
| $w$                       | product weight (ton/unit);                                                                             |
| $c_1$                     | average vehicle fuel consumption when empty (liter/km);                                                |
| $c_2$                     | average additional fuel consumption per ton of load (liter/km/ton);                                    |
| $T_x$                     | carbon emission tax (\$/tonCO <sub>2</sub> );                                                          |
| $F_e$                     | average emissions from fuel combustion (tonCO <sub>2</sub> /liter);                                    |
| $E_e$                     | average emissions from electricity generation (tonCO <sub>2</sub> /kWh);                               |
| $e_1$                     | transportation emission cost (\$/km); $e_1 = c_1 F_e T_x$ ;                                            |
| $e_2$                     | average additional transportation emission cost per unit product (\$/unit/km); $e_2 = c_2 w F_e T_x$ ; |
| $e_c$                     | average warehouse energy consumption per unit product (kWh/unit/year);                                 |
| $w_e$                     | warehouse emissions cost per unit product (\$/unit/year); $w_e = e_c E_e T_x$ ;                        |
| $T$                       | cycle length;                                                                                          |
| $T_1$                     | production period for the manufacturer in each cycle;                                                  |
| $T_2$                     | nonproduction period for the manufacturer in each cycle;                                               |
| $T_i$                     | inspection time per delivery for the retailer;                                                         |
| $T_b$                     | inventory cycle length per delivery for the retailer; $T_b = T/n$ ;                                    |
| $I_p(t)$                  | manufacturer's inventory level at time $t$ ;                                                           |
| $I_{pd}(t)$               | manufacturer's inventory for defective products at time $t$ ;                                          |
| $I_d(t)$                  | retailer's inventory level at time $t$ ;                                                               |
| $ETC_d$                   | retailer's expected total cost per year (\$/year);                                                     |
| $ETC_p$                   | manufacturer's expected total cost per year (\$/year);                                                 |
| $ETC$                     | joint expected total cost per year (\$/year);                                                          |
| $ETE_d$                   | retailer's expected total carbon emissions per year (tonCO <sub>2</sub> /year);                        |
| $ETE_p$                   | manufacturer's expected total carbon emissions per year (tonCO <sub>2</sub> /year);                    |
| $ETE$                     | joint expected total carbon emissions per year (tonCO <sub>2</sub> /year);                             |
| <b>Decision variables</b> |                                                                                                        |
| $Q$                       | delivery lot size (unit);                                                                              |
| $n$                       | number of deliveries per order (positive integer).                                                     |
| $*$                       | indicates optimal solution                                                                             |



**Figure 3.** Linear function of average fuel consumption vs. total weight for regional traffic (Data source: Volvo Corporation, 2018).

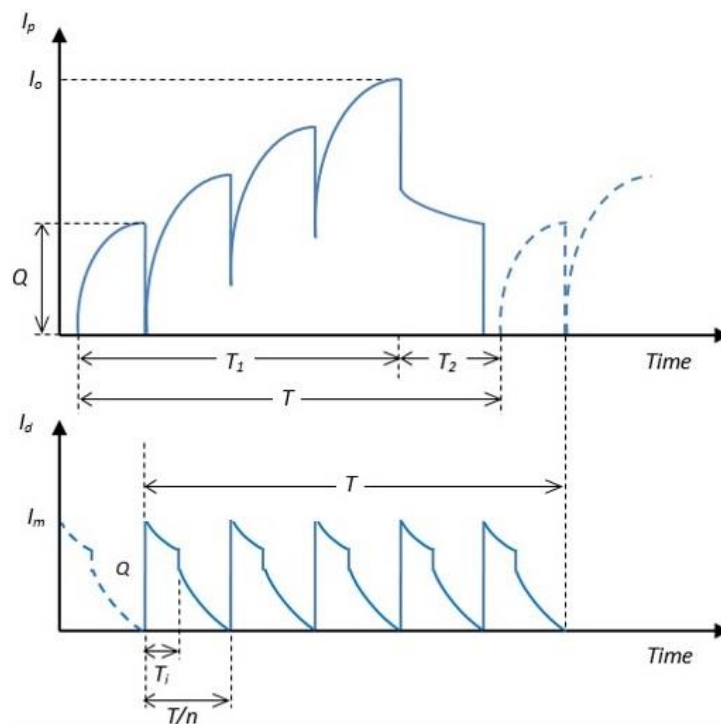
#### 4. Model Development

This section provides model development for two inspection cases.

##### 4.1. Model Development with Retailer Inspection

This sub-section presents model development when quality inspection becomes the retailer's responsibility. The model is adapted from Tiwari et al. [15]. However, this study considers weight and distance-dependent transportation cost.

The inventory level of the manufacturer and the retailer is illustrated in Figure 4. In one production cycle, the manufacturer produces  $PT_1$  units of the item, and delivers all the produced items to the retailer  $n$  times with a constant lot size  $Q$ . Right after receiving each lot, the retailer starts the quality inspection that ends at  $T_i$ . At  $T_i$ ,  $uQ$  units of defective products will be removed from the inventory. During the period  $[0, T/n]$ , the retailer's inventory decreases due to demand.



**Figure 4.** Manufacturer's and retailer's inventory model for constantly deteriorating items with retailer's inspection for  $n = 5$ .



#### 4.1.1. Retailer Cost and Emission

As  $c$  is the retailer's ordering cost, the ordering cost per year is given by  $c/T$  (Lee and Kim [22], Yang and Wee [52]). After a lot arrived, the 100% quality inspection starts and then finishes at  $T_i$ . As there are fixed inspection costs per delivery,  $i_c$ , and unit inspection costs,  $u_c$  (Sarkar et al. [12]), the inspection cost per year is given by:

$$i_c \frac{n}{T} + u_c Q \frac{n}{T} = \frac{n}{T} (i_c + u_c Q) \quad (1)$$

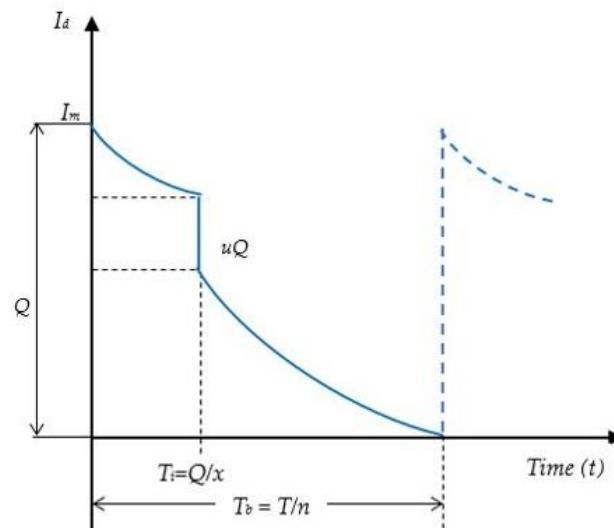


Figure 5. Retailer's inventory model with imperfect quality per delivery cycle.

Figure 5 illustrates the retailer's on-hand inventory per delivery cycle. The inventory level, considering deterioration and imperfect quality, has been studied by researchers such as Jaggi et al. [53] and results in the following equations:

$$I_d(t) = Qe^{-\theta t} + \frac{D}{\theta} (e^{-\theta t} - 1), \quad 0 \leq t \leq Q/x \quad (2)$$

$$I_d(t) = Qe^{-\theta t} + \frac{D}{\theta} (e^{-\theta t} - 1) - uQ, \quad Q/x \leq t \leq T/n \quad (3)$$

At  $t = T/n$ ,  $I_d(T/n) = 0$ , therefore equation (3) becomes:

$$Qe^{-\theta T/n} + \frac{D}{\theta} (e^{-\theta T/n} - 1) - uQ = 0$$

Solving the equation for  $Q$ , one has:

$$Q = -\frac{D(e^{-\theta T/n} - 1)}{\theta(e^{-\theta T/n} - u)} = \frac{D(e^{-\theta T/n} - 1)}{\theta(u - e^{-\theta T/n})} \text{ which is } = \frac{D(e^{\theta T/n} - 1)}{\theta(1 - ue^{\theta T/n})} \text{ (Jaggi et al. [53])}$$

Hence:

$$Q = I_d(0) = \frac{D(e^{\theta T/n} - 1)}{\theta(1 - ue^{\theta T/n})} \quad (4)$$

Further, the on-hand inventory per year for the retailer is:

$$\frac{n}{T} \left[ \int_0^{Q/x} I_d(t) dt + \int_{Q/x}^{T/n} I_d(t) dt \right]$$

$$\frac{n}{T} \left[ \frac{Q}{\theta} \left( 1 - e^{-\frac{\theta Q}{x}} \right) - \frac{D}{\theta^2} \left( \frac{Q\theta}{x} + e^{-\frac{\theta Q}{x}} - 1 \right) - \frac{1}{\theta} \left( e^{-\frac{\theta T}{n}} - e^{-\frac{\theta Q}{x}} \right) \left( Q + \frac{D}{\theta} \right) - \left( \frac{T}{n} - \frac{Q}{x} \right) \left( uQ + \frac{D}{\theta} \right) \right] \quad (5)$$

We assumed that storing the items requires electrical energy with a certain amount of carbon footprint. Therefore, substituting Equations (4) with (5) and considering the retailer's holding costs and emissions, the inventory holding and emission cost per year becomes:

$$(h_d + w_e) \frac{n}{T} \left[ \frac{D}{\theta^2 \left( u e^{\frac{\theta T}{n}} - 1 \right)^2} \left( \frac{u D}{x} \left( 1 + e^{\frac{2\theta T}{n}} - 2e^{\frac{\theta T}{n}} \right) + u \left( 1 - e^{\frac{2\theta T}{n}} + u e^{\frac{2\theta T}{n}} - u e^{\frac{\theta T}{n}} \right) + \frac{\theta T}{n} \left( u - 1 + u e^{\frac{\theta T}{n}} - u^2 e^{\frac{\theta T}{n}} \right) + e^{\frac{\theta T}{n}} - 1 \right) \right] \quad (6)$$

