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Wolfgang Albrecht

Scheduling in Green Supply Chain Management

A Mixed-Integer Approach

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Preface

Because of negative consequences of anthropogenic climate change, protecting our environment should be something that matters to all of us. An important paradigm shift is necessary for the worldwide economy. Due to increasing globalization, business operations are typically organized in complex supply chain networks, while a coordinated scheduling of production, distribution, and sales allows for realizing transient monetary benefits. Although the field of green supply chain management has been established for a few years in the literature, there is still a backlog in modeling objectives and constraints of sustainability. For this reason, this book proposes new integrated mathematical optimization models and problem-tailored solution algorithms that may contribute to a reconciliation of economic and environmental issues.

The initial manuscript of this book has been accepted in January 2020 by the University of Greifswald's Faculty of Law and Economics. It is a habilitation thesis, i.e., a research monograph for postdoctoral qualification in Germany.

First of all, I would like to express my deep gratitude to my academic advisor, Professor Dr. Martin Steinrücke (University of Greifswald). During my time as a postdoctoral researcher at his chair, several common articles have been published in international peer-reviewed journals in the field of supply chain management. In addition, he finally encouraged me to write this monograph. While acting as the first reviewer of my habilitation thesis, his broad expertise was the basis of many fruitful discussions. Additional external reviewers were Professor Dr. Richard Lackes (Technical University of Dortmund) and Professor Dr. Hans Corsten (Technical University of Kaiserslautern). I greatly appreciate the valuable comments of all three reviewers. Besides, I am much obliged to Professor Dr. Jan Körnert (University of Greifswald) for chairing the habilitation commission.

Sincere thanks to Springer and the series editor of "International Series in Operations Research & Management Science" for accepting my manuscript for publication.

Finally, I would like to acknowledge the support of all friends, colleagues, and students who accompanied me on my way to completing my habilitation. Warm thanks go to my family.

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Wolfgang Albrecht

About this Book

This book offers practical tools and new perspectives to researchers and professionals in the field of supply chain management. It deals with hierarchical scheduling of operations at/between sites of generic multi-stage networks taking into account aspects of sustainability. Driven by an increasing environmental awareness as well as current initiatives of legislation for reducing greenhouse gas emissions and waste, it proposes new mixed-integer programming models combining problems of procurement, production, distribution, sales, recycling, disposal, and emissions trading simultaneously in consideration of existing interdependencies. The modularized approach distinguishes between material flows of non-perishable and perishable goods and additionally captures an aligned financial planning. Discrete-time models are used for establishing closed-loop structures on the medium-term level. On the short-term level, continuous-time scheduling in 24/7 operating networks allows for coordinating decisions exactly while striving for a reconciliation of economic and environmental issues. Computational experiments conducted on state-of-the-art high-performance software and hardware reveal that instances of realistic scope cannot be solved to optimality within acceptable times. For this reason, problem-tailored variants of relax-and-fix heuristics and genetic algorithms are proposed.

Contents

Abbreviations

CPU	Central processing unit
EU	European Union
EU ETS	European Union's Emissions Trading System
GA	Genetic algorithm
GAMS	General Algebraic Modeling System
GB	gigabyte
GHz	gigahertz
GSCM	Green supply chain management
GT/s	gigatransfers per second
ISO	International Organization for Standardization
MILP	Mixed-integer linear program
MIP	Mixed-integer program
RAM	Random-access memory
R&F	Relax and fix
SC	Supply chain
SCM	Supply chain management

List of Symbols

Sets and Indices

A	set of liquidity periods; $a \in A \coloneqq \{1, \ldots, \lvert A \rvert\}$
$C_{s\tau}$	set of capacity profiles, selectable for a site $s \in S_\sigma$, if the site has been set up for operations before the planning horizon ($\tau = -1$) or the site is set up for operations in time $\tau = 0, \ldots, t_E - 1$, respectively; $c \in C_{s\tau}$
F	set of quality grades; $f \in F$
I	set of generations in genetic algorithm, $\iota \in I \coloneqq \{1, \ldots, \lvert I \rvert\}$
K	set of feasible combinations of SC stages for describing potential material flows [depending on the specific model formulation]

