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A quantitative sustainable sourcing model for supplier selection and order allocation

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Abstract

The historical agreement on climate change in Paris in 2015 has recalled the global attention for the pivotal subject of sustainability. Sustainable sourcing, i.e. integrating environmental, social, and economic issues into sourcing decisions, has been studied as a relevant part of sustainability in academic and managerial research papers. However, the focus has been set on conceptual models: Only ten percent of sustainable sourcing models are quantitative. To fill this lacuna in research, in this research paper we have developed a quantitative sustainable sourcing model to select suppliers and determine order quantities. In detail, we have considered a multiple supplier problem with capacity constraints, fixed charges and salvage values. Based on the newsvendor model, we have – for the first time to our knowledge – considered the end product demand and price as functions of the suppliers' sustainability level. Having empirically tested our model by sensitivity analyses and 42 representative examples, we have three findings: First, our model has determined that, despite increasing demand uncertainty, the benefit of higher order quantities does not always compensate the reduction of the end product price when switching to another, less sustainable pool with higher capacities. Second, the benefit of higher stocks does not consistently outweigh the additional fixed charges if supplementary other suppliers in the same pool were procured from. Third, the coefficient of variation of demand has to be considered within supplier selections to avoid negative profits. Future research may enhance our single to a multi-period model and explore more deeply the correlation of parameter changes and profit under sustainability constraints.

Keywords: Sustainable Sourcing; Quantitative Model; Supplier Selection; Order Allocation; Newsvendor Model

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1. Introduction: The need for quantitative sustainable sourcing models

The historic climate change agreement in Paris in 2015 has attracted the worlds' attention for the pivotal subject of sustainability: The balanced use of environmental, social, and economic resources defined as sustainability (Elkington, 1998; Kleindorfer et al., 2005) is more relevant than ever to reach the ambitious target of limiting global warming to two degree Celsius. Managers have to consider the three aspects of sustainability in their sourcing decisions with regard to supplier selection and order allocation: Not the supplier with the lowest costs, but the supplier that enables the most sustainable business has to be chosen to ensure steady profits in the long-term.

Just as in sourcing decisions, the same shift from cost focus to sustainability focus has taken place in customers' purchase decisions: Around 70 percent of global customers are "willing to pay more for sustainable goods" (Nielsen Global Survey, 2015). Furthermore, even nine out of ten global citizens say they would boycott companies exhibiting the impression of acting irresponsibly (Cone Communications, 2015). Such evidence strongly pushes firms to holistically embrace all three aspects of sustainability, i.e. environmental, social, and economic aspects in their sourcing and pricing decisions.

However, the occurrence of events such as the present emissions scandal of Volkswagen (VW) reveals that social and environmental concerns have not been considered as relevant as quick wins by all companies. Thus, to reach the legally binding climate targets of Paris, it is necessary to include all sustainability aspects also in firms' supplier selection decisions with the help of models and tools. Nevertheless, a review paper by Tang and Zhou (2012) suggests a shortage of quantitative models for making sustainable sourcing decisions. They observe that "there are very few (almost none) quantitative procurement/sourcing models that deal with environmental/social responsibility issues." This lack of quantitative sustainable sourcing models has been confirmed by a recent review of more than 1,000 publications by Fahimnia et al. (2015): Only ten percent use quantitative models. Hence, we fill the identified lacuna in the world of sustainable supply chain management (SSCM) with our research by developing a quantitative supplier selection and order allocation model for sustainable sourcing.

We aim at incorporating three aspects in our model: First, we develop a mathematical sustainable sourcing model that a manufacturer of a short life cycle can use to select the suppliers to source a component from and to determine the quantity to procure from each supplier. Second, we suppose sustainability impacts demand positively: Paralleling the idea that a greener product generates higher demand (Nouira et al., 2014; Raz et al., 2013), we posit that the use of more sustainable suppliers enables the manufacturer to increase the demand for its end product. Third, we simultaneously assume that sustainability affects the price in such a way that the selection of more sustainable suppliers allows the manufacturer to request a higher price for its end product (Armstrong et al., 2015; Gupta and Palsule-Desai, 2011; Nielsen Global Survey, 2015). By integrating these premises into our model, we show how a sustainable sourcing decision impacts both revenue management and cost containment to maximize final profits.

The remainder of this paper is organized as follows: In the next section, we review relevant literature on sourcing models incorporating sustainability and mathematical approaches. In the subsequent section, we describe our problem setting of interest and present our mathematical problem formulation as a mixed integer programming model. In the penultimate section we run sensitivity analyses to determine the impact of our variables, exercise our mathematical programming model for 42 representative examples and discuss our findings. We end the paper with a summary of our work, point out implications and delineate avenues for future research.

2. Literature review: Sustainable sourcing models lack quantitative approaches

The research we present in this paper is related to two streams of research: research on sourcing models incorporating sustainability and mathematical sourcing models with a focus on the newsvendor model. In the subsequent sections, we provide a brief review of both streams and identify the research gap that motivates our research.

2.1. Sourcing models incorporating sustainability

As part of SSCM, sustainable sourcing integrates sourcing decisions with explicit consideration of environmental and social aspects in addition to traditional economic aspects (Singhry, 2015). Thereby, supplier selection and order quantities are determined under consideration of sustainability aspects (Azadnia et al., 2015). In doing so, a positive effect on a firm's financial performance and competitive advantage can be shown (Ağan et al., 2016; Singhry, 2015).

Many research papers have investigated the subject of sustainability along the supply chain (Brandenburg et al., 2014; Fahimnia et al., 2015; Sarkis and Dhavale, 2015). However, mostly conceptual models have been employed: Only about 10 percent of SSCM papers integrate quantitative models into their research (Brandenburg et al., 2014; Fahimnia et al., 2015). This lack of quantitative sourcing models that incorporate sustainability issues can be confirmed by recent literature reviews (Ashby et al., 2012; Hassini et al., 2012; Miemczyk et al., 2012; Seuring, 2013; Tang and Zhou, 2012; Taticchi et al., 2015).

Hitherto, it has been shown that a greener product increases its demand and price (Nouira et al., 2014; Raz et al., 2013). We transfer these findings and assume that the sustainability level of suppliers positively affects both demand and price of the end product.

Motivated by the previously presented lacuna in research, we develop a quantitative sourcing model that uses suppliers' sustainability levels to select the optimal suppliers as well as to determine optimal order quantities in order to maximize a manufacturer's profit.

2.2. Mathematical sourcing models with a focus on the newsvendor model

Sourcing can be divided into three phases:

1- Supplier evaluation: establishing a supplier base;
2- Supplier selection: choosing suppliers from the base;

3- Quantity allocation: determining the quantity to procure from each supplier selected (Burke et al., 2007).

In this paper we assume the manufacturer has already established a supplier base. Thus, we focus on the literature of mathematical sourcing models pertaining to the supplier selection and quantity allocation problem.

Mathematical models, such as linear programming, multi-objective programming or data envelopment analysis, have been applied in general supplier selection problems (Kannan et al., 2013; Snyder et al., 2016). As basis for our model we use the linear programming model. In particular, we make use of the so-called newsvendor model, which determines optimal order quantities restricted by uncertain demand and salvage value in a single period model (Dada et al., 2007). As in the problem setting studied by Zhang and Zhang (2011), we set up a newsvendor model with multiple suppliers, finite capacities and fixed charges facing stochastic demand. Following the studies on price-sensitive demand by Yu et al. (2009), we additionally integrate both sustainability-sensitive demand and price determined by different sustainability levels of the selected suppliers.