Considering the expected probability value of the defective products ( $E[u]$ ), the average warehouse energy consumption per unit product ( $e_c$ ), and the average emission from electricity generation ( $E_e$ ), from Equation (6), the retailer's expected carbon footprint ( $ETE_d$ ) per year of holding the inventory is:

$$\begin{aligned} ETE_d &= (e_c E_e) \frac{n}{T} \left[ \frac{D}{\theta^2 \left( E[u] e^{\frac{\theta T}{n}} - 1 \right)^2} \left( \frac{E[u] D}{x} \left( 1 + e^{\frac{2\theta T}{n}} - 2e^{\frac{\theta T}{n}} \right) \right. \right. \\ &\quad \left. \left. + E[u] \left( 1 - e^{\frac{2\theta T}{n}} + E[u] e^{\frac{2\theta T}{n}} - E[u] e^{\frac{\theta T}{n}} \right) \right. \right. \\ &\quad \left. \left. + \frac{\theta T}{n} \left( E[u] - 1 + E[u] e^{\frac{\theta T}{n}} - E[u]^2 e^{\frac{\theta T}{n}} \right) + e^{\frac{\theta T}{n}} - 1 \right) \right] \end{aligned} \quad (7)$$

The retailer's deteriorating cost per year is:

$$\frac{d_d n}{T} \left( Q - uQ - \frac{DT}{n} \right) = d_d \left( \frac{(1-u)n}{T} \frac{D(e^{\theta T/n} - 1)}{\theta(1 - u e^{\theta T/n})} - D \right) \quad (8)$$

The retailer's total cost is the sum of the ordering, inspection, deteriorating, inventory holding, and emission costs. Therefore, considering the probability of the defective products, the expected total cost per year is:

$$\begin{aligned} ETC_d &= \frac{c}{T} + \frac{n}{T} \left( i_c + u_c \frac{D(e^{\frac{\theta T}{n}} - 1)}{\theta(1 - E[u] e^{\frac{\theta T}{n}})} \right) + d_d \left( \frac{(1-E[u])n}{T} \frac{D(e^{\theta T/n} - 1)}{\theta(1 - E[u] e^{\theta T/n})} - D \right) \\ &\quad + (h_d + w_e) \frac{nD}{T \theta^2 \left( E[u] e^{\frac{\theta T}{n}} - 1 \right)^2} \left( \frac{E[u] D}{x} \left( 1 + e^{\frac{2\theta T}{n}} - 2e^{\frac{\theta T}{n}} \right) \right. \\ &\quad \left. + E[u] \left( 1 - e^{\frac{2\theta T}{n}} + E[u] e^{\frac{2\theta T}{n}} - E[u] e^{\frac{\theta T}{n}} \right) \right. \\ &\quad \left. + \frac{\theta T}{n} \left( E[u] - 1 + E[u] e^{\frac{\theta T}{n}} - E[u]^2 e^{\frac{\theta T}{n}} \right) + e^{\frac{\theta T}{n}} - 1 \right) \end{aligned} \quad (9)$$

#### 4.1.2. Manufacturer Cost and Emission

After the arrival of the retailer's order, the manufacturer starts the production of  $nQ$  units of the item at a production rate  $P$ . Since  $s$  is the setup cost per production cycle, the manufacturer's setup cost per year is  $s/T$ .

The first delivery occurs as soon as the quantity is met. The following deliveries occur at  $T/n$  intervals. The transportation cost belongs to the manufacturer and consist of fixed and variable costs. Swenseth and Godfrey [54], Nie et al. [55], Rahman et al. [56], and Wangsa and Wee [57] incorporated the variable transportation cost, which is affected by the shipping distance and truckloads. The manufacturer's transportation cost per delivery is given by:

$$t_f + 2dc_1 t_v + dQwc_2 t_v \quad (10)$$

The first element is the fixed transportation setup cost. The second element calculates the transportation cost of an empty truck. As the truck goes from the manufacturer to the retailer and then goes back, the distance is multiplied by two. Then, the transportation cost for the truckload is calculated, which depends on the delivery distance and quantity, product weight, additional fuel consumption per ton per km, and the fuel price. Substituting Equation (4) to (10), the manufacturer's transportation cost per year is given by:

$$\frac{n}{T} \left( t_f + 2dc_1t_v + d \frac{D(e^{\theta T/n} - 1)}{\theta(1 - ue^{\theta T/n})} wc_2t_v \right) \quad (11)$$

Wahab et al. [10] identified that the emissions from transportation were affected by the delivery distance, actual shipment weight, fuel consumption per km, and CO<sub>2</sub> emissions per liter of fuel. Therefore, the amount of the manufacturer's carbon emission per year as the result of transportation activity can be derived as follows:

$$\frac{n}{T} (2dc_1 + dQwc_2) F_e = \frac{n}{T} \left( 2dc_1 + d \frac{D(e^{\theta T/n} - 1)}{\theta(1 - ue^{\theta T/n})} wc_2 \right) F_e \quad (12)$$

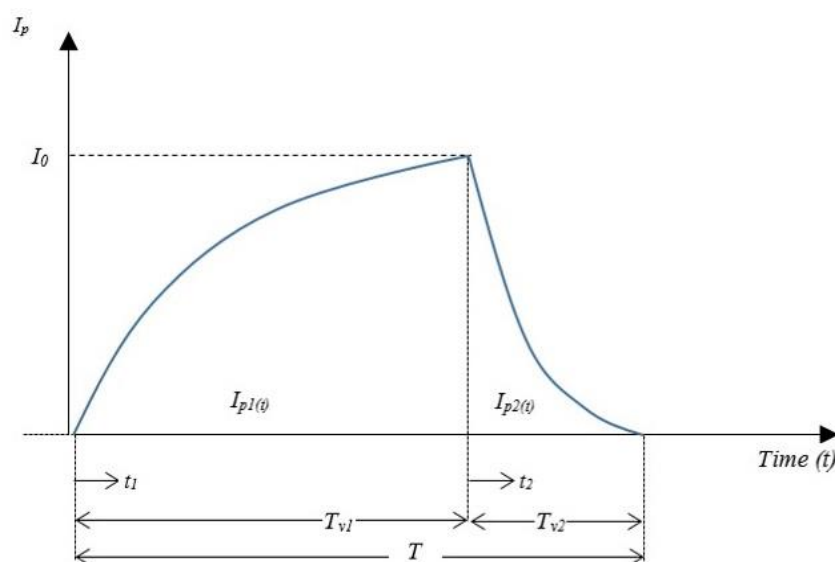


Figure 6.  $I_{p1}(t_1)$  and  $I_{p2}(t_2)$  vs. time.

As depicted in Figure 6, Lee and Kim [22] studied a similar inventory model for the manufacturer using Yang and Wee's [52] approach. Both production and consumption occur during  $T_1$ , while only consumption occurs during  $T_2$ . Hsu [58] suggested some revision considering the effect of defective products. Due to defective products and the retailer's quality inspection, the effective demand rate for the manufacturer becomes  $D/(1-u)$ . Therefore, the inventory functions are as follows:

$$I_{p1}(t_1) = \frac{P - (D/(1-u))}{\theta} (1 - e^{-\theta t_1}), \quad 0 \leq t_1 \leq T_1 \quad (13)$$

$$I_{p2}(t_2) = \frac{(D/(1-u))}{\theta} (e^{\theta(T_2-t_2)} - 1), \quad 0 \leq t_2 \leq T_2 \quad (14)$$

From the boundary condition  $I_{p1}(T_1) = I_{p2}(0)$  and following Misra's [59] approximation:

$$\left( P - \frac{D}{1-u} \right) T_1 \left( 1 - \frac{1}{2} \theta T_1 \right) = \left( \frac{D}{1-u} \right) T_2 \left( 1 + \frac{1}{2} \theta T_2 \right)$$

Hence, one has:

$$T_1 \approx \frac{D}{(1-u)P-D} T_2 \left( 1 + \frac{1}{2} \theta T_2 \right) \quad (15)$$

$$T \approx \frac{T_2}{(1-u)P-D} \left( (1-u)P + \frac{1}{2} D \theta T_2 \right) \quad (16)$$

From Yang and Wee [52], the manufacturer's inventory per cycle is:

$$\int_0^{T_1} I_{p1}(t_1) dt_1 + \int_0^{T_2} I_{p2}(t_2) dt_2 - n \int_0^{T/n} I_d(t) dt \quad (17)$$

Hence, the manufacturer's holding cost per year is:

$$\begin{aligned} & \frac{h_p}{T} \left[ \frac{P-(D/(1-u))}{\theta} T_1 + \frac{P-(D/(1-u))}{\theta^2} (e^{-\theta T_1} - 1) \right. \\ & \quad \left. - \frac{(D/(1-u))T_2}{\theta} - \frac{(D/(1-u))}{\theta^2} (1 - e^{\theta T_2}) \right] \\ & - n \left( \frac{D}{\theta^2 (ue^{\frac{\theta T}{n}} - 1)^2} \left( \frac{uD}{x} \left( 1 + e^{\frac{2\theta T}{n}} - 2e^{\frac{\theta T}{n}} \right) + u \left( 1 - e^{\frac{2\theta T}{n}} + ue^{\frac{2\theta T}{n}} - ue^{\frac{\theta T}{n}} \right) \right. \right. \\ & \quad \left. \left. + \frac{\theta T}{n} \left( u - 1 + ue^{\frac{\theta T}{n}} - u^2 e^{\frac{\theta T}{n}} \right) + e^{\frac{\theta T}{n}} - 1 \right) \right) \end{aligned} \quad (18)$$