$K=\{(\sigma = 1, \ldots, W + 1) \times (\lambda = \sigma + 1) \wedge (\sigma = W + 2) \times (\lambda = 1, \ldots, W)\}$

within the discrete-time model [Sect. 5.1]

$K=\{(\sigma = 1, \ldots, W) \times (\lambda = \sigma + 1, \ldots, W + 1) \wedge (\sigma = 2, \ldots, W) \times (\lambda = 1, \ldots, \sigma - 1) \wedge (\sigma = 2, \ldots, W) \times (\lambda = W + 2)\}$

within the continuous-time model for internal recycling [Sect. 6.1.1.1]

$K=\{(\sigma = 1, \ldots, W) \times (\lambda = \sigma + 1, \ldots, W + 1) \wedge (\sigma = W + 1) \times (\lambda = W + 2) \wedge (\sigma = W + 2) \times (\lambda = 1, \ldots, W)\}$

within the continuous-time model for external recycling [Sect. 6.1.1.2]

$K=\{(\sigma = 1, \ldots, W) \times (\lambda = \sigma + 1, \ldots, W + 1) \wedge (\sigma = W + 1) \times (\lambda = W + 2) \wedge (\sigma = W + 2) \times (\lambda = 1, \ldots, W) \wedge (\sigma = 2, \ldots, W) \times (\lambda = 1, \ldots, \sigma - 1) \wedge (\sigma = 2, \ldots, W) \times (\lambda = W + 2)\}$

within the continuous-time model for combined recycling [Sect. 6.1.1.3]

$K=\{(\sigma = 1, \ldots, W) \times (\lambda = \sigma + 1, \ldots, W + 1) \wedge (\sigma = W + 1) \times (\lambda = W + 2) \wedge (\sigma = 2, \ldots, W) \times (\lambda = W + 2)\}$

within the continuous-time model for perishable goods [Sect. 6.1.2]

L set of SC stages with recycling [depending on the specific model formulation]

$L = \{2, \ldots, W\}$

within the continuous-time model for internal recycling [Sect. 6.1.1.1]

$L = \{W + 2\}$

within the discrete-time model [Sect. 5.1], the continuous-time model for external recycling [Sect. 6.1.1.2], and the continuous-time model for perishable goods [Sect. 6.1.2]

$L = \{2, \ldots, W, W + 2\}$

within the continuous-time model for combined recycling [Sect. 6.1.1.3]

N_{sqU} set of sites belonging to one potential material flow between sites s and q; $N_{sqU} \coloneqq U \cup \{s, q\}$; $U \in \wp'(SW)$; $(s, q) \in S_1 \times S_{W+1}$

O set of financial transactions; $o \in O$

[note: credits ($o = 1$) and investments ($o = 2$) in discrete-time scheduling, financial alternatives in continuous-time scheduling]

P set of human-induced greenhouse gases; $p \in P$

S_σ set of sites assigned to SC stage $\sigma \in \Gamma$; s, q, i, $j \in S_\sigma$

SG set of sites selected for consideration in a genetic algorithm; $SG \subseteq \bigcup_{\sigma=1}^{W+1} S_\sigma$

SW set of all sites belonging to SC stages $\sigma = 2, \ldots, W$; $SW = \bigcup_{\sigma=2}^{W} S_\sigma$

T_- set of points in time representing decisions on site states; t, $\tau \in T_- \coloneqq \{-1, 0, \ldots, t_E - 1\}$

[note: $t = -1$ represents the initial site state]

T set of points in time representing decisions on operations; t, $\tau \in T \coloneqq \{0, \ldots, t_E - 1\}$

T_+ set of points in time representing monetary surpluses/withdrawals; $t, \tau \in T_+ \coloneqq \{0, \ldots, t_E\}$

Z set of event boundaries; $z \in Z$; $Z \coloneqq \{1; 2\}$

[note: $z = 1$ for start of an event, $z = 2$ for end of an event]

Γ set of SC stages; σ, $\lambda \in \Gamma$; $\Gamma \coloneqq \{1, \ldots, W + 2\}$

[note: the assignment of operations to SC stages depends on the model; in general, $\sigma = 1, \ldots, W$ are before-market stages (e.g., for production, distribution, or recycling), $\sigma = W+1$ represents the market stage, and $\sigma = W+2$ is an after-market stage (e.g., for recycling, disposal)]