2.3. Objective of this paper: Mathematical model incorporating sustainability

As presented in the previous sections, relevant research has been conducted with respect to sustainable sourcing models on the one hand and mathematical sourcing models on the other hand. However, there are three research issues that have not been studied comprehensively yet, which we want to investigate in this paper:

First, there are almost no quantitative sustainable sourcing models (Fahimnia et al., 2015). Furthermore, the few prior works that adopt the newsvendor model to the field of sustainability do not holistically embrace the issue of sustainability as they only consider green issues and do not take social issues into account (Raz et al., 2013; Rosič and Jammernegg, 2013).

Second, research is missing with regard to sustainability levels determining order allocations (Azadnia et al., 2015). Moreover, sustainability aspects should be considered to develop classical inventory models, i.e. the newsvendor model, to shield against uncertainty (e.g. in demand) and maximize profits (Azadnia et al., 2015; Bushuev et al., 2015).

Third, the impact of price-setting determined by sustainability has not been explored yet in the newsvendor model: Recent papers with a focus on the newsvendor model call for further research on the relation of price and demand by varying main input variables (e.g. sustainability) (Rubio-Herrero et al., 2015; Xu and Lu, 2013).

In summary, we refer to the calls for further research regarding quantitative sustainable sourcing methodologies. Thus, we want to develop a model that investigates a setting with multiple suppliers with different capacity constraints, component prices and fixed charges as well as with diverse sustainability levels that determine end product price and end product's expected demand. In this paper we treat, for the first time to our knowledge, end product demand and end product price as a function of the sustainability of the suppliers used by the manufacturer.

3. Development of a mathematical sustainable sourcing model

3.1. Problem setting

In the following section we present the framework and introduce necessary constraints of our model. We consider a manufacturer of a short life cycle end product implying that the end product has a short selling season. The demand for the end product is stochastic. The main component of the end product has a substantial lead time and must be procured from one or more suppliers in advance of the sales period. Each supplier of the main component is restricted in its capacity. When the manufacturer orders from a supplier a fixed charge may be incurred in addition to a cost per unit. Any unsold main components the manufacturer has left over after the sales period have a salvage value that is supplier-specific depending on the supplier's sustainability degree and which may be negative, i.e. there may be a disposal cost.

The target of the manufacturer is to maximize its profits. Hence, the manufacturer is interested in low purchasing cost on the one hand and in high revenues by high demand and high selling prices on the other hand. Though, the characteristics of the main component and of its supplier(s) may impact the price of and the demand for its end product. In this paper we examine a sourcing problem where the manufacturer is able to obtain a higher price and generate greater demand for its end product if it has been procured from more sustainable suppliers.

Another main construct in our approach to model this problem is a so-called pool. A pool is a collection of one or more suppliers. We assume that the level of a pool's sustainability is determined by the member of the pool with the lowest level of sustainability. Furthermore, we suppose that sourcing from a pool with a higher measure of sustainability enables the manufacturer to obtain a price for the end product that is always at least as high as the price that can be obtained by sourcing from a pool with a lower level of sustainability. The same logic is applied to demand determination by a pool's sustainability level.

We present a mathematical programming model for sustainable sourcing that a manufacturer in this setting can use to determine the optimal supplier pool and the optimal quantity of the main component to procure from each supplier in the pool for maximum profits. The newsvendor model serves as basic input for our mathematical programming model. Candidate procurement quantities are generated to determine an optimal sourcing plan. In our newsvendor model demand for the end product is stochastic and the short life cycle of the product to be sold is reflected. Aside from serving as an appropriate model to be employed in this instance, another benefit of using a newsvendor model is that its overage parameter can be used to explicitly capture a main component's salvage value. In our setting, a salvage value signals a supplier's commitment to sustainability: The salvage value conveys information about a main component's environmental characteristics, such as material chemistry, disassembly and recyclability, and social characteristics, such as conditions of production referring to workplace safety and health as well as respect for human and workplace rights.

In conclusion, we consider suppliers' diverse sustainability levels by three factors: They are reflected in different salvage values, in different end product prices and in different end product demand.

3.2. Model variables

In this section, we define parameters and variables for our mathematical model formulation. The fixed model parameters are defined in Table 1.

Table 1. Definition of fixed model parameters

Parameter	**Values**		**Explanation**
N	$\in \mathbb{N}$		Number of suppliers; also number of pools
S	$\in \mathbb{N}$	$= \{1, \dots, N\}$	Set of suppliers where 1 denotes the supplier with the highest measure of sustainability, 2 denotes the supplier with the second highest measure of sustainability, etc.
$S_k = \{\alpha_{k1}, \dots, \alpha_{kk}\}$		$k = 1, \dots N$ $\alpha \in \mathbb{N}$	Set consisting of the first k suppliers from the set $\mathcal{S}$ ordered according to main component cost where α_{k1} denotes the index of the supplier in S (among the first k suppliers) with the lowest main component cost, α_{k2} denotes the index of the supplier in S (among the first k suppliers) with the second lowest main component cost, etc. Each such set is referred to as a pool in the sequel.
μ_i	$\in \mathbb{R}_{\geq 0}$	$i = 1, \dots N$	Average demand for the end product if the main component is procured from pool S_i.
σ_i	$\in \mathbb{R}_{\geq 0}$	$i = 1, \dots N$	Standard deviation of demand for the end product if the main component is procured from pool S_i
P_i	$\in \mathbb{N}$	$i = 1, \dots N$	Price the manufacturer is able to obtain for a unit of the end product if the main component is procured from pool S_i in \$.
D	$\in \mathbb{R}_{\geq 0}$		Manufacturer's production cost for common components and direct labor for a unit of the end product in \$.
R_i	$\in \mathbb{R}$	$i = 1, \dots N$	Net revenue obtained by the manufacturer for a unit of the end product if the main component is procured from pool S_i in \$; in particular $R_i = P_i - D$.
C_j	$\in \mathbb{N}$	$j = 1, \dots N$	Per unit cost of the main component if it is procured from supplier j in \$.
V_j	$\in \mathbb{R}$	$j = 1, \dots N$	Salvage value of a unit of the main component if it is procured from supplier j in \$.

F_j	$\in \mathbb{N}_0$	$j = 1, \dots N$	Fixed charge incurred if one or more units of the main component are procured from supplier j in \$.
L_j	$\in \mathbb{N}_0$	$j = 1, \dots N$	Limit on the number of units of the main component that supplier j is able to provide, i.e. capacity of supplier j.
Q_{ij}	$\in \mathbb{N}$	$i = 1, \dots N$ $j = 1, \dots N$	Newsvendor quantity[1] for supplier j in pool S_i.
I_{ij}	$\in \mathbb{N}$	$i = 1, \dots N$ $j = 1, \dots N$	Expected number of unsold main components if units of the main component are procured from supplier j in pool S_i.
E_{ij}	$\in \mathbb{R}$	$i = 1, \dots N$ $j = 1, \dots N$	Expected reduction in profit due to unsold main components if units of the main component are procured from supplier j in pool S_i in \$.
M	$\in \mathbb{N}$		Scaling factor

The parameters that vary in the optimization process are presented in Table 2.