The amount of a manufacturer's carbon emissions per year as the result of warehousing activity can be derived as follows:

$$\begin{aligned} & \frac{e_c E_e}{T} \left[ \frac{P-(D/(1-u))}{\theta} T_1 + \frac{P-(D/(1-u))}{\theta^2} (e^{-\theta T_1} - 1) \right. \\ & \quad \left. - \frac{(D/(1-u))T_2}{\theta} - \frac{(D/(1-u))}{\theta^2} (1 - e^{\theta T_2}) \right] \\ & - n \left( \frac{D}{\theta^2 (ue^{\frac{\theta T}{n}} - 1)^2} \left( \frac{uD}{x} \left( 1 + e^{\frac{2\theta T}{n}} - 2e^{\frac{\theta T}{n}} \right) + u \left( 1 - e^{\frac{2\theta T}{n}} + ue^{\frac{2\theta T}{n}} - ue^{\frac{\theta T}{n}} \right) \right. \right. \\ & \quad \left. \left. + \frac{\theta T}{n} \left( u - 1 + ue^{\frac{\theta T}{n}} - u^2 e^{\frac{\theta T}{n}} \right) + e^{\frac{\theta T}{n}} - 1 \right) \right) \end{aligned} \quad (19)$$

The manufacturer's carbon emissions per year come from Equations (12) and (19). Therefore, the manufacturer's carbon emission cost is:

$$\begin{aligned} & \frac{n}{T} \left( 2de_1 + d \frac{D(e^{\theta T/n} - 1)}{\theta(1 - ue^{\theta T/n})} e_2 \right) \\ & + \frac{w_e}{T} \left[ \frac{P-(D/(1-u))}{\theta} T_1 + \frac{P-(D/(1-u))}{\theta^2} (e^{-\theta T_1} - 1) - \frac{(D/(1-u))T_2}{\theta} - \frac{(D/(1-u))}{\theta^2} (1 - e^{\theta T_2}) \right. \\ & \quad \left. - n \left( \frac{D}{\theta^2 (ue^{\frac{\theta T}{n}} - 1)^2} \left( \frac{uD}{x} \left( 1 + e^{\frac{2\theta T}{n}} - 2e^{\frac{\theta T}{n}} \right) + u \left( 1 - e^{\frac{2\theta T}{n}} + ue^{\frac{2\theta T}{n}} - ue^{\frac{\theta T}{n}} \right) \right. \right. \right. \\ & \quad \left. \left. + \frac{\theta T}{n} \left( u - 1 + ue^{\frac{\theta T}{n}} - u^2 e^{\frac{\theta T}{n}} \right) + e^{\frac{\theta T}{n}} - 1 \right) \right) \right] \end{aligned} \quad (20)$$

The loss due to deterioration in the manufacturer's inventory is the total production during the period  $T_1$ , minus the total delivered products to the retailer's inventory. Therefore, the manufacturer's deteriorating cost per year is:

$$\frac{d_p}{T} \left( PT_1 - n \left( \frac{D(e^{\theta T/n} - 1)}{\theta(1 - ue^{\theta T/n})} \right) \right) \quad (21)$$

From Equations (11), (18), (20), and (21), as well as the setup cost, and considering the probability of the defective products, the manufacturer's expected total cost per year is:

$$\begin{aligned}
 ETC_p = & \frac{s}{T} + \frac{n}{T} \left( t_f + 2dc_1t_v + d \frac{D(e^{\theta T/n} - 1)}{\theta(1-E[u]e^{\theta T/n})} wc_2t_v \right) \\
 & + \frac{(h_p + w_e)}{T} \left[ \frac{P - (D/(1-E[u]))}{\theta} T_1 + \frac{P - (D/(1-E[u]))}{\theta^2} (e^{-\theta T_1} - 1) \right. \\
 & \left. - \frac{(D/(1-E[u]))T_2}{\theta} - \frac{(D/(1-E[u]))}{\theta^2} (1 - e^{\theta T_2}) \right. \\
 & \left. - n \left( \frac{D}{\theta^2 (E[u]e^{\frac{\theta T}{n}} - 1)} \left( e^{\frac{\theta T}{n}} - 1 + \frac{E[u]D}{x} \left( 1 + e^{\frac{2\theta T}{n}} - 2e^{\frac{\theta T}{n}} \right) \right. \right. \right. \\
 & \left. \left. + E[u] \left( 1 - e^{\frac{2\theta T}{n}} + E[u]e^{\frac{2\theta T}{n}} - E[u]e^{\frac{\theta T}{n}} \right) \right. \right. \\
 & \left. \left. + \frac{\theta T}{n} \left( E[u] - 1 + E[u]e^{\frac{\theta T}{n}} - E[u]^2 e^{\frac{\theta T}{n}} \right) \right) \right] \\
 & + \frac{n}{T} \left( 2de_1 + d \frac{D(e^{\theta T/n} - 1)}{\theta(1-E[u]e^{\theta T/n})} e_2 \right) + \frac{d_p}{T} \left( PT_1 - n \left( \frac{D(e^{\theta T/n} - 1)}{\theta(1-ue^{\theta T/n})} \right) \right)
 \end{aligned} \quad (22)$$

#### 4.1.3. The Integrated Manufacturer and Retailer Cost Function

In an integrated decision, the manufacturer and the retailer jointly specify  $n$ , which minimizes the expected total cost ( $ETC$ ). The  $ETC$  is the sum of  $ETC_d$  and  $ETC_p$  in Equations (9) and (22).

Using Taylor's series expansion for a small value of  $\theta T/n$ ,  $\theta T_1$ , and  $\theta T_2$ , we can solve the cost function by assuming  $e^x$  as  $1 + x + x^2/2 + x^3/6$ . Furthermore, the expected total emissions ( $ETE$ ) per year from the manufacturer and the retailer can be derived from Equations (7), (12), and (19).

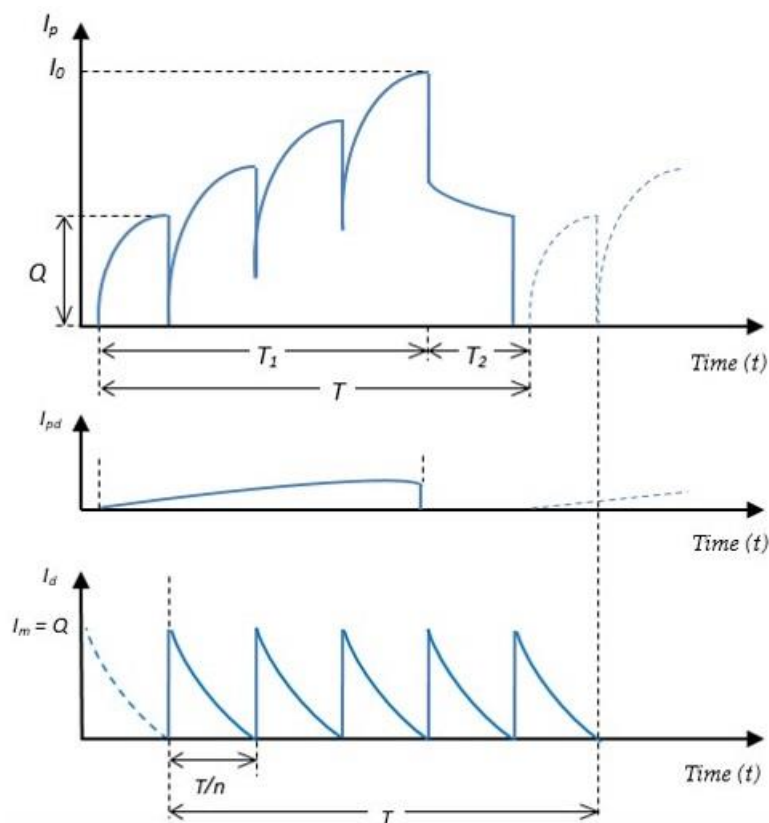
#### 4.1.4. Methodology and Solution Search

The objective is to determine the optimal number of deliveries ( $n^*$ ) that minimize the expected total cost function ( $ETC$ ). The value of  $n^*$  and the respective  $T$ ,  $T_1$ , and  $T_2$  will lead us to the optimal delivery quantity  $Q^*$  and production quantity  $R$ . The proposed procedure to derive the positive integer decision variable  $n$  is adapted from Tiwari et al. [15] and Yang and Wee [52] as follows:

- Step 1. Substitute the  $T_1$  and  $T$  functions in Equations (15) and (16) into  $ETC$ ;
- Step 2. Input all the known parameters;
- Step 3. Set  $n = 1$ ;
- Step 4. Derive the partial derivative of  $ETC$  with respect to  $T_2$  and set it to zero. Solve the equation to find the value of  $T_2$ ;
- Step 5. Use the known  $n$  and  $T_2$  to find the value of  $T_1$  and  $T$  using Equations (15) and (16).
- Step 6. Derive the corresponding  $ETC$ ;
- Step 7. If  $ETC(n) > ETC(n - 1)$ , then  $n^* = n - 1$  and go to Step 8; otherwise, set  $n = n + 1$  and go back to Step 4;
- Step 8. Use  $n^*$  and the corresponding  $T^*$  to find  $Q^*$  from Equation (4) and calculate  $R = PT_1^*$ .

#### 4.2. Model Development with Manufacturer Inspection

This sub-section presents the model development when quality inspection becomes the manufacturer's responsibility. The purpose of such a policy is to prevent transporting defective products. The manufacturer performs a quality inspection of all the produced products and keeps the defective products separately until the end of the production period  $T_1$ . The defective products will be sold at a discounted price to the secondary market. The inventory level for both the manufacturer ( $I_p$ ) and the retailer ( $I_d$ ), including the manufacturer's inventory of the defective products ( $I_{pd}$ ), is illustrated in Figure 7. In this model, the  $I_{pd}$  is accumulated during the  $T_1$  period. Besides,  $I_d$  decreases solely due to demand.