$(\Gamma_{N_{sqU}}, \leq)$ ordered set of SC stages representing the sites, which belong to a potential material flow according to N_{sqU}; $\Gamma_{N_{sqU}} \subseteq \Gamma$

Λ set of steps in relax-and-fix algorithm, $h \in \Lambda \coloneqq \{1, \ldots, |\Lambda|\}$

Θ set of genes in genetic algorithm, $\theta \in \Theta \coloneqq \{1, \ldots, |\Theta|\}$

Υ_h subset of binary variables to be optimized in the h-th step of a relax-and-fix algorithm

Ω set of chromosomes in genetic algorithm, $\omega \in \Omega \coloneqq \{1, \ldots, |\Omega|\}$ [note: $\omega*$ represents the rank of the chromosome within a set that is ordered according to a descending sequence of fitness values]

$\wp'(SW)$ filtered power set of the set SW; $\wp'(SW) \coloneqq \{U | U \subseteq SW \wedge |U \cap S_\sigma| \leq 1, \sigma = 2, \ldots, W\}$

Parameters

$B^{\lambda\sigma}$ usable units of a product manufactured in SC stage $\lambda = 1, \ldots, \sigma - 1$, which are required to manufacture one unit of a product in SC stage $\sigma = 2, \ldots, W$

B^{σ} usable units of a product manufactured in SC stage $\lambda = \sigma - 1$, which are required to manufacture one unit of a product in SC stage $\sigma = 2, \ldots, W$

BB^{λ} units of a product manufactured in SC stage $\lambda = 1, \ldots, W$, which can be obtained from recycling one unit of a final product in SC stage $\sigma = W + 2$

BE_t buying price of an emission allowance in time $t \in T$

BM_t maximum number of buyable emission allowances in time $t \in T$

CA_{st} availability costs for site $s \in S_\sigma$ of SC stage $\sigma = 1, \ldots, W + 2$ in time $t \in T$ [note: represents marketing costs for $\sigma = W + 1$]

CC_{sct} capacity costs for site $s \in S_\sigma$ of SC stage $\sigma = 1, \ldots, W, W + 2$ in time $t \in T$, if capacity profile $c \in C_{s\tau}$ is selected

CD_{st} shutdown costs for site $s \in S_\sigma$ of SC stage $\sigma = 1, \ldots, W, W + 2$ in time $t \in T$

CE_p tons of carbon dioxide that are assumed to be comparable to one ton of greenhouse gas $p \in P$ (factor for determining the carbon dioxide equivalent) [note: factor is one for carbon dioxide itself]

$CO_{\iota\theta}$ equals 1 if the allele of the gene $\theta \in \Theta$ belonging to a specific chromosome of the generation $\iota - 1$ is to be transferred to the same gene on the chromosome of the new generation $\iota \in \mathrm{I}$ during crossover procedure, or 0 otherwise [randomly generated binary parameter for the genetic algorithm]

CS_{st} setup costs for site $s \in S_\sigma$ of SC stage $\sigma = 1, \ldots, W, W + 2$ in time $t \in T$

D_s demand at market site $s \in S_{W+1}$

D_s^{λ} demand of the product manufactured in SC stage $\lambda = 1, \ldots, W$ at market site $s \in S_{W+1}$

D_{st} demand of the final product at market site $s \in S_{W+1}$ in time $t \in T$

DC_s costs of tardiness in demand satisfaction at market site $s \in S_{W+1}$ (per day)

DD_s due date for meeting the demand at market site $s \in S_{W+1}$

DQ_{st} returnable quantity of the final product at market site $s \in S_{W+1}$ in time $t \in T$

E end time of the planning horizon

ED_{ps} tons of greenhouse gas $p \in P$ emitted from recycling at site $s \in S_\sigma$ of SC stage $\sigma \in L$ (per product)

ED_{pst} tons of greenhouse gas $p \in P$ emitted from recycling at site $s \in S_{W+2}$ in time $t \in T$ (per product)

EF_{ps} tons of greenhouse gas $p \in P$ emitted from disposal at site $s \in S_{W+2}$ (per product)

EM emission cap (tons of carbon dioxide equivalent) during the entire planning horizon