Table 2. Definition of parameters that vary during the optimization process.

Parameter	Values		Explanation
x_i	$\in \mathbb{N}$	$i = 1, \dots N$	Units of the main component procured from pool S_i
y_{ij}	$\in \mathbb{N}$	$i = 1, \dots N$ $j = 1, \dots N$	Units of the main component procured from supplier j in pool S_i
z_i	$\in \{0, 1\}$	$i = 1, \dots N$	Selection of one pool only: One if the main component is procured from pool S_i, otherwise zero
u_{ij}	$\in \{0, 1\}$	$i = 1, \dots N$ $j = 1, \dots N$	Selection of supplier in a pool: One if the main component is procured from supplier j in pool S_i, otherwise zero
v_{ij}	$\in \{0, 1\}$	$i = 1, \dots N$ $j = 1, \dots N$	Selection of subsequent supplier in a pool: One if the main component is procured from supplier j but not supplier $j + 1$ in pool S_i, otherwise zero

3.3. Mathematical model formulation

We formulate our supplier selection and quantity allocation problem as a mixed integer programming model. The model determines the pool of suppliers to choose, the suppliers in the chosen pool to be employed and the number of the main components to procure from each employed supplier to maximize profits.

Mathematical model formulation:

$$\max_{\{x,y,z,u,v\}} \sum_{i=1}^{N} R_i x_i - \sum_{i=1}^{N} \sum_{j=1}^{i} C_{\alpha_{ij}} y_{ij} - \sum_{i=1}^{N} \sum_{j=1}^{i} F_{\alpha_{ij}} u_{ij} - \sum_{i=1}^{N} \sum_{j=1}^{i} E_{ij} v_{ij}$$

[1] Specified in section 3.3.

The constraints for our mathematical formulation are specified in the subsequent Table 3.

Table 3. Specification of constraints for our mathematical formulation.

Constraints	Values			No.
$x_i = \sum_{j \in S_i} y_{ij}$	$i = 1, \dots, N$			(1)
$y_{ij} \leq L_{\alpha ij}$	$i = 1, \dots, N$	$j = 1, \dots, i$		(2)
$\sum_{k=1}^{j} y_{ik} - M(1 - u_{ij}) \leq Q_{ij}$	$i = 1, \dots, N$	$j = 1, \dots, i$		(3)
$y_{ij} - Mu_{ij} \leq 0$	$i = 1, \dots, N$	$j = 1, \dots, i$		(4)
$u_{ij} = v_{ij}$	$i = 1, \dots, N$	$j = i$		(5)
$u_{ij} - u_{ij+1} = v_{ij}$	$j = 1, \dots, i$	$j \neq i$		(6)
$y_{ij} + M(1 - u_{ij+1}) \geq L_{\alpha ij}$	$i = 1, \dots, N$	$j = 1, \dots, i$	$j \neq i$	(7)
$x_i \leq Mz_i$	$i = 1, \dots, N$			(8)
$\sum_{i \in S} z_i = 1$				(9)
$x_i \geq 0$	$i = 1, \dots, N$			(10)
$y_{ij} \geq 0$	$i = 1, \dots, N$	$j = 1, \dots, i$		(11)
$z_i = 0 \; or \; 1$	$i = 1, \dots, N$			(12)
$u_{ij} = 0 \; or \; 1$	$i = 1, \dots, N$	$j = 1, \dots, i$		(13)
$v_{ij} = 0 \; or \; 1$	$i = 1, \dots, N$	$j = 1, \dots, i$		(14)

The first term of our mathematical model formulation determines the net revenue that the manufacturer can generate when selling the units procured from the pool selected for a price determined by that pool less the manufacturer's direct production costs. The second term calculates the total variable cost of procuring the main component. The third term measures the total fixed charges incurred when procuring the main component. The fourth term of the objective function captures the reduction in profit due to unsold main components.

The first constraint says that the number of main components procured from pool S_i must equal the total number of main components procured from the suppliers in pool S_i. The second constraint requires that the number of main components procured from supplier *j* in pool S_i must be less than or equal the capacity limit of supplier *j*. The third constraint demands that the number of main components procured from supplier *j* in pool S_i plus the number of main components procured from suppliers in pool S_i with main component cost lower than supplier *j* must be less than or equal the optimal number of main components to procure from supplier *j* in pool S_i, i.e. supplier *j* 's newsvendor quantity in pool S_i. The fourth constraint activates the third constraint for supplier j in pool S_i when supplier j is procured from. The fifth and sixth constraints together ensure that the cost of unsold main components is captured in the objective function only once in case of procuring from pool S_i. The seventh constraint allows the main component to be procured from supplier j in pool S_i only if the entire capacity of supplier $j-1$ is consumed. The eighth and ninth constraints together ensure that the main components are procured from only one pool. The tenth and eleventh constraints are non-negativity constraints. The twelfth constraint enforces an either or decision with regard to selecting one pool only. Finally, the last two constraints enforce an either or decision from each supplier in each pool with respect to procuring.

For every supplier, the newsvendor quantity must be calculated for each pool the supplier is a member of (implied by the third constraint). Supplier 1 of set S is a member of N pools, hence it has N associated newsvendor quantities. Supplier 2 of set S is a member of $N-1$ pools, hence it has $N-1$ associated newsvendor quantities, etc. In order to determine Q_{ij}, i.e. the newsvendor quantity for supplier j in pool S_i, it involves the calculation of the critical ratio

$$Q_{ij} = \frac{c_u}{c_u + c_o}$$

where c_u is the cost of underage and c_o is the cost of overage (Porteus 2002). For supplier j in pool S_i, $c_u = R_i - C_{\alpha_{ij}}$ and $c_o = C_{\alpha_{ij}} - V_{\alpha_{ij}}$.

The calculation of E_{ij}, the expected reduction in profit due to unsold main components, is detailed next. In the following, the term lead supplier refers to supplier 1 of a pool. First, we consider the case where the manufacturer procures the main components exclusively from the lead supplier. If the supplier's capacity is greater than the supplier's newsvendor quantity, then the latter will be procured from the supplier else the quantity procured will equal the capacity of the supplier. In either case $E_{i1} = I_{i1} \cdot \left(R_i - V_{\alpha_{i1}}\right)$. Second, we reflect the case where it is optimal to procure from supplier 2 of pool S_i in addition to the lead supplier. If supplier 2 is procured from, then the entire capacity of the lead supplier has been exhausted. When supplier 2's capacity plus the capacity of the lead supplier is greater than the newsvendor quantity of supplier 2, then the quantity procured from supplier 2 will equal its newsvendor quantity less the capacity of the lead supplier, otherwise the quantity procured from supplier 2 will equal its capacity. In the former case

$$E_{i2} = min\left\{I_{i2}, \max\left\{0, Q_{i2} - L_{\alpha_{i1}}\right\}\right\} \cdot \left(R_i - V_{\alpha_{i2}}\right) + \left(I_{i2} - min\left\{I_{i2}, \max\left\{0, Q_{i2} - L_{\alpha_{i1}}\right\}\right\}\right) \cdot \left(R_i - V_{\alpha_{i1}}\right)$$

while in the latter

$$E_{i2} = min\left\{I_{i2}, L_{\alpha_{i2}}\right\} \cdot \left(R_i - V_{\alpha_{i2}}\right) + \left(I_{i2} - min\left\{I_{i2}, L_{\alpha_{i2}}\right\}\right) \cdot \left(R_i - V_{\alpha_{i1}}\right).$$

The assumption that main components procured from the lead supplier will be used before those procured from supplier 2 is implicit in these calculations. A similar assumption is made in all cases where more than one supplier is employed.