**Figure 7.** Manufacturer's and retailer's inventory model for constant deteriorating items with manufacturer's inspection for  $n = 5$ .

#### 4.2.1. Retailer Cost and Emission

The retailer's total cost is the sum of the ordering, inventory holding, deteriorating, and emission costs. The ordering cost per year is given by  $c/T$ , which is similar to Model 1 (Section 4.1.1). During the  $T/n$  period,  $I_d$  decreases due to demand and deterioration. From Yang and Wee [52], the inventory function is as follows:

$$I_d(t) = \frac{D}{\theta} \left( e^{\theta(\frac{T}{n} - t)} - 1 \right), 0 \leq t \leq T/n \quad (23)$$

and

$$Q = I_d(0) = \frac{D}{\theta} \left( e^{\frac{\theta T}{n}} - 1 \right) \quad (24)$$

and the holding cost per year is:

$$h_d \frac{n}{T} \left( \int_0^{T/n} I_d(t) dt \right) = h_d \frac{n}{T} \left( \frac{D}{\theta} \left( \frac{1}{\theta} \left( e^{\frac{\theta T}{n}} - 1 \right) - \frac{T}{n} \right) \right) \quad (25)$$

Further, the deteriorating cost per year is:

$$d_d \frac{n}{T} \left( Q - D \frac{T}{n} \right) = d_d \frac{n}{T} \left( \frac{D}{\theta} \left( e^{\frac{\theta T}{n}} - 1 \right) - \frac{DT}{n} \right) \quad (26)$$

$$ETE_d = e_c E_e \left( \frac{n}{T} \frac{D}{\theta} \left( \frac{1}{\theta} \left( e^{\frac{\theta T}{n}} - 1 \right) - \frac{T}{n} \right) \right) \quad (27)$$

Equation (27) shows the retailer's carbon emission ( $ETE_d$ ) from holding the inventory. Therefore, the retailer's carbon emission cost per year is:

$$w_e \left( \frac{n}{T} \frac{D}{\theta} \left( \frac{1}{\theta} \left( e^{\frac{\theta T}{n}} - 1 \right) - \frac{T}{n} \right) \right) \quad (28)$$

The retailer's expected total cost per year ( $ETC_d$ ) becomes:

$$ETC_d = \frac{c}{T} + (h_d + w_e) \frac{n}{T} \left( \frac{D}{\theta} \left( \frac{1}{\theta} \left( e^{\frac{\theta T}{n}} - 1 \right) - \frac{T}{n} \right) \right) + d_d \frac{n}{T} \left( \frac{D}{\theta} \left( e^{\frac{\theta T}{n}} - 1 \right) - \frac{DT}{n} \right) \quad (29)$$

#### 4.2.2. Manufacturer Cost and Emission

Due to some percentage of defective products, the production rate of the perfect product is  $(1 - u)P$ . The manufacturer's setup cost per year is  $s/T$ . In this model, the manufacturer will have an additional inspection cost. Since the total number of products being produced per production cycle is  $PT_1$ , considering a fixed inspection cost per cycle ( $i_c$ ) and unit inspection cost ( $u_c$ ), the manufacturer's inspection cost per year is:

$$\frac{i_c}{T} + \frac{u_c PT_1}{T} \quad (30)$$

The manufacturer's transportation function is similar to Equation (10); therefore, the transportation cost and emissions per year become:

$$\frac{n}{T} \left( t_f + 2dc_1 t_v + d \frac{D}{\theta} \left( e^{\frac{\theta T}{n}} - 1 \right) wc_2 t_v \right) \quad (31)$$

$$\frac{n}{T} \left( 2dc_1 + d \frac{D}{\theta} \left( e^{\frac{\theta T}{n}} - 1 \right) wc_2 \right) F_e \quad (32)$$

From Figure 6, the inventory differential equations are:

$$dI_{p1}(t_1) = ((1 - u)P - D)dt_1 - \theta I_{p1}(t_1)dt_1, \quad 0 \leq t_1 \leq T_1$$

$$dI_{p2}(t_2) = -Ddt_2 - \theta I_{p2}(t_2)dt_2, \quad 0 \leq t_2 \leq T_2$$

For the boundary condition for  $t_1 = 0$ ,  $I_1(0) = 0$  and for  $t_2 = 0$ ,  $I_2(0) = I_0$  and for  $t_2 = T_2$ ,  $I_2(T_2) = 0$ , the manufacturer's inventory functions for the good products are:

$$I_{p1}(t_1) = \frac{(1 - u)P - D}{\theta} \left( 1 - e^{-\theta t_1} \right), \quad 0 \leq t_1 \leq T_1 \quad (33)$$

$$I_{p2}(t_2) = \frac{D}{\theta} \left( e^{\theta (T_2 - t_2)} - 1 \right), \quad 0 \leq t_2 \leq T_2 \quad (34)$$

From the boundary condition  $I_{p1}(T_1) = I_{p2}(0)$ , we have the following equation:

$$\frac{((1 - u)P - D)}{\theta} \left( 1 - e^{-\theta T_1} \right) = \frac{D}{\theta} \left( e^{\theta T_2} - 1 \right) \quad (35)$$

From Taylor's series expansion and the assumption of  $\theta T \ll 1$ , following Misra's [59] approximation, one has:

$$((1 - u)P - D)T_1 \left( 1 - \frac{1}{2}\theta T_1 \right) = DT_2 \left( 1 + \frac{1}{2}\theta T_2 \right)$$

$$T_1 \approx \frac{D}{(1-u)P-D} T_2 \left(1 + \frac{1}{2} \theta T_2\right) \quad (36)$$

$$T \approx \frac{T_2}{(1-u)P-D} \left((1-u)P + \frac{1}{2} D \theta T_2\right) \quad (37)$$

Therefore, the manufacturer's inventory for good products becomes:

$$\int_0^{T_1} \frac{(1-u)P-D}{\theta} (1 - e^{-\theta t_1}) dt_1 + \int_0^{T_2} \frac{D}{\theta} (e^{\theta(T_2-t_2)} - 1) dt_2 - n \left[ \frac{D}{\theta} \left( \frac{1}{\theta} (e^{\frac{\theta T}{n}} - 1) - \frac{T}{n} \right) \right] \quad (38)$$

Besides, there is an inventory of defective products. From Figure 6, the inventory differential equation for the defective products is:

$$dI_{pd}(t_1) = uP dt_1 - \theta I_{pd}(t_1) dt_1, \quad 0 \leq t_1 \leq T_1$$

For the boundary condition for  $t_1 = 0$ ,  $I_1(0) = 0$ , the manufacturer's inventory function for the defective products is:

$$I_{pd}(t_1) = \frac{uP}{\theta} (1 - e^{-\theta t_1}), \quad 0 \leq t_1 \leq T_1$$

Therefore, the manufacturer's inventory of the defective products becomes:

$$\int_0^{T_1} \frac{uP}{\theta} (1 - e^{-\theta t_1}) dt_1 \quad (39)$$

Hence, the manufacturer's holding cost per year is:

$$\begin{aligned} \frac{h_p}{T} & \left( \frac{(1-u)P-D}{\theta} T_1 + \frac{(1-u)P-D}{\theta^2} (e^{-\theta T_1} - 1) - \frac{DT_2}{\theta} - \frac{D}{\theta^2} (1 - e^{\theta T_2}) \right. \\ & \left. - n \left( \frac{D}{\theta} \left( \frac{1}{\theta} (e^{\frac{\theta T}{n}} - 1) - \frac{T}{n} \right) \right) + \frac{uPT_1}{\theta} + \frac{uP}{\theta^2} (e^{-\theta T_1} - 1) \right) \end{aligned} \quad (40)$$

Therefore, based on Equations (32) and (40), the manufacturer's carbon emission cost and the total expected carbon emissions per year can be calculated as follows:

$$\begin{aligned} \frac{n}{T} & \left( 2de_1 + d \frac{D}{\theta} \left( e^{\frac{\theta T}{n}} - 1 \right) e_2 \right) \\ & + \frac{w_e}{T} \left( \frac{(1-u)P-D}{\theta} T_1 + \frac{(1-u)P-D}{\theta^2} (e^{-\theta T_1} - 1) - \frac{DT_2}{\theta} \right. \\ & \left. - \frac{D}{\theta^2} (1 - e^{\theta T_2}) - n \left( \frac{D}{\theta} \left( \frac{1}{\theta} (e^{\frac{\theta T}{n}} - 1) - \frac{T}{n} \right) \right) + \frac{uPT_1}{\theta} \right. \\ & \left. + \frac{uP}{\theta^2} (e^{-\theta T_1} - 1) \right) \end{aligned} \quad (41)$$

$$\begin{aligned} ETE_p & = \frac{n}{T} \left( 2dc_1 + d \frac{D}{\theta} \left( e^{\frac{\theta T}{n}} - 1 \right) wc_2 \right) F_e \\ & + \frac{e_c E_e}{T} \left( \frac{(1-u)P-D}{\theta} T_1 + \frac{(1-u)P-D}{\theta^2} (e^{-\theta T_1} - 1) - \frac{DT_2}{\theta} \right. \\ & \left. - \frac{D}{\theta^2} (1 - e^{\theta T_2}) - n \left( \frac{D}{\theta} \left( \frac{1}{\theta} (e^{\frac{\theta T}{n}} - 1) - \frac{T}{n} \right) \right) + \frac{uPT_1}{\theta} \right. \\ & \left. + \frac{uP}{\theta^2} (e^{-\theta T_1} - 1) \right) \end{aligned} \quad (42)$$