EM_t emission cap (tons of carbon dioxide equivalent) in time period $t \in T$

EP_{ps} tons of greenhouse gas $p \in P$ emitted from production at site $s \in S_\sigma$ of SC stage $\sigma = 1, \ldots, W$ (per product)

EP_{pst} tons of greenhouse gas $p \in P$ emitted from production at site $s \in S_\sigma$ of SC stage $\sigma = 1, \ldots, W$ in time $t \in T$ (per product)

ET_{psq} tons of greenhouse gas $p \in P$ emitted from transportation from site $s \in S_\sigma$ to site $q \in S_\lambda$ of the SC stages $(\sigma, \lambda) \in K$ (per product)

ET_{psqt} tons of greenhouse gas $p \in P$ emitted from transportation from site $s \in S_\sigma$ to site $q \in S_\lambda$ of the SC stages $(\sigma, \lambda) \in K$ in time $t \in T$ (per product)

EV maximum emission (tons of carbon dioxide equivalent) per emission allowance

FA_o credit limit of financing alternative $o \in O$

FC_s maximum disposal capacity at site $s \in S_{W+2}$

FD_s speed of disposal at site $s \in S_{W+2}$

$FL_{ot\tau}$ limit of a single credit ($o = 1$) or investment ($o = 2$), respectively, which starts in time $t \in T$ and ends in time $\tau \in T_+$

FP_{ot} limit of all credits ($o = 1$) or investments ($o = 2$), respectively, which start in time $t \in T$

FT overall credit limit during the planning horizon

FV_s variable costs of disposal at site $s \in S_{W+2}$ (per product)

FZ_o term of financing alternative $o \in O$ (difference between the end time and the start time of a financing alternative)

i_o credit rate of financing alternative $o \in O$

$i_{ot\tau}$ interest rate of a credit ($o = 1$) or an investment ($o = 2$), respectively, which starts in time $t \in T$ and ends in time $\tau \in T_+$

IA_s equals 1 if site $s \in S_\sigma$ of SC stage $\sigma = 1, \ldots, W, W + 2$ has been set up for operations before the planning horizon, and 0 otherwise

M a sufficiently large number

MC_s fixed marketing costs at market site $s \in S_{W+1}$

$MU_{\iota\omega}$ integer number in the interval $[1;|\Theta|]$ representing the index of a mutated gene on a chromosome $\omega \in \Omega$ of generation $\iota \in \mathrm{I}$
[randomly generated integer parameter for the genetic algorithm]

$MV_{\iota\omega\theta}$ binary number representing the new allele of a mutated gene $\theta \in \Theta$ on a chromosome $\omega \in \Omega$ of generation $\iota \in \mathrm{I}$
[randomly generated binary parameter for the genetic algorithm]

MZ minimum processing time for operating sites

NF_s maximum number of transports starting from a site $s \in S_\sigma$ of SC stage $\sigma = 1, \ldots, W + 2$