4. Testing and discussing the model

We empirically test our model in a two-step approach: First, we run sensitivity analyses to investigate the impact of selected variables in certain ranges of values. Second, we define representative examples to illustrate how the model can be used by a manager in making a supplier selection and quantity allocation decision. Both examinations are implemented and run in MATLAB R2016a. The results will be presented and discussed next.

4.1. Sensitivity analyses

We conduct sensitivity analyses for diverse ranges of values: to start with, we investigate moderate ranges of ±50 percent. Then we explore the behavior of the model for extreme small values close to zero (up to -99.98 percent of the basis value) and extreme large values (up to +99,900 percent of the basis value). Additionally, we vary the number of suppliers under consideration from one to five. As our model integrates a multitude of variables, we concentrate on three variables in our sensitivity analyses that are component price, salvage value and capacity constraints. We thus expect to reveal relevant characteristics of our model.

The procedure of our sensitivity analyses is depicted schematically in Figure 1: First, we define a basis scenario with five suppliers having different component prices, salvage values and capacities (see table "Basis Matrix" in Figure 1). We write these values as component price vector, salvage value vector and capacity vector. Subsequently, each of the vector is varied by a linear shift of 10 percent each, i.e. from -50 percent to +50 percent, while the other values are kept fix. The variations are designated scenarios 1 to 11 with scenario 6 as a basis scenario meaning the variation there is 0 percent. Consequently, in total 33 scenarios are presented as the three vectors get shifted eleven times each.

4.1.1. Sensitivity analysis of component price

The results of our sensitivity analyses are depicted in Figure 2. When analyzing the first sensitivity analysis with variations of the component price, it can be seen that the price impacts the profit directly in all eleven scenarios as expected: The higher the component price, the smaller the profit. Therefore, the profit curve is decreasing almost linearly if the price increases with shifts of 10 each. Hence, in all scenarios 1-11, the component price has an impact on the final profits.

4.1.2. Sensitivity analysis of salvage value

Regarding the results of the second sensitivity analysis with variations of the salvage value that reflects the suppliers' sustainability level (as described in section 3.1.) a contrariwise dependency can be detected: The higher the salvage value, the higher the profit. Interestingly, this relation only holds true for scenarios 7 to 11, where profits almost exhibit an exponential growth even though salvage values rise in linear shifts of 10 percent. Otherwise, the profit is indifferent to the salvage value in scenarios 1-6. Accordingly, it can be stated that in our model the salvage value has to reach a certain value (here: scenario 7 with +10 percent) to have an impact on the final profit. This phenomenon can also be seen in the next section 4.2, where we investigate the results if salvage values are reduced around two third of the original values. Thus, this non-linearity confirms the need for our sustainable sourcing model as a sourcing manager cannot intuitively take different salvage values into account which are relevant for his final decision.

4.1.3. Sensitivity analysis of capacity

With respect to the third sensitivity analysis with variations of the suppliers' capacities, a similar behavior can be noticed in parts: Even though the capacity increases in linear shifts, the profit curve stays parallel to the x-axis. Accordingly, no impact of the capacity on the profit can be detected within our scenarios of varying the original capacity values in a range of ±50 percent. This demonstrates the significance of our construct of a pool: We assume that the capacity of the lead supplier can be enhanced by the capacity of the other suppliers in the pool. Consequently, the constraint of each supplier's capacity and newsvendor quantity in the context of a pool is crucial when determining optimal order quantities and final profits. We consider this in the next section 4.2 where we focus on the selection of a certain pool and certain suppliers thereof.

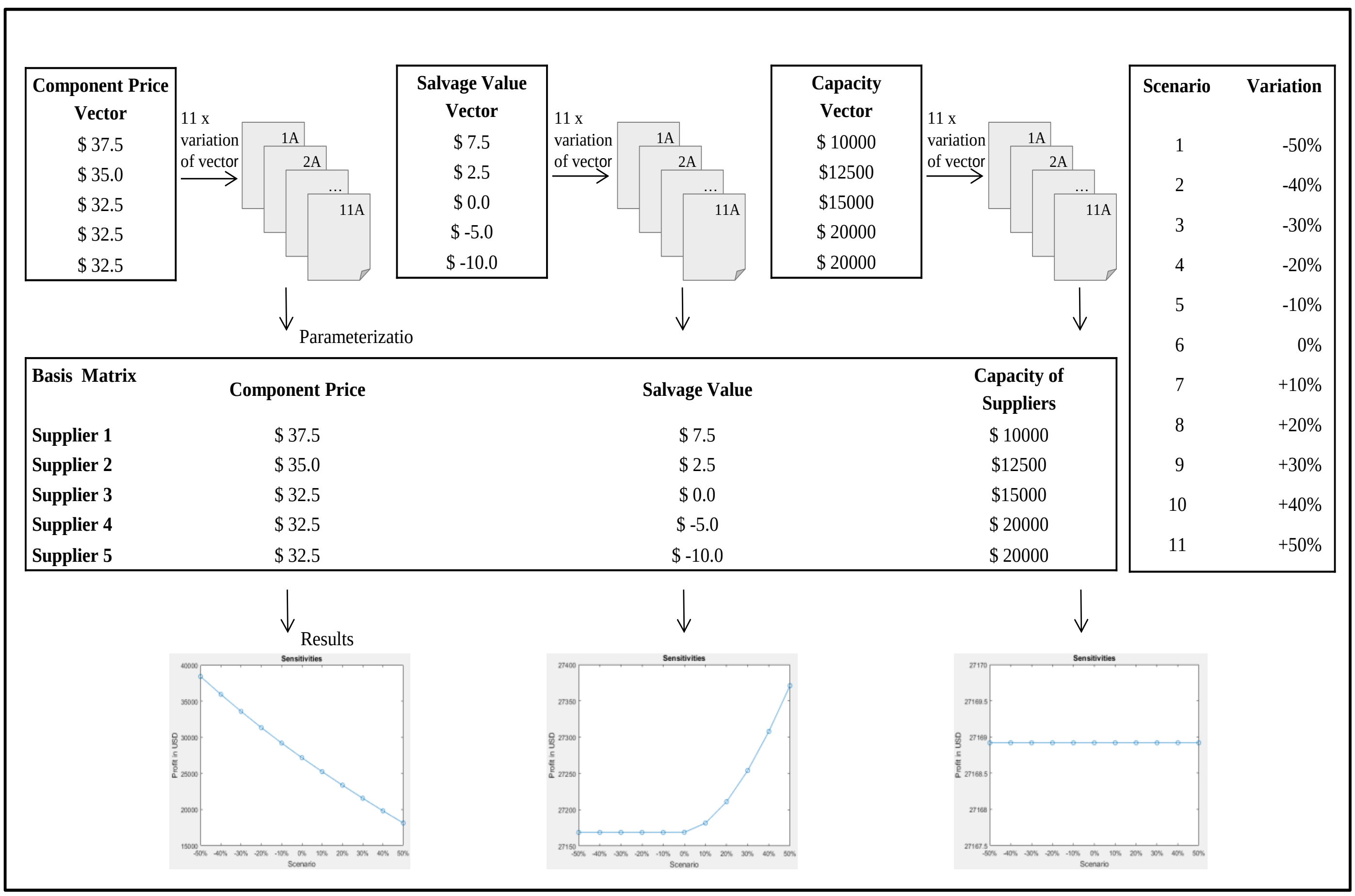
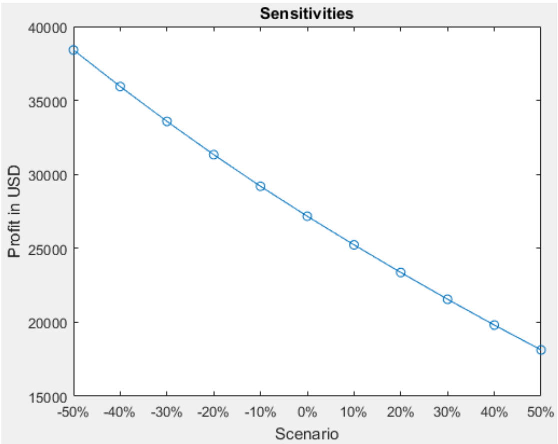