The number of deteriorated items in the manufacturer's inventory is the total production during the period  $T_1$ , minus the total products delivered to the buyer and the inventory of the defective products. Therefore, the manufacturer's deteriorating cost per year is:

$$\frac{d_p}{T} \left( (1-u)PT_1 - n \left( \frac{D}{\theta} (e^{\frac{\theta T}{n}} - 1) \right) + \left( uPT_1 - \frac{uP}{\theta} (1 - e^{-\theta T_1}) \right) \right) \quad (43)$$



Considering the additional inspection cost and the probability of the defective products, the manufacturer's expected total cost per year is:

$$\begin{aligned}
 ETC_p = & \frac{s}{T} + \frac{i_c}{T} + \frac{u_c PT_1}{T} + \frac{n}{T} \left( t_f + 2dc_1 t_v + d \frac{D}{\theta} \left( e^{\frac{\theta T}{n}} - 1 \right) wc_2 t_v \right) \\
 & + \frac{n}{T} \left( 2de_1 + d \frac{D}{\theta} \left( e^{\frac{\theta T}{n}} - 1 \right) e_2 \right) \\
 & + \frac{(h_p + w_e)}{T} \left( \frac{(1-E[u])P-D}{\theta} T_1 + \frac{(1-E[u])P-D}{\theta^2} (e^{-\theta T_1} - 1) \right. \\
 & \left. - \frac{DT_2}{\theta} - \frac{D}{\theta^2} (1 - e^{\theta T_2}) - n \left( \frac{D}{\theta} \left( \frac{1}{\theta} \left( e^{\frac{\theta T}{n}} - 1 \right) - \frac{T}{n} \right) \right) + \frac{E[u]PT_1}{\theta} \right. \\
 & \left. + \frac{E[u]P}{\theta^2} (e^{-\theta T_1} - 1) \right) \\
 & + \frac{d_p}{T} \left( (1 - E[u])PT_1 - n \left( \frac{D}{\theta} \left( e^{\frac{\theta T}{n}} - 1 \right) \right) \right. \\
 & \left. + \left( E[u]PT_1 - \frac{E[u]P}{\theta} (1 - e^{-\theta T_1}) \right) \right)
 \end{aligned} \quad (44)$$

#### 4.2.3. The Integrated Manufacturer and Retailer Cost Function

The *ETC* of the integrated system is the sum of Equations (29) and (44). Using Taylor's series expansion for a small value of  $\theta T/n$ ,  $\theta T_1$ , and  $\theta T_2$ , we can solve the cost function by assuming  $e^x$  as  $1 + x + x^2/2 + x^3/6$ . Furthermore, the *ETE* can be derived from Equation (27) and Equation (42).

#### 4.2.4. Methodology and Solution Search

Similar to Model 1, the objective is to determine the optimal number of deliveries ( $n^*$ ) that minimize the expected total cost function *ETC*. The proposed procedure to search for the optimum solution is as follows:

- Step 1. Substitute the  $T_1$  and  $T$  functions in Equations (36) and (37) into *ETC*;
- Step 2. Input all the known parameters;
- Step 3. Set  $n = 1$ ;
- Step 4. Derive the partial derivative of *ETC* with respect to  $T_2$  and set it to zero. Solve the equation to find the value of  $T_2$ ;
- Step 5. Use the known  $n$  and  $T_2$  to find the value of  $T_1$  and  $T$  using Equations (36) and (37).
- Step 6. Derive the corresponding *ETC*;
- Step 7. If  $ETC(n) > ETC(n-1)$  then  $n^* = n - 1$  and go to step 8, otherwise set  $n = n + 1$  and back to Step 4;
- Step 8. Use  $n^*$  and the corresponding  $T^*$  to find  $Q^*$  from Equation (24) and calculate  $R = PT_1^*$ .

### 5. Numerical Example and Management Insights

#### 5.1. Numerical Example 1

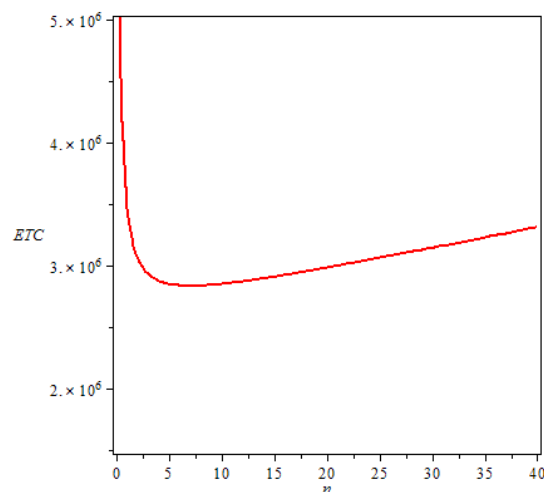
The values of the parameters are considered by adopting data from Yang and Wee [52], Hariga et al. [30], and Tiwari et al. [15] as  $P = 2,000,000$  units/year,  $D = 500,000$  units/year,  $x = 1,725,000$  unit/year,  $i_c = \$500/\text{delivery}$ ,  $u_c = \$0.5/\text{unit}$ ,  $c = \$2,000/\text{order}$ ,  $s = \$100,000/\text{setup}$ ,  $h_d = \$60/\text{unit/year}$ ,  $h_p = \$40/\text{unit/year}$ ,  $d_d = \$600/\text{unit}$ ,  $d_p = \$400/\text{unit}$ ,  $\theta = 0.1$ ,  $d = 100$  km,  $t_f = \$1000/\text{delivery}$ ,  $t_v = \$0.75/\text{liter}$ ,  $w = 0.01$  ton/unit,  $c_1 = 27$  L/100 km,  $c_2 = 0.57$  L/100 km/ton truckload,  $e_c = 1.44$  kWh/unit/year,  $T_x = \$75/\text{tonCO}_2$ ,  $F_e = 2.6 \times 10^{-3}$  tonCO<sub>2</sub>/L (US. EPA [60]),  $E_e = 0.5 \times 10^{-3}$  tonCO<sub>2</sub>/kWh (McCarthy [61]), and  $u$  is uniformly distributed in which  $\alpha = 0$  and  $\beta = 0.04$ , with  $E[u] = 0.02$ .

The minimum value of joint expected total cost can be obtained at  $n^* = 7$  with  $T_2 = 0.0651856$ ,  $T_1 = 0.0223966$ , and  $T = 0.0875822$ , as shown in Table 3. The *ETC* is \$2,834,922/year, which is from Equation (4), the optimum  $Q$  is 6,387.7 units. The optimum  $R$  is 44,793.2 units, and the *ETE* is 30.598 tonCO<sub>2</sub>/year. If the supply chain solely minimizes the total amount of carbon footprint, the decision is to perform a single-setup single-delivery (SSSD) as  $n = 1$  with *ETE* = 18.460 tonCO<sub>2</sub>/year (saving

39.7%). However, this situation increases the  $ETC$  into \$3,366,391 (18.7%). Figure 8 shows the convexity of  $ETC$  when  $n = 7$ .

**Table 3.** Expected total cost for different  $n$  in Model 1.

| $n$ | $T_2(10^{-5})$ | $T_1(10^{-5})$ | $T(10^{-5})$ | $ETC_d$   | $ETC_p$   | $ETC$     | $ETE$  |
|-----|----------------|----------------|--------------|-----------|-----------|-----------|--------|
| 1   | 4960           | 1703           | 6663         | 2,348,991 | 1,017,400 | 3,366,391 | 18.460 |
| 2   | 5641           | 1937           | 7578         | 1,463,323 | 1,568,493 | 3,031,816 | 21.333 |
| 3   | 5961           | 2048           | 8009         | 1,122,012 | 1,799,193 | 2,921,205 | 23.501 |
| 4   | 6161           | 2117           | 8278         | 941,509   | 1,930,509 | 2,872,018 | 25.422 |
| 5   | 6306           | 2167           | 8473         | 830,673   | 2,017,748 | 2,848,421 | 27.216 |
| 6   | 6422           | 2206           | 8628         | 756,370   | 2,081,526 | 2,837,896 | 28.935 |
| 7 * | 6518           | 2240           | 8758         | 703,611   | 2,131,311 | 2,834,922 | 30.598 |
| 8   | 6603           | 2269           | 8872         | 664,620   | 2,172,067 | 2,836,687 | 32.218 |
| 9   | 6680           | 2295           | 8976         | 634,952   | 2,206,651 | 2,841,603 | 33.805 |
| 10  | 6751           | 2320           | 9071         | 611,889   | 2,236,823 | 2,848,712 | 35.360 |



**Figure 8.** Graphical representation of expected total cost ( $ETC$ ) for a fixed  $n$  in Model 1.

When the probability of defective products, unit inspection costs, carbon tax, and variable transport cost are equal to zero ( $E[u] = u_c = T_x = t_v = 0$ ), the results are  $n = 7$ ,  $T = 0.08791$ , and  $ETC = \$2,559,246$  which are similar to the results of Yang and Wee [52].

## 5.2. Numerical Example 2

We consider the parameters in numerical example one and solve it using the Model 2 results of the following values. The minimum value of joint expected total cost can be obtained at  $n^* = 9$  and  $T = 0.08869$ , as shown in Table 4. The  $Q$ ,  $R$ , and  $ETC$  are 4,929.6 units, 45,360.7 units, and \$2,782,396/year, respectively. The  $ETE$  is 33.52 tonCO<sub>2</sub>/year.