NL	maximum quantity of recyclable products being disposed of
PC_s	maximum production capacity at site $s \in S_\sigma$ of SC stage $\sigma = 1, \ldots, W$ [interpretable as maximum storage capacity for distribution stages]
PC_{sct}	maximum production capacity at site $s \in S_\sigma$ of SC stage $\sigma = 1, \ldots, W$ in time $t \in T$, if capacity profile $c \in C_{s\tau}$ is selected
PF_s	fixed production costs at site $s \in S_\sigma$ of SC stage $\sigma = 1, \ldots, W$ [interpretable as fixed storage costs for distribution stages]
PI_{st}	variable inventory costs at site $s \in S_\sigma$ of SC stage $\sigma = 1, \ldots, W$ in time $t \in T$ (per product)
PV_s	variable production costs at site $s \in S_\sigma$ of SC stage $\sigma = 1, \ldots, W$ (per product) [interpretable as variable storage costs for distribution stages]
PV_{st}	variable production costs at site $s \in S_\sigma$ of SC stage $\sigma = 1, \ldots, W$ in time $t \in T$ (per product) [interpretable as variable storage costs for distribution stages]
R_{fs}	revenue of a product package of perishable goods in quality grade $f \in F$ according to the demand of market $s \in S_{W+1}$
$\widetilde{R}_s$	expected revenue of a perishable product recycled at site $s \in S_{W+2}$
$R^\lambda{}_s$	revenue of the product manufactured in SC stage λ at market site $s \in S_{W+1}$ (per product)
R_{st}	revenue of the final product at market site $s \in S_{W+1}$ in time $t \in T$ (per product)
RC_s	maximum recycling capacity at site $s \in S_\sigma$ of SC stage $\sigma \in L$
RC_{sct}	maximum recycling capacity at site $s \in S_{W+2}$ in time $t \in T$, if capacity profile $c \in C_{s\tau}$ is selected
RD_s	speed of recycling at site $s \in S_\sigma$ of SC stage $\sigma \in L$
RF_s	fixed costs of reverse operations (recycling and/or disposal) at site $s \in S_\sigma$ of relevant SC stage σ
RG_{fsq}	maximum distribution range (i.e., time difference between the end and the beginning of a realized material flow) between sites $q \in S_{W+1}$ and $s \in S_1$ that is allowed for a product package to be sold in grade $f \in F$
RT_s	time period at a market $s \in S_{W+1}$ between demand satisfaction and product return
RV_s	variable costs of recycling at site $s \in S_\sigma$ of SC stage $\sigma \in L$ (per product)
RV_{st}	variable costs of recycling at site $s \in S_{W+2}$ in time $t \in T$ (per product)
SB_{sq}	maximum temporary storage time allowed for transports from site $s \in S_\sigma$ to site $q \in S_\lambda$ of SC stages $(\sigma, \lambda) \in K$
SD_s	speed of production at site $s \in S_\sigma$ of SC stage $\sigma = 1, \ldots, W$
SE_t	selling price of an emission allowance in time $t \in T$
SM_t	maximum number of saleable emission allowances in time $t \in T$
TC_{sq}	maximum transportation capacity for transports from site $s \in S_\sigma$ to site $q \in S_\lambda$ of the SC stages $(\sigma, \lambda) \in K$

TC_{sqt} maximum transportation capacity for transports from site $s \in S_\sigma$ to site $q \in S_\lambda$ of the SC stages $(\sigma, \lambda) \in K$ in time $t \in T$
TF_{sq} fixed transportation costs for transports from site $s \in S_\sigma$ to site $q \in S_\lambda$ of the SC stages $(\sigma, \lambda) \in K$
TF_{sqt} fixed transportation costs for transports from site $s \in S_\sigma$ to site $q \in S_\lambda$ of the SC stages $(\sigma, \lambda) \in K$ in time $t \in T$
TS_{sq} variable costs of temporary storage for transports from site $s \in S_\sigma$ to site $q \in S_\lambda$ of the SC stages $(\sigma, \lambda) \in K$ (per day)
TV_{sq} variable transportation costs for transports from site $s \in S_\sigma$ to site $q \in S_\lambda$ of the SC stages $(\sigma, \lambda) \in K$ (per product)
TV_{sqt} variable transportation costs for transports from site $s \in S_\sigma$ to site $q \in S_\lambda$ of the SC stages $(\sigma, \lambda) \in K$ in time $t \in T$ (per product)
TZ_{sq} transportation time from site $s \in S_\sigma$ to site $q \in S_\lambda$ of the SC stages $(\sigma, \lambda) \in K$
W number of SC stages belonging to forward operations [equals the number of SC stages before the market stage]
XC_s maximum throughput capacity for recycled products at site $s \in S_\sigma$ of SC stage $\sigma = 1, \ldots, W$
XC_{st} maximum throughput capacity for recycled and stocked products at site $s \in S_\sigma$ of SC stage $\sigma = 1, \ldots, W$ in time $t \in T$
α_{fs} share of quantities in quality grade $f \in F$ at site $s \in S_{W+1}$ that needs to be processed in reverse logistics (recycling or disposal)
α_s share of quantities at site $s \in S_{W+1}$ that needs to be processed in reverse logistics (recycling or disposal)
β_{fs} share of quantities in quality grade $f \in F$ at site $s \in S_{W+2}$ that can be recycled [note: $(1 - \beta_{fs})$ represents the share of quantities that cannot be recycled and, thus, needs to be disposed of]
β_s share of quantities at site $s \in S_\sigma$ of relevant SC stage σ that can be recycled [note: $(1 - \beta_s)$ represents the share of quantities that cannot be recycled and, thus, needs to be disposed of]
γ_s share of perishable quantities at site $s \in S_\sigma$ of SC stage $\sigma = 2, \ldots, W$ that needs to be disposed of
δ_s ratio between products supplied from SC stage λ that must be processed in reverse logistics, and products supplied from SC stage λ that can be used for manufacturing at site $s \in S_\sigma$ of SC stage $\sigma = 2, \ldots, W$
η_t technical parameter: $\eta_0 = 0, \eta_1 = \ldots = \eta_{t_E - 1} = 1$
κ_o technical parameter: $\kappa_1 = 1, \kappa_2 = -1$
υ_t weighting factor of surpluses realized in time $t \in T_+$