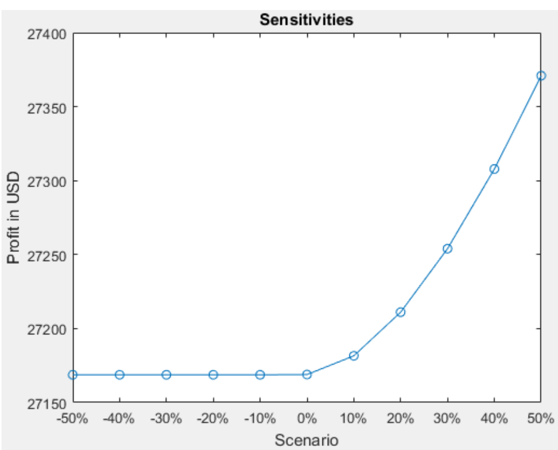
Figure 1. Schematic presentation of the sensitivity analyses

Price



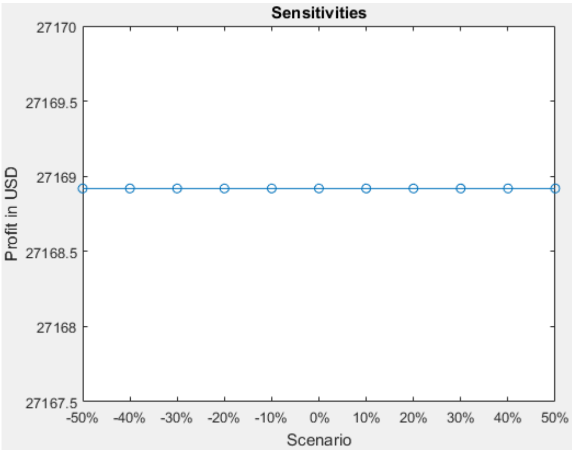
Scenario	Variation	Max Profit
1	-50%	$38,410
2	-40%	$35,940
3	-30%	$33,580
4	-20%	$31,330
5	-10%	$29,190
6	0%	$27,170
7	+10%	$25,230
8	+20%	$23,360
9	+30%	$21,560
10	+40%	$19,810
11	+50%	$18,130

Salvage Value



Scenario	Variation	Max Profit
1	-50%	$27,170
2	-40%	$27,170
3	-30%	$27,170
4	-20%	$27,170
5	-10%	$27,170
6	0%	$27,170
7	+10%	$27,180
8	+20%	$27,210
9	+30%	$27,250
10	+40%	$27,310
11	+50%	$27,370

Capacity



Scenario	Variation	Max Profit
1	-50%	$27,170
2	-40%	$27,170
3	-30%	$27,170
4	-20%	$27,170
5	-10%	$27,170
6	0%	$27,170
7	+10%	$27,170
8	+20%	$27,170
9	+30%	$27,170
10	+40%	$27,170
11	+50%	$27,170

Figure 2. Overview of the sensitivity analyses with variations of the component price, salvage value and capacities.

4.2. Representative examples

In this section, we present the results from 42 representative examples (see Table 4 and Table 5). The 42 examples are set up as follows: The first 21 examples are all identical except for their demand parameters (μ and σ; in every example we assume demand is log-normally distributed), which also impact the newsvendor quantities $\{Q_{ij}\}$, the expected number of unsold main components $\{I_{ij}\}$, and the expected reduction in profit due to unsold main components $\{E_{ij}\}$. The second set of 21 examples is identical to the first 21 except for a change in salvage values where positive values have been reduced by 65 percent, i.e. by around two third compared to their original values. This means basically all 42 examples are identical except for the parameters μ, σ, Q_{ij}, I_{ij}, E_{ij} and V_{ij}.

To illustrate the examples' settings, we present the details for one example, i.e. Example 5, where we consider a setting with five suppliers ($N = 5$), hence $S = \{1,2,3,4,5\}$. The remaining data for Example 5 is shown in the Appendix (Appendix-Chapter IV 1).

Each of the five suppliers is deemed qualified. In our context, a supplier is qualified if an assessment has determined that the supplier should be able to deliver on time and provide a main component that meets quality standards. Supplier 1 of S is designated as supplier 1 because it is the best supplier from a sustainability perspective. It should be observed that while supplier 1's main component has the highest per unit cost (see vector C), its main component also has the highest salvage value (see vector V), hence supplier 1 can be seen as providing a component with more appealing characteristics in terms of sustainability. At the same time, the capacity of supplier 1 is the most limited of all suppliers (see vector L) and using supplier 1 incurs a fixed charge that is as high as or higher than that of all other suppliers (see vector F). If the manufacturer procures the main component exclusively from supplier 1, the expected end product price will be highest (see vector P).

Supplier 5 is at the other end of the spectrum which is the worst supplier from sustainability perspective. However, supplier 5's main component has the lowest per unit cost and using supplier 5 incurs no fixed charge although the use of this supplier results in the lowest end product price. Moreover, supplier 5's main component has the lowest salvage value, in fact one that is negative implying that it possesses unappealing characteristics in terms of sustainability so that additional cost incur for example for disposal. Supplier 5 also happens to have the highest capacity of all suppliers. If the manufacturer procures any amount of the main component from supplier 5, the expected end product price will be lowest. The remaining suppliers have profiles that lie between the extremes of suppliers 1 and 5.

4.3. Results and discussion

4.3.1. General results: Overview

We give a short overview of the general results of our representative examples (depicted in Figure 3) before presenting the results in detail.