**Table 4.** Expected total cost for different  $n$  in Model 2.

| $n$ | $T_2(10^{-5})$ | $T_1(10^{-5})$ | $T(10^{-5})$ | $ETC_d$   | $ETC_p$   | $ETC$     | $ETE$ |
|-----|----------------|----------------|--------------|-----------|-----------|-----------|-------|
| 1   | 4977           | 1709           | 6686         | 2,041,005 | 1,312,795 | 3,353,800 | 18.22 |
| 2   | 5653           | 1941           | 7595         | 1,167,506 | 1,844,193 | 3,011,699 | 21.07 |
| 3   | 5963           | 2048           | 8011         | 827,178   | 2,067,759 | 2,894,937 | 23.21 |
| 4   | 6151           | 2113           | 8264         | 644,684   | 2,195,273 | 2,839,957 | 25.12 |
| 5   | 6282           | 2158           | 8441         | 530,652   | 2,280,088 | 2,810,741 | 26.91 |
| 6   | 6384           | 2193           | 8577         | 425,568   | 2,342,142 | 2,794,711 | 28.63 |
| 7   | 6467           | 2222           | 8689         | 395,714   | 2,390,607 | 2,786,322 | 30.29 |
| 8   | 6538           | 2246           | 8784         | 352,240   | 2,430,297 | 2,782,747 | 31.92 |
| 9 * | 6601           | 2268           | 8869         | 318,411   | 2,463,985 | 2,782,396 | 33.52 |
| 10  | 6658           | 2288           | 8945         | 290,923   | 2,493,378 | 2,784,301 | 35.11 |

Table 5 provides the cost comparison between the two models for the result of examples one and two. The number of deliveries per cycle ( $n$ ) is higher in Model 2 (when the manufacturer performs the quality inspection), while the delivery lot size ( $Q$ ) is lower. All the retailer's cost components decrease, while all the manufacturer's cost components increase, except for the setup cost. In total, the  $ETC$  of Model 2 is 1.85% lower than the  $ETC$  in Model 1. However, the retailer's total costs were reduced by 54.7%, while the manufacturer's total costs increased by 15.6%. Considering this situation, cost-saving compensation from the retailer to the manufacturer is an alternative solution so that both parties take advantage of the implementation of the second inspection policy. Based on Goyal [62]:

$$z = \frac{ETC_{d-case1}}{ETC_{case1}}$$

$z$  is the retailer's cost coefficient. Therefore,  $ETC_d$  and  $ETC_p$  after cost-saving compensation are

$$ETC_d^a = zETC_{case2}$$

$$ETC_p^a = (1 - z)ETC_{case2}$$

**Table 5.** Comparison between Model 1 and Model 2.

| Decision Variables and Cost Items                          | Model 1     | Model 2     | Saving (%) |
|------------------------------------------------------------|-------------|-------------|------------|
| Number of deliveries per cycle ( $n^*$ )                   | 7           | 9           |            |
| Cycle time ( $T$ )                                         | 0.08758     | 0.08869     |            |
| Delivery lot size ( $Q$ ); units                           | 6387.7      | 4929.6      |            |
| Ordering cost (\$)                                         | 22,835.7    | 22,550.7    | 1.25       |
| Inspection cost (\$)                                       | 295,230.7   | 0           | 100        |
| Inventory holding cost (\$)                                | 190,027.5   | 147,863.7   | 22.2       |
| Deteriorating cost (\$)                                    | 195,346.3   | 147,863.7   | 24.3       |
| Emission cost (\$)                                         | 171.0       | 133.1       | 22.2       |
| Total retailer's cost per year (\$)                        | 703,611.2   | 318,909.1   | 54.7       |
| Total retailer's cost per year after compensation (\$)     |             | 690,574.4   | 1.85       |
| Setup cost (\$)                                            | 1,141,784.6 | 1,127,534.2 | 1.25       |
| Inspection cost (\$)                                       | 0           | 261,366.3   | −100       |
| Transportation cost (\$)                                   | 85,289.5    | 107,690.0   | −26.3      |
| Inventory holding cost (\$)                                | 539,976.9   | 567,658.3   | −5.13      |
| Deteriorating cost (\$)                                    | 362,122.2   | 397,345.0   | −9.73      |
| Emission cost (\$)                                         | 2,138.0     | 2390.9      | −11.8      |
| Total manufacturer's cost per year (\$)                    | 2,131,311.2 | 2,463,984.8 | −15.6      |
| Total manufacturer's cost per year after compensation (\$) |             | 2,091,821.6 | 1.85       |
| Expected total cost (\$)                                   | 2,834,922.4 | 2,782,396.0 | 1.85       |
| Expected total emission (tonCO <sub>2</sub> /year)         | 30.598      | 33.523      | −9.56      |

Hence, the retailer and manufacturer total cost per year become \$690,574.4 and \$2,091,821.6, respectively. Finally, by using this compensation policy, the cost decreases \$13,036.7 for the retailer and \$39,489.6 for the vendor, or 1.85% for both parties. Table 5 also shows that the *ETE* of Model 2 is 33.52 tonCO<sub>2</sub>/year, which is 9.55% higher than the *ETE* in Model 1. We can obtain both the cost-saving and emissions-reducing objectives from Table 4, as there is a chance to reduce the *ETE* of Model 2. For  $n = 7$ , the *ETE* is 30.292, and the *ETC* is \$2,781,779 in which now the *ETE* and the *ETC* are 1.0% and 1.87% lower than those of Model 1, respectively. Thus, the objectives of cost efficiency and carbon footprint level reduction can be obtained simultaneously. The new comparison between the two models is presented in Table 6. It is also observed that the total delivered products to the retailer in Model 2 after adjustment (Model 2<sup>adj</sup>) is less than those in Model 1.

**Table 6.** Comparison between Model 1 and the adjusted Model 2.

| Decision Variables and Cost Items                          | Model 1     | Model 2 <sup>adj</sup> | Saving (%) |
|------------------------------------------------------------|-------------|------------------------|------------|
| Number of deliveries per cycle ( $n^*$ )                   | 7           | 7                      |            |
| Cycle time ( $T$ )                                         | 0.08758     | 0.08704                |            |
| Delivery lot size ( $Q$ ); units                           | 6,387.7     | 6221.2                 |            |
| Ordering cost (\$)                                         | 22,835.7    | 22,977.4               | −0.62      |
| Inspection cost (\$)                                       | 295,230.7   | 0                      | 100        |
| Inventory holding cost (\$)                                | 190,027.5   | 186,596.1              | 1.80       |
| Deteriorating cost (\$)                                    | 195,346.3   | 186,596.1              | 4.48       |
| Emission cost (\$)                                         | 171.0       | 167.9                  | 1.81       |
| Total retailer's cost per year (\$)                        | 703,611.2   | 396,337.5              | 43.7       |
| Total retailer's cost per year after compensation (\$)     |             | 690,428.8              | 1.87       |
| Setup cost (\$)                                            | 1,141,784.6 | 1,148,869.4            | −0.62      |
| Inspection cost (\$)                                       | 0           | 261,461.4              | −100       |
| Transportation cost (\$)                                   | 85,289.5    | 85,764.5               | −0.55      |
| Inventory holding cost (\$)                                | 539,976.9   | 529,446.7              | 1.95       |
| Deteriorating cost (\$)                                    | 362,122.2   | 357,812.1              | 1.20       |
| Emission cost (\$)                                         | 2,138.0     | 2117.7                 | 0.95       |
| Total manufacturer's cost per year (\$)                    | 2,131,311.2 | 2,385,471.8            | −11.9      |
| Total manufacturer's cost per year after compensation (\$) |             | 2,091,380.5            | 1.87       |
| Expected total cost (\$)                                   | 2,834,922.4 | 2,781,809.3            | 1.87       |
| Expected total emission (tonCO <sub>2</sub> /year)         | 30.598      | 30.292                 | 1.00       |

Sensitivity analysis is performed by increasing or decreasing the value of the parameter by  $\pm 25\%$  and  $\pm 50\%$  from the original values, as shown in Table 7. The results confirm that the second model is superior to the first model in terms of total cost. The number of deliveries per cycle ( $n$ ) is sensitive to changes in parameters  $P$ ,  $D$ ,  $s$ ,  $h_d$ ,  $h_p$ ,  $d_d$ ,  $d_p$ , and  $t_f$ . As the values of parameters  $P$ ,  $h_p$ ,  $d_p$ , and  $t_f$  increase, the smaller the value of  $n$ . Contradictory conditions occur for parameters  $D$ ,  $s$ ,  $h_d$ , and  $d_d$ . The expected total cost is highly sensitive to the changes in parameters  $P$ ,  $D$ ,  $\theta$ ,  $s$ ,  $u_c$ ,  $h_d$ ,  $h_p$ ,  $d_d$ ,  $d_p$ , and  $t_f$ , and almost insensitive to the changes in other parameters.

It is observed that when the deterioration rate ( $\theta$ ) increases, the expected total cost and the number of deliveries increase, but the delivery quantity decreases. When the probability of defective products ( $u$ ) increases, the expected total cost increases very slightly, especially when the inspection is performed by the vendor. When the carbon tax ( $T_x$ ) increases, the number of deliveries remains stable. Otherwise, the delivery quantity and expected total cost increase are very small.