Variables

af_{oa}^{z} credit amount $(z = 1)$ or repayment amount $(z = 2)$ of financing alternative $o \in O$, assigned to liquidity period $a \in A$
ap_{sa} costs of forward and reverse operations at site $s \in S_\sigma$ of SC stage $\sigma = 1, \ldots, W, W + 2$, assigned to liquidity period $a \in A$

ar_{sa} revenues (adjusted for marketing costs) at market site $s \in S_{W+1}$, assigned to liquidity period $a \in A$

at_{sa} transportation costs for transports starting from site $s \in S_\sigma$ of SC stage $\sigma = 1, \ldots, W + 2$, assigned to liquidity period $a \in A$

b auxiliary variable to be used as a counter

dr_s recycled quantity at site $s \in S_\sigma$ of SC stage $\sigma \in L$

eb_t number of emission allowances bought in time $t \in T$

es_t number of emission allowances sold in time $t \in T$

fi_o^z amount paid in after realizing a financing alternative $o \in O$ ($z = 1$) or amount paid out for repaying the financing alternative ($z = 2$)

$fi_{ot\tau}$ amount paid in after realizing a credit ($o = 1$) or amount paid out after realizing an investment ($o = 2$), which starts in time $t \in T$ and ends in time $\tau \in T_+$

fr_s disposed quantity at site $s \in S_{W+2}$

g_{fs} equals 1 if market $s \in S_{W+1}$ is supplied with a product package of grade $f \in F$, and 0 otherwise

gr_{fsq} quantity in quality grade $f \in F$ at market site $s \in S_{W+1}$ that needs to be processed in reverse logistics at site $q \in S_{W+2}$

$ha_{\iota\omega\theta}$ allele of the gene $\theta \in \Theta$ on chromosome $\omega \in \Omega$ in generation $\iota \in \mathrm{I}$

$hr_{\iota\omega*\theta}$ allele of the gene $\theta \in \Theta$ that belongs to the chromosome, which is on rank $\omega* \in \Omega$ in generation $\iota \in \mathrm{I}$

hs_θ allele of the gene $\theta \in \Theta$ that belongs to the chromosome, which is on the first rank $\omega* = 1$ in the final generation $\iota = |\mathrm{I}|$

in_{st} inventory at site $s \in S_\sigma$ of SC stage $\sigma = 1, \ldots, W$ in time $t \in T$, $t \geq 1$
[note: initial stocks can be considered by a parameter in_{s0}]

lf_{oa}^z equals 1 if financing alternative $o \in O$ starts ($z = 1$) or ends ($z = 2$) within liquidity period $a \in A$, and 0 otherwise

lp_{sa}^z equals 1 if operation at site $s \in S_\sigma$ of SC stage $\sigma = 1, \ldots, W, W + 2$ starts ($z = 1$) or ends ($z = 2$) within liquidity period $a \in A$, or if demand at site $s \in S_{W+1}$ is satisfied ($z = 1$) or returned ($z = 2$) within liquidity period $a \in A$, respectively, and 0 otherwise

nu_s recyclable quantity at site $s \in S_{W+2}$, which is disposed of

nu_s^λ recyclable quantity of the product manufactured in SC stage λ at site $s \in S_\sigma$ of SC stage $\sigma \in L$, which is disposed of

$oc_{\iota\omega}$ fitness value of the chromosome $\omega \in \Omega$ in generation $\iota \in \mathrm{I}$
[note: equals the objective value of the submodel that results from the fixation of the binary variables according to the chromosome's alleles]