As expected, it is valid for all Examples 1-42: The higher the demand, the higher the profit. Likewise it can be observed for all examples: The more units procured, the higher the profit. Concerning the level of uncertainty it can be noted for each triple presented (e.g. triple 19-21), the higher the standard deviation, the lower the profit. With respect to the selection of pools, it is observable that in Examples 1-21, there is a higher diversity when selecting pools, while in Examples 22-42 there is a higher concentration on pool 3. Interestingly in Examples 22-42, pool 1 and 2 are not selected at all. Another difference between the two sets of examples can be noticed when focusing on the suppliers selected: While in Examples 1-21, there is a clear preference for more sustainable suppliers, in Examples 22-42 with the reduction of the salvage value, however, there is a shift to less sustainable suppliers. Regarding the highest profit per supplier in average, noteworthy in Examples 1-21, the least sustainable suppliers (supplier 4 and 5) have an average profit above overall average profit – and though are selected fewest. In Examples 22-42, the most (supplier 1) and the least sustainable suppliers (supplier 4 and 5) generate average profits above overall average profit – and yet again are chosen fewest.

The overview of the general results stresses the complexity of the sustainable sourcing problem. Neither the most sustainable pool nor the pool with the highest profit on average are always selected. This emphasizes the need for our mathematical sustainable sourcing model to determine the optimal solution in terms of supplier respectively pool selection, order quantities and profit maximization.

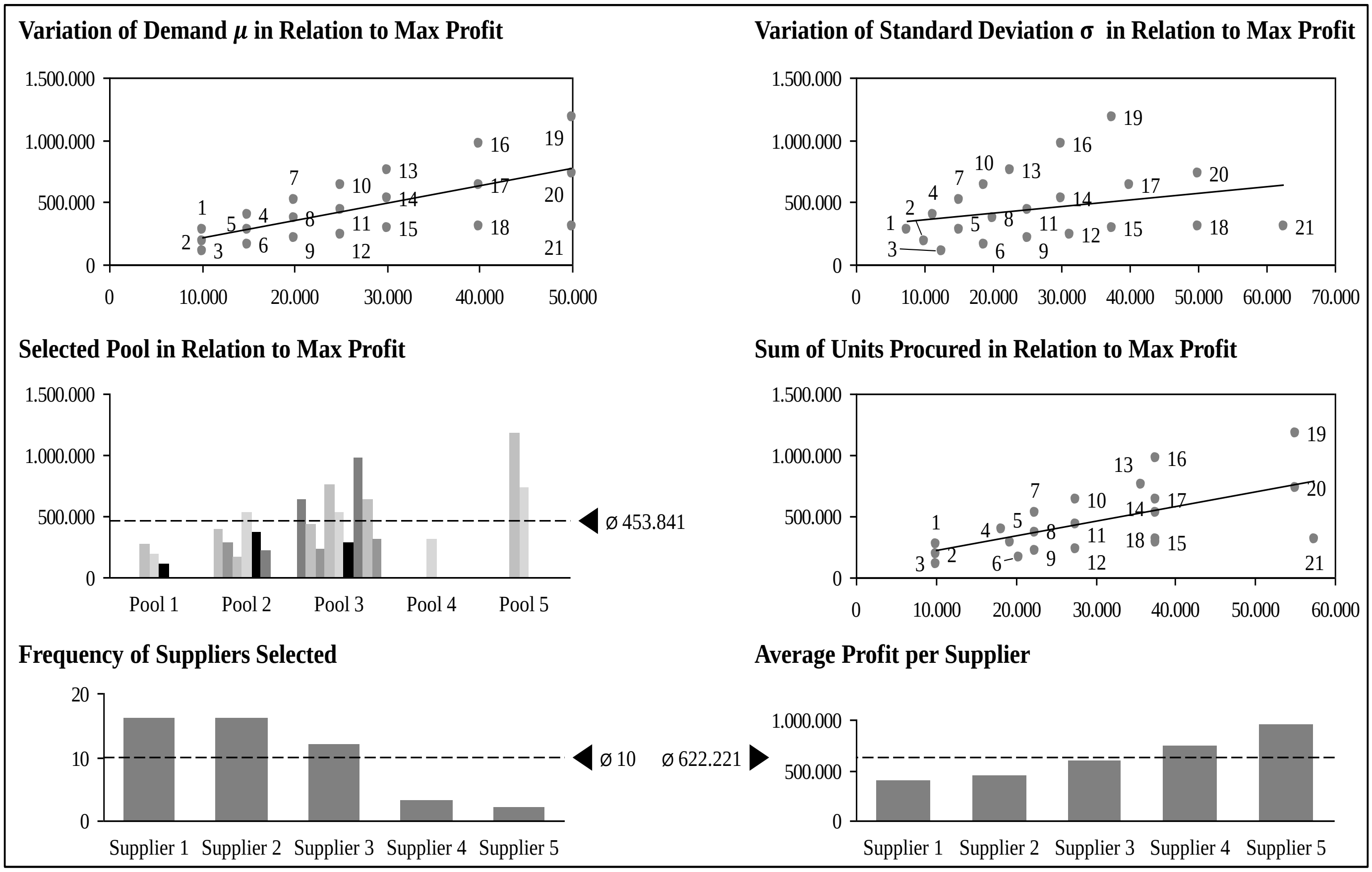


Figure 3. Overview of the general results of the Examples 1-21.

4.3.2. Results of variation of average demand $\boldsymbol{\mu}$ *and standard deviation* $\boldsymbol{\sigma}$

We first present the findings for the Examples 1-21 where demand μ and standard deviation σ are varied while the other variables stay the same.

Solving our model using the data of Example 5, we find the value of the objective function equals \$280,793 , i.e. the expected maximum profit. The decision variables are all zero with the exception of $z_2 = 1$ (choose pool 2), $u_{12} = u_{22} = 1$ (employ suppliers 1 and 2 of $S_2 = 1$ (suppliers 1 and 2 of S)), $x_2 = 19{,}303$ (main components procured in total), $y_{21} = 12{,}500$ (main components procured from supplier 1 of S_2 (supplier 2 of S)), $y_{22} = 6{,}803$ (main components procured from supplier 2 of S_2 (supplier 1 of S)), S_2

(supplier 1 of S)), and $v_{22} = 1$ (hence the expected reduction in profit due to unsold main components is calculated recognizing that units of the main component are procured from supplier 2 of S_2 (supplier 1 of S)).

In Example 5, using pool 2 instead of pool 1 brings a 4.5 percent reduction in the price for the manufacturer's end product (the price shrinks from \$110 to \$105) and increases fixed charges by 100 percent (fixed charges raise from \$5,000 to \$10,000). Nevertheless, using pool 2 instead of pool 1 allows the bulk of the main components to be procured for approximately 6.7 percent less per unit (the greater part of the components costs \$35 instead of \$37.50 each). Eventually, the model has determined it is optimal (in the sense of profit maximizing) for the manufacturer to procure main components from supplier 1 of S_2 (supplier 2 of S) up to its capacity limit and to procure an additional 6,803 main components supplier 2 of S_2 (supplier 1 of S), which all together equals Q_{22}, the newsvendor quantity for supplier 2 of S_2.

Table 4. Summary of results for $V_1 = \$7.50$ and $V_2 = \$2.50$.