Table 7. Sensitivity analysis of the two models.

| Parameter       | Value Change | Model 1 |        |         |           |       | Model 2 |        |        |             |       |
|-----------------|--------------|---------|--------|---------|-----------|-------|---------|--------|--------|-------------|-------|
|                 |              | $n^*$   | $T$    | $Q^a$   | $ETC$     | %CTC  | $n^*$   | $T$    | $Q^b$  | $ETC$       | %CTC  |
| $P = 2,000,000$ | +50%         | 7       | 0.0816 | 5949.3  | 3,024,249 | 6.68  | 8       | 0.0819 | 5120.3 | 2,966,117.1 | 6.60  |
|                 | +25%         | 7       | 0.0839 | 6117.1  | 2,948,615 | 4.01  | 8       | 0.0842 | 5263.2 | 2,892,821.2 | 3.97  |
|                 | 0            | 7       | 0.0876 | 6387.7  | 2,834,922 | 0     | 9       | 0.0887 | 4929.6 | 2,782,396.0 | 0     |
|                 | −25%         | 8       | 0.0959 | 6120.6  | 2,643,862 | −6.74 | 9       | 0.0957 | 5322.0 | 2,596,679.1 | −6.67 |
|                 | −50%         | 8       | 0.1147 | 7321.0  | 2,253,495 | −20.5 | 11      | 0.1153 | 5296.5 | 2,217,427.4 | −20.3 |
| $D = 500,000$   | +50%         | 8       | 0.0816 | 7811.6  | 3,190,858 | 12.5  | 10      | 0.0822 | 6168.2 | 3,136,392.1 | 12.7  |
|                 | +25%         | 8       | 0.0841 | 6705.8  | 3,044,190 | 7.38  | 9       | 0.0840 | 5833.6 | 2,989,178.5 | 7.43  |
|                 | 0            | 7       | 0.0876 | 6387.7  | 2,834,922 | 0     | 9       | 0.0887 | 4929.6 | 2,782,396.0 | 0     |
|                 | −25%         | 7       | 0.0958 | 5242.7  | 2,548,150 | −10.1 | 8       | 0.0962 | 4510.9 | 2,499,238.8 | −10.2 |
|                 | −50%         | 6       | 0.1100 | 4683.3  | 2,151,051 | −24.1 | 8       | 0.1120 | 3501.7 | 2,108,977.7 | −24.2 |
| $c = 2000$      | +50%         | 7       | 0.0880 | 6415.9  | 2,846,315 | 0.40  | 9       | 0.0891 | 4951.6 | 2,793,646.2 | 0.40  |
|                 | +25%         | 7       | 0.0878 | 6401.8  | 2,840,625 | 0.20  | 9       | 0.0889 | 4940.6 | 2,788,027.5 | 0.20  |
|                 | 0            | 7       | 0.0876 | 6387.7  | 2,834,922 | 0     | 9       | 0.0887 | 4929.6 | 2,782,396.0 | 0     |
|                 | −25%         | 7       | 0.0874 | 6373.5  | 2,829,207 | −0.20 | 9       | 0.0885 | 4918.6 | 2,776,752.0 | −0.20 |
|                 | −50%         | 7       | 0.0872 | 6359.3  | 2,823,479 | −0.40 | 9       | 0.0883 | 4907.5 | 2,771,095.4 | −0.41 |
| $s = 100,000$   | +50%         | 9       | 0.1074 | 6090.8  | 3,348,784 | 18.1  | 11      | 0.1081 | 4917.3 | 3,292,159.7 | 18.3  |
|                 | +25%         | 8       | 0.0979 | 6250.1  | 3,104,546 | 9.51  | 10      | 0.0988 | 4945.1 | 3,049,823.5 | 9.61  |
|                 | 0            | 7       | 0.0876 | 6387.7  | 2,834,922 | 0     | 9       | 0.0887 | 4929.6 | 2,782,396.0 | 0     |
|                 | −25%         | 6       | 0.0760 | 6464.7  | 2,529,737 | −10.8 | 8       | 0.0773 | 4834.4 | 2,480,006.3 | −10.9 |
|                 | −50%         | 5       | 0.0625 | 6383.9  | 2,169,316 | −23.5 | 6       | 0.0631 | 5257.7 | 2,122,805.7 | −23.7 |
| $i_c = 500$     | +50%         | 7       | 0.0883 | 6437.1  | 2,854,827 | 0.70  | 9       | 0.0888 | 4935.1 | 2,785,213.3 | 0.10  |
|                 | +25%         | 7       | 0.0879 | 6412.4  | 2,844,894 | 0.35  | 9       | 0.0887 | 4932.4 | 2,783,805.1 | 0.05  |
|                 | 0            | 7       | 0.0876 | 6387.7  | 2,834,922 | 0     | 9       | 0.0887 | 4929.6 | 2,782,396.0 | 0     |
|                 | −25%         | 7       | 0.0872 | 6362.9  | 2,824,912 | −0.35 | 9       | 0.0886 | 4926.8 | 2,780,986.3 | −0.05 |
|                 | −50%         | 7       | 0.0869 | 6338.0  | 2,814,883 | −0.71 | 9       | 0.0886 | 4924.1 | 2,779,575.6 | −0.10 |
| $u_c = 0.5$     | +50%         | 7       | 0.0876 | 6387.5  | 2,962,557 | 4.50  | 9       | 0.0887 | 4929.0 | 2,910,260.4 | 4.60  |
|                 | +25%         | 7       | 0.0876 | 6387.6  | 2,898,740 | 2.25  | 9       | 0.0887 | 4929.3 | 2,846,328.1 | 2.30  |
|                 | 0            | 7       | 0.0876 | 6387.7  | 2,834,922 | 0     | 9       | 0.0887 | 4929.6 | 2,782,396.0 | 0     |
|                 | −25%         | 7       | 0.0876 | 6387.8  | 2,771,105 | −2.25 | 9       | 0.0887 | 4929.9 | 2,718,463.9 | −2.30 |
|                 | −50%         | 7       | 0.0876 | 6387.9  | 2,707,289 | −4.50 | 9       | 0.0887 | 4930.2 | 2,654,531.7 | −4.60 |
| $h_d = 60$      | +50%         | 9       | 0.0872 | 4947.9  | 2,916,253 | 2.87  | 11      | 0.0880 | 4003.7 | 2,848,604.1 | 2.38  |
|                 | +25%         | 8       | 0.0873 | 5571.5  | 2,878,457 | 1.54  | 10      | 0.0883 | 4014.8 | 2,817,636.9 | 1.27  |
|                 | 0            | 7       | 0.0876 | 6387.7  | 2,834,922 | 0     | 9       | 0.0887 | 4929.6 | 2,782,396.0 | 0     |
|                 | −25%         | 6       | 0.0882 | 7502.8  | 2,782,702 | −1.84 | 7       | 0.0885 | 6327.8 | 2,739,318.4 | −1.55 |
|                 | −50%         | 5       | 0.0893 | 9119.2  | 2,716,341 | −4.18 | 5       | 0.0889 | 8901.6 | 2,680,745.8 | −3.65 |
| $h_p = 40$      | +50%         | 5       | 0.0779 | 7955.9  | 3,075,129 | 8.47  | 5       | 0.0776 | 7768.5 | 3,033,547.3 | 9.03  |
|                 | +25%         | 6       | 0.0823 | 7002.8  | 2,962,650 | 4.51  | 7       | 0.0827 | 5908.5 | 2,915,155.6 | 4.77  |
|                 | 0            | 7       | 0.0876 | 6387.7  | 2,834,922 | 0     | 9       | 0.0887 | 4929.6 | 2,782,396.0 | 0     |
|                 | −25%         | 8       | 0.0940 | 5999.5  | 2,691,834 | −5.05 | 10      | 0.0951 | 4758.0 | 2,634,200.0 | −5.33 |
|                 | −50%         | 9       | 0.1020 | 5786.3  | 2,531,836 | −10.7 | 13      | 0.1051 | 4044.5 | 2,468,523.7 | −11.3 |
| $d_d = 600$     | +50%         | 9       | 0.0872 | 4944.1  | 2,918,318 | 2.94  | 11      | 0.0880 | 4003.7 | 2,848,604.1 | 2.38  |
|                 | +25%         | 8       | 0.0873 | 5569.0  | 2,879,619 | 1.58  | 10      | 0.0883 | 4416.4 | 2,817,636.9 | 1.27  |
|                 | 0            | 7       | 0.0876 | 6387.7  | 2,834,922 | 0     | 9       | 0.0887 | 4929.6 | 2,782,396.0 | 0     |
|                 | −25%         | 6       | 0.0882 | 7507.4  | 2,781,144 | −1.90 | 7       | 0.0885 | 6327.8 | 2,739,318.4 | −1.55 |
|                 | −50%         | 3       | 0.0872 | 14852.7 | 2,703,928 | −4.62 | 5       | 0.0889 | 8901.6 | 2,680,745.8 | −3.65 |
| $d_p = 400$     | +50%         | 7       | 0.0820 | 5981.9  | 3,010,061 | 6.18  | 6       | 0.0806 | 6721.3 | 2,957,798.8 | 6.30  |
|                 | +25%         | 7       | 0.0847 | 6174.8  | 2,923,924 | 3.14  | 7       | 0.0839 | 5999.6 | 2,875,189.0 | 3.33  |
|                 | 0            | 7       | 0.0876 | 6387.7  | 2,834,922 | 0     | 9       | 0.0887 | 4929.6 | 2,782,396.0 | 0     |
|                 | −25%         | 8       | 0.0922 | 5884.4  | 2,738,923 | −3.39 | 10      | 0.0933 | 4668.1 | 2,679,457.1 | −3.70 |
|                 | −50%         | 9       | 0.0976 | 5538.2  | 2,632,492 | −7.14 | 12      | 0.0997 | 4155.5 | 2,566,509.0 | −7.76 |
| $\theta = 0.1$  | +50%         | 7       | 0.0794 | 5794.4  | 3,100,001 | 9.35  | 9       | 0.0804 | 4470.6 | 3,041,924.7 | 9.33  |
|                 | +25%         | 7       | 0.0832 | 6069.2  | 2,970,737 | 4.79  | 9       | 0.0843 | 4683.2 | 2,915,364.1 | 4.78  |
|                 | 0            | 7       | 0.0876 | 6387.7  | 2,834,922 | 0     | 9       | 0.0887 | 4929.6 | 2,782,396.0 | 0     |
|                 | −25%         | 7       | 0.0927 | 6762.9  | 2,691,447 | −5.06 | 9       | 0.0939 | 5219.8 | 2,641,938.0 | −5.05 |
|                 | −50%         | 7       | 0.0989 | 7213.9  | 2,538,850 | −10.4 | 8       | 0.0992 | 5516.8 | 2,492,404.9 | −10.4 |
| $t_f = 1000$    | +50%         | 6       | 0.0874 | 7440.5  | 2,872,436 | 1.32  | 7       | 0.0883 | 6308.3 | 2,826,288.0 | 1.58  |
|                 | +25%         | 7       | 0.0883 | 6437.1  | 2,854,827 | 0.70  | 8       | 0.0886 | 5542.6 | 2,805,413.7 | 0.83  |
|                 | 0            | 7       | 0.0876 | 6387.7  | 2,834,922 | 0     | 9       | 0.0887 | 4929.6 | 2,782,396.0 | 0     |
|                 | −25%         | 8       | 0.0879 | 5612.0  | 2,814,046 | −0.74 | 10      | 0.0885 | 4425.0 | 2,756,197.9 | −0.94 |
|                 | −50%         | 9       | 0.0880 | 4991.1  | 2,790,972 | −1.55 | 12      | 0.0884 | 3685.7 | 2,725,660.0 | −2.04 |
| $t_v = 0.75$    | +50%         | 7       | 0.0876 | 6391.8  | 2,837,605 | 0.09  | 9       | 0.0888 | 4933.7 | 2,785,501.1 | 0.11  |
|                 | +25%         | 7       | 0.0876 | 6389.7  | 2,836,264 | 0.05  | 9       | 0.0887 | 4931.6 | 2,783,948.8 | 0.06  |
|                 | 0            | 7       | 0.0876 | 6387.7  | 2,834,922 | 0     | 9       | 0.0887 | 4929.6 | 2,782,396.0 | 0     |
|                 | −25%         | 7       | 0.0876 | 6385.7  | 2,833,581 | −0.05 | 9       | 0.0886 | 4927.6 | 2,780,842.7 | −0.06 |
|                 | −50%         | 7       | 0.0875 | 6383.6  | 2,832,239 | −0.09 | 9       | 0.0886 | 4925.5 | 2,779,289.1 | −0.11 |