$or_{\iota\omega*}$ fitness value of the chromosome on rank $\omega* \in \Omega$ in generation $\iota \in \mathrm{I}$

pr_s production quantity at site $s \in S_\sigma$ of SC stage $\sigma = 1, \ldots, W$
[interpretable as storage quantity for distribution stages]

pr_{st} production quantity at site $s \in S_\sigma$ of SC stage $\sigma = 1, \ldots, W$ in time $t \in T$
[interpretable as storage quantity for distribution stages]

q_a liquidity in period $a \in A$

q_t liquidity withdrawal in time $t \in T_+$

qr_{sq}^{λ} quantity of the product manufactured in SC stage λ at market site $s \in S_{W+1}$, which needs to be processed in reverse logistics at site $q \in S_{W+2}$

qr_{st} quantity of the final product, which needs to be processed in reverse logistics at site $s \in S_{W+2}$ in time $t \in T$

rr_{s}^{λ} quantity of the product manufactured in SC stage λ available at site $s \in S_{\sigma}$ of SC stage $\sigma = 2, \ldots, W$, which needs to be processed in reverse logistics

sf_{o}^{z} start time ($z = 1$) or end time ($z = 2$) of financing alternative $o \in O$

sl_{s} tardiness in demand satisfaction at market site $s \in S_{W+1}$ (in days)

sn_{st} equals 1 if site $s \in S_{\sigma}$ of SC stage $\sigma = 1, \ldots, W, W + 2$ is shut down in time $t \in T$, and 0 otherwise

sp_{s}^{z} start time ($z = 1$) or end time ($z = 2$) of operations (e.g., production, storage, recycling, disposal) at site $s \in S_{\sigma}$ of SC stage $\sigma = 1, \ldots, W, W + 2$, or time of satisfying demand ($z = 1$) or returning products ($z = 2$) at market site $s \in S_{W+1}$

st_{sq} temporary storage time for transports from site $s \in S_{\sigma}$ to site $q \in S_{\lambda}$ of SC stages $(\sigma, \lambda) \in K$

su_{st} equals 1 if site $s \in S_{\sigma}$ of SC stage $\sigma = 1, \ldots, W, W + 2$ is set up in time $t \in T$, and 0 otherwise

tp_{sq} equals 1 if transportation from site $s \in S_{\sigma}$ to site $q \in S_{\lambda}$ of the SC stages $(\sigma, \lambda) \in K$ is conducted, and 0 otherwise

tp_{sqt} equals 1 if transportation from site $s \in S_{\sigma}$ to site $q \in S_{\lambda}$ of the SC stages $(\sigma, \lambda) \in K$ is conducted in time $t \in T$, and 0 otherwise

ud_{s} auxiliary variable representing the variable recycling costs at site $s \in S_{\sigma}$ of SC stage $\sigma = 1, \ldots, W, W + 2$

uf_{s} auxiliary variable representing the variable disposal costs at site $s \in S_{\sigma}$ of SC stage $\sigma = 1, \ldots, W, W + 2$

up_{s} auxiliary variable representing the fixed and variable production costs at site $s \in S_{\sigma}$ of SC stage $\sigma = 1, \ldots, W, W + 2$

ur_{s} auxiliary variable representing the fixed costs of reverse operations at site $s \in S_{\sigma}$ of SC stage $\sigma = 1, \ldots, W, W + 2$

v_{sqU} auxiliary variable (see set N_{sqU})

ve_{t} auxiliary variable representing the overall monetary consequences of environmental decisions in time $t \in T$

vo_{t} auxiliary variable representing the overall monetary consequences of decisions on operations in time $t \in T_{+}$

vs_{t} auxiliary variable representing the overall monetary consequences of decisions on site states in time $t \in T$

x_{sq} transportation quantity from site $s \in S_{\sigma}$ to site $q \in S_{\lambda}$ of SC stages $(\sigma, \lambda) \in K$

x_{sqt} transportation quantity from site $s \in S_{\sigma}$ to site $q \in S_{\lambda}$ of SC stages $(\sigma, \lambda) \in K$ in time $t \in T$

y_{s} equals 1 if production/storage at site $s \in S_{\sigma}$ of SC stage $\sigma = 1, \ldots, W$ is conducted [for all continuous-time models], or if market site $s \in S_{W+1}$ is selected [for all continuous-time models except the one for perishable goods, see Sect. 6.1.2], and 0 otherwise