Ex.	μ	σ	Pool	Units Procured	Sum of Units Procured	Profit
1	10,000	7,500	1	$y_{11} = 10{,}000$	10,000	\$273,154
2	10,000	10,000	1	$y_{11} = 10{,}000$	10,000	\$190,873
3	10,000	12,500	1	$y_{11} = 10{,}000$	10,000	\$108,591
4	15,000	11,250	2	$y_{21} = 12{,}500, y_{22} = 5{,}728$	18,228	\$397,157
5	15,000	15,000	2	$y_{21} = 12{,}500, y_{22} = 6{,}803$	19,303	\$280,793
6	15,000	18,750	2	$y_{21} = 12{,}500, y_{22} = 7{,}879$	20,379	\$164,429
7	20,000	15,000	2	$y_{21} = 12{,}500, y_{22} = 10{,}000$	22,500	\$522,928
8	20,000	20,000	2	$y_{21} = 12{,}500, y_{22} = 10{,}000$	22,500	\$369,940
9	20,000	25,000	2	$y_{21} = 12{,}500, y_{22} = 10{,}000$	22,500	\$209,946
10	25,000	18,750	3	$y_{31} = 15{,}000, y_{32} = 12{,}500$	27,500	\$632,525
11	25,000	25,000	3	$y_{31} = 15{,}000, y_{32} = 12{,}500$	27,500	\$434,379

12	25,000	31,250	3	$y_{31} = 15{,}000, y_{32} = 12{,}500$	27,500	$232,562
13	30,000	22,500	3	$y_{31} = 15{,}000, y_{32} = 12{,}500, y_{33} = 8{,}200$	35,700	$762,453
14	30,000	30,000	3	$y_{31} = 15{,}000, y_{32} = 12{,}500, y_{33} = 10{,}000$	37,500	$528,797
15	30,000	37,500	3	$y_{31} = 15{,}000, y_{32} = 12{,}500, y_{33} = 10{,}000$	37,500	$288,045
16	40,000	30,000	3	$y_{31} = 15{,}000, y_{32} = 12{,}500, y_{33} = 10{,}000$	37,500	$968,566
17	40,000	40,000	3	$y_{31} = 15{,}000, y_{32} = 12{,}500, y_{33} = 10{,}000$	37,500	$640,295
18	40,000	50,000	3	$y_{31} = 15{,}000, y_{32} = 12{,}500, y_{33} = 10{,}000$	37,500	$311,681
19	50,000	37,500	5	$y_{51} = 20{,}000, y_{52} = 20{,}000, y_{53} = 15{,}000$	55,000	$1,175,619
20	50,000	50,000	5	$y_{51} = 20{,}000, y_{52} = 20{,}000, y_{53} = 15{,}000$	55,000	$729,791
21	50,000	62,500	4	$y_{41} = 20{,}000, y_{42} = 15{,}000, y_{43} = 12{,}500, y_{44} = 10{,}000$	57,500	$308,128

We now turn our attention to the rest of the examples in Table 4. For each example we provide the parameters of the log-normal demand model, the optimal pool to source from, the optimal quantity to procure from each supplier in the chosen pool (when other than zero), the optimal order quantity in total and the manufacturer's expected maximum profit. We consider examples where the coefficient of variation of demand ($\frac{\sigma}{\mu}$) varies from 0.75 to 1.00 or 1.25 in every triple that has the same average demand μ. Those triples of same average demand are Examples 1-3, 4-6, 7-9, 10-12, 13-15, 16-18, 19-21.

In the classical newsvendor problem, i.e. a single supplier problem without any capacity constraints or fixed charges, with increase of demand variability it becomes optimal to increase stock quantities assuming the economics are attractive meaning the cost of underage is greater than the cost of overage. This correlation can only be confirmed in our Examples 4-6 (as described with the presentation of Example 5), 13-14 and 20-21.

In fact, our sourcing model – that embraces multiple suppliers with capacity constraints, fixed charges and different sustainability levels as determining optimum factor – reveals three impact factors that lead to a stocking behavior that is different to that expected in the classical newsvendor problem.

The first impact factor we expose is the suppliers' sustainability level that determine the manufacturer's end product price. In Examples 1-3, it can be seen that the stock quantity, i.e. the sum of units procured, is the same in each example with 10,000 components procured. As the economic environment is attractive in this setting, it would have been reasonable to expect higher stock levels in Examples 2 and 3 than in Example 1 because of increased demand variability (higher standard deviations in Examples 2 and 3). However, our model has determined that the benefit of increased stock going into the sales period does not outweigh the reduction of the end product price that would come with tapping another pool. Thus, despite higher demand variability, higher capacities provided by less sustainable suppliers from another pool do not always compensate the decrease in selling prices generated with these less sustainable suppliers. This phenomenon has been identified in addition to Examples 1-3 in Examples 7-9 and 16-18 where the whole capacity of the respective pool is consumed. But instead of switching to a pool with a higher capacity but a lower sustainability ranking in the given scenarios of increasing demand variability, the examples in the respective triples stay with procuring the same order quantities from a pool with a higher sustainability ranking. Hence, the impact of sustainability levels respectively end product prices on order quantities and finally maximum profit is the first factor we identify.

The second factor we determined to affect order quantities respectively maximum profit is fixed cost. Therefore, consider Examples 10-12 where the stock quantity again is the same in each example with 27,500 components procured. Given the economic environment is attractive, once more it would be rational to expect higher stock levels in Examples 11 and 12 than in Example 10 because of increased demand variability. Yet, our model detects that the benefit of increased stock going into the sales season does not outweigh the rise of additional fixed cost that would be incurred if supplier 3 of that pool was supplementary procured from. The impact of fixed cost can also be seen in Examples 19 and 20 where our model has determined that the increase in stocks does not outweigh the extra fixed charges that would occur if additionally supplier 4 and supplier 5 of the considered pool 5 were procured from. Accordingly, fixed cost is the second factor impacting stock quantities and thus maximum profit we determined in our examples.

The third impact factor on stock levels we identify is the coefficient of variation of demand $\frac{\sigma}{\mu}$. We find that when the coefficient of variation is greater than one and the average demand is greater than 20,000, it is unprofitable for the manufacturer to procure solely from supplier 1. In other words, if the manufacturer went into the sales period with just the 10,000 main components that supplier 1 is able to provide, then the expected profit of the manufacturer would be even negative, implying losses under the aforementioned conditions. This is valid for instance for Example 12 caused by a confluence of effects. One effect is that for this stock quantity, the probability of a demand realization where the entire stock is consumed is quite high (e.g. almost 70 percent in Example 12) on the one hand but simultaneously the probability of a demand realization where most of the demand goes uncaptured is also quite high (e.g. over 50 percent in Example 12), on the other hand. The other effect is because of the high level of demand uncertainty, the probability of a demand realization where demand is next to nil is not insignificant (e.g. about 20 percent in Example 12). All in all, these effects imply that the manufacturer significantly misses out on sales, and hence, profits if the demand is high, while if the demand is low, the manufacturer ends up with piles of unsold inventory and financial losses. To be profitable under the aforementioned conditions, the manufacturer needs to go into the sales period with a higher stock quantity – by not solely procuring from supplier 1, but instead for instance in Example 12 from supplier 2 and supplier 3. This offers the manufacturer the opportunity to generate more sales if the demand is high and reduce losses due to lower component cost if the demand is low. This effect of the coefficient of variation of demand can likewise be noticed in Examples 15, 18 and 21: Here, the coefficient of variation is greater than one and the average demand is greater than 20,000 and thus it is unprofitable to solely acquire the components from supplier 1 due to the reasons described by means of Example 12. Accordingly, for the examples regarded here this demonstrates a certain need to source from less sustainable, cheaper suppliers to consider the impact of the coefficient of demand. Interestingly, for some of the examples it is even profitable to source from supplier 5, the supplier with the lowest sustainability ranking, but not from supplier 1, the supplier with the highest sustainability ranking. Thus, the analysis of the third impact factor identified, the coefficient of variation of demand, underlines the requirement for our model to maximize profit in complex sourcing decisions.