Table 7. Cont.

| Parameter                 | Value Change | Model 1 |        |         |           |        | Model 2 |        |        |             |        |
|---------------------------|--------------|---------|--------|---------|-----------|--------|---------|--------|--------|-------------|--------|
|                           |              | $n^*$   | $T$    | $Q^a$   | $ETC$     | %CTC   | $n^*$   | $T$    | $Q^b$  | $ETC$       | %CTC   |
| $d = 100$                 | +50%         | 7       | 0.0877 | 6392.8  | 2,838,309 | 0.12   | 9       | 0.0888 | 4934.7 | 2,786,313.0 | 0.14   |
|                           | +25%         | 7       | 0.0876 | 6390.3  | 2,836,616 | 0.06   | 9       | 0.0887 | 4932.2 | 2,784,355.0 | 0.07   |
|                           | 0            | 7       | 0.0876 | 6387.7  | 2,834,922 | 0      | 9       | 0.0887 | 4929.6 | 2,782,396.0 | 0      |
|                           | −25%         | 7       | 0.0875 | 6385.1  | 2,833,229 | −0.06  | 9       | 0.0886 | 4927.0 | 2,780,436.7 | −0.07  |
|                           | −50%         | 7       | 0.0875 | 6382.6  | 2,831,535 | −0.12  | 9       | 0.0886 | 4924.5 | 2,778,476.4 | −0.14  |
| $E[u] = 0.02$             | +50%         | 7       | 0.0874 | 6437.8  | 2,843,908 | 0.32   | 9       | 0.0887 | 4931.3 | 2,784,137.7 | 0.063  |
|                           | +25%         | 7       | 0.0875 | 6412.6  | 2,839,414 | 0.16   | 9       | 0.0887 | 4930.5 | 2,783,248.6 | 0.031  |
|                           | 0            | 7       | 0.0876 | 6387.7  | 2,834,922 | 0      | 9       | 0.0887 | 4929.6 | 2,782,396.0 | 0      |
|                           | −25%         | 7       | 0.0877 | 6363.1  | 2,830,435 | −0.16  | 9       | 0.0887 | 4928.7 | 2,781,579.0 | −0.029 |
|                           | −50%         | 7       | 0.0878 | 6338.7  | 2,825,951 | −0.32  | 9       | 0.0887 | 4927.7 | 2,780,796.5 | −0.058 |
| $w = 0.01$                | +50%         | 7       | 0.0876 | 6387.7  | 2,835,956 | 0.04   | 9       | 0.0887 | 4929.6 | 2,783,408.9 | 0.036  |
|                           | +25%         | 7       | 0.0876 | 6387.7  | 2,835,439 | 0.02   | 9       | 0.0887 | 4929.6 | 2,782,902.6 | 0.018  |
|                           | 0            | 7       | 0.0876 | 6387.7  | 2,834,922 | 0      | 9       | 0.0887 | 4929.6 | 2,782,396.0 | 0      |
|                           | −25%         | 7       | 0.0876 | 6387.7  | 2,834,405 | −0.02  | 9       | 0.0887 | 4929.6 | 2,781,889.5 | −0.018 |
|                           | −50%         | 7       | 0.0876 | 6,387.7 | 2,833,889 | −0.04  | 9       | 0.0887 | 4929.6 | 2,781,383.0 | −0.036 |
| $c_1, c_2 = 0.27, 0.0057$ | +50%         | 7       | 0.0876 | 6388.7  | 2,835,627 | 0.02   | 9       | 0.0887 | 4930.5 | 2,783,244.8 | 0.031  |
|                           | +25%         | 7       | 0.0876 | 6388.2  | 2,835,275 | 0.01   | 9       | 0.0887 | 4930.0 | 2,782,838.6 | 0.016  |
|                           | 0            | 7       | 0.0876 | 6387.7  | 2,834,922 | 0      | 9       | 0.0887 | 4929.6 | 2,782,396.0 | 0      |
|                           | −25%         | 7       | 0.0876 | 6387.2  | 2,834,570 | −0.01  | 9       | 0.0887 | 4928.9 | 2,782,026.3 | −0.013 |
|                           | −50%         | 7       | 0.0876 | 6386.7  | 2,834,218 | −0.02  | 9       | 0.0887 | 4928.4 | 2,781,620.2 | −0.028 |
| $e_c = 1.44$              | +50%         | 7       | 0.0876 | 6386.6  | 2,835,372 | 0.016  | 9       | 0.0887 | 4928.7 | 2,782,845.7 | 0.016  |
|                           | +25%         | 7       | 0.0876 | 6387.1  | 2,835,148 | 0.008  | 9       | 0.0887 | 4929.2 | 2,782,620.8 | 0.008  |
|                           | 0            | 7       | 0.0876 | 6387.7  | 2,834,922 | 0      | 9       | 0.0887 | 4929.6 | 2,782,396.0 | 0      |
|                           | −25%         | 7       | 0.0876 | 6388.3  | 2,834,698 | −0.008 | 9       | 0.0887 | 4930.0 | 2,782,171.2 | −0.008 |
|                           | −50%         | 7       | 0.0876 | 6388.8  | 2,834,472 | −0.016 | 9       | 0.0887 | 4930.5 | 2,781,946.2 | −0.016 |
| $T_x = 75$                | +50%         | 7       | 0.0876 | 6387.7  | 2,836,077 | 0.04   | 9       | 0.0887 | 4929.8 | 2,783,658.0 | 0.045  |
|                           | +25%         | 7       | 0.0876 | 6387.7  | 2,835,500 | 0.02   | 9       | 0.0887 | 4929.7 | 2,783,027.1 | 0.023  |
|                           | 0            | 7       | 0.0876 | 6387.7  | 2,834,922 | 0      | 9       | 0.0887 | 4929.6 | 2,782,396.0 | 0      |
|                           | −25%         | 7       | 0.0876 | 6387.7  | 2,834,345 | −0.02  | 9       | 0.0887 | 4929.5 | 2,781,764.9 | −0.023 |
|                           | −50%         | 7       | 0.0876 | 6387.6  | 2,833,768 | −0.04  | 9       | 0.0887 | 4929.4 | 2,781,134.2 | −0.045 |

## 6. Conclusions and Future Research

This study considers a two-echelon supply chain consisting of a manufacturer and a retailer where the production activities are resulting in a certain percentage of defective products. The supply chain entities are willing to reduce their environmental impact by coordinating the delivery quantity and number of deliveries per cycle. The effect of carbon emissions, item deterioration, and two choices of inspection are examined. The models are illustrated with two numerical examples, and the results give some insights. This study is an initial exploratory study that attempts to provide a mathematical solution for a controlled situation; it may be applied to handle larger problems of cost minimization and carbon emission reduction in the future.

From the research finding, it is observed that the numbers of delivered products from the manufacturer are less when the inspection is performed by the vendor. As a result, the total cost of the supply chain is less, because the total inventory-holding cost and the total deteriorating cost are decreasing. However, the vendor's total cost becomes higher when it performs the inspection. Therefore, the retailer needs to compensate a certain amount of cost-saving to the manufacturer so that both parties take advantage.

The research finding also revealed that although the total cost is less when the inspection is performed by the vendor, it does not guarantee a reduction in emissions. However, both the cost-saving and emission-reducing objectives can still be obtained simultaneously by reducing the level of cost savings. In this situation, there is a tradeoff between cost savings and reduction in carbon emissions.

Although this study addresses some practical aspects of a supply chain scenario to deal with lower carbon emissions, the scope has a wide opportunity to be extended. Applying the approach in a three-echelon supply chain or more is one opportunity. Future works can consider the possibility of reworking the defective products, the capacity of the vehicle and storage facility, and investment to reduce the carbon emissions. This study assumes a 100% inspection by the manufacturer. Future

research may assume a sampling inspection by the manufacturer, as well as incorporate the issue of imperfect quality inspection.

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