4.3.3. Results of variation of salvage value $\boldsymbol{V_j}$

Next we discuss the results of reducing the positive salvage values by around two third of their original values as carried out for the Examples 22-42 presented in Table 5.

The impact of all three previously identified factors that affect order quantities respectively maximum profit could be confirmed: The impact of the first factor, i.e. suppliers' sustainability levels that determine the manufacturer's end product price, can be observed in Examples 37-39: The total capacity of the suppliers in pool 3 is consumed. However, the benefit of increasing sales capacity by switching to another pool does not outweigh the reduction of the end product price that comes along with the procurement from a less sustainable pool of suppliers.

The impact of the second factor identified, i.e. fixed cost that influence order quantities and thus maximum profit, can be noticed in Examples 31-33: Although there is an increase in demand variability, the benefit of raising sales capacity by supplementary procuring from supplier 3 of the same pool does not compensate the fixed cost that would then be charged additionally.

The impact of the third factor, the coefficient of variation of demand, can be noted in Examples 33, 36, 39 and 42: Here, the coefficient of variation is greater than one and the average demand is greater than 20,000, and thus it is unprofitable to solely procure from supplier 1 due to the explained reasons.

Nevertheless, the reduced salvage value has a remarkable influence that affect different results for the Examples 22-42 compared to the results for the Examples 1-21. Therefore, consider Examples 31-33 first. The supplier considered by the model but not added to the mix is supplier 1 of S as already exposed. Furthermore, it can be seen for the examples of Table 5 that there is a general aversion to use supplier 1. While in Examples 1-21, supplier 1 is part of the solution for sixteen times (in Examples 1-9, 13-18 and 21), now in Examples 22-42, supplier 1 is part of the solution only for four times (in Examples 34 and 37-39) (see Figure 3). Clearly the reduction of supplier 1's salvage value in Examples 22-42 has made the use of supplier 1 unattractive in most situations although the supplier still has the highest salvage value among all suppliers in addition to the highest sustainability ranking, which leads to the best end product pricing. Although the reduction in supplier 1's salvage value is higher than that of supplier 2 in absolute terms (supplier 1: reduction of \$4.86; supplier 2: reduction of \$1.63), the reduction in percentage terms is the same in both cases (reduction of 65 percent each). As such, one might expect supplier 2 to be similarly avoided, however this is not the case. Supplier 2 is part of a solution only three times less in Examples 22-42 than in Examples 1-21. This would suggest that intuition may be of limited value in complex sustainable sourcing problems, underscoring the need for our mathematical modeling approach.

Table 5. Summary of results for $V_1 = \$2.625$ and $V_2 = \$0.875$.

Ex.	μ	σ	Pool	Units Procured	Sum of Units Procured	Profit
22	10,000	7,500	3	$y_{31} = 12{,}018$	12,018	$259,430
23	10,000	10,000	3	$y_{31} = 12{,}691$	12,691	$180,073
24	10,000	12,500	3	$y_{31} = 13{,}363$	13,363	$100,717
25	15,000	11,250	3	$y_{31} = 15{,}000, y_{32} = 2{,}327$	17,327	$380,919
26	15,000	15,000	3	$y_{31} = 15{,}000, y_{32} = 3{,}102$	18,102	$260,392
27	15,000	18,750	3	$y_{31} = 15{,}000, y_{32} = 3{,}878$	18,878	$139,865
28	20,000	15,000	3	$y_{31} = 15{,}000, y_{32} = 8{,}102$	23,102	$501,882
29	20,000	20,000	3	$y_{31} = 15{,}000, y_{32} = 9{,}137$	24,137	$341,564
30	20,000	25,000	3	$y_{31} = 15{,}000, y_{32} = 10{,}171$	25,171	$180,861
31	25,000	18,750	3	$y_{31} = 15{,}000, y_{32} = 12{,}500$	27,500	$618,231
32	25,000	25,000	3	$y_{31} = 15{,}000, y_{32} = 12{,}500$	27,500	$416,060
33	25,000	31,250	3	$y_{31} = 15{,}000, y_{32} = 12{,}500$	27,500	$212,250
34	30,000	22,500	3	$y_{31} = 15{,}000, y_{32} = 12{,}500, y_{33} = 6{,}090$	33,590	$723,256
35	30,000	30,000	4	$y_{41} = 20{,}000, y_{42} = 15{,}000$	35,000	$488,271
36	30,000	37,500	4	$y_{41} = 20{,}000, y_{42} = 15{,}000$	35,000	$238,585
37	40,000	30,000	3	$y_{31} = 15{,}000, y_{32} = 12{,}500, y_{33} = 10{,}000$	37,500	$919,816

38	40,000	40,000	3	$y_{31} = 15{,}000, y_{32} = 12{,}500, y_{33} = 10{,}000$	37,500	\$591,545
39	40,000	50,000	3	$y_{31} = 15{,}000, y_{32} = 12{,}500, y_{33} = 10{,}000$	37,500	\$262,931
40	50,000	37,500	5	$y_{51} = 20{,}000, y_{52} = 20{,}000, y_{53} = 15{,}000$	55,000	\$1,175,619
41	50,000	50,000	5	$y_{51} = 20{,}000, y_{52} = 20{,}000, y_{53} = 15{,}000$	55,000	\$729,791
42	50,000	62,500	5	$y_{51} = 20{,}000, y_{52} = 20{,}000, y_{53} = 15{,}000$	55,000	\$282,773

5. Conclusions and implications

The historical agreement on climate change in Paris in 2015 has recalled global attention for the relevant field of sustainability. Both academic and managerial research papers have considered the object of sustainability, e.g. in the context of sourcing. However, so far their main focus has been on conceptual models lacking quantitative sourcing models that incorporate environmental and social concerns. Therefore, we have developed a mathematical sourcing model that takes into account – for the first time to our knowledge – suppliers' sustainability levels as determining factor for the end product price and end product demand. As further new component, we have integrated supplier capacity constraints as well as the construct of a pool in our newsvendor model formulation.

5.1. Academic contributions

We have developed a quantitative sustainable sourcing model for supplier selection and order allocation decisions. In detail, we have extended the classical newsvendor problem, i.e. a single supplier problem without any capacity constraints or fixed charges, and investigated a multiple supplier problem with capacity constraints, fixed charges and a sustainability component. Moreover, we have integrated the issue of sustainability holistically in a mathematical sourcing model. Thereby, we have introduced the demand for the end product as determined by different suppliers' sustainability levels in our quantitative sustainable sourcing model. Furthermore, we have treated the price the manufacturer obtains for its end product as a function of the sustainability of the suppliers the manufacturer uses to provide the main component. In doing so, we fill the lacuna in research on SSCM and in particular on sustainable sourcing as presented in previous sections.

For the purpose of robustness and testing our model, we have run 33 sensitivity analyses with variations of the component price, salvage value and suppliers' capacity first. As expected, the salvage value has a positive impact on the profit, while the component price has a negative impact. Interestingly, the profit is indifferent to the suppliers' capacity explored in the context of a pool in our sensitivity analysis scenarios.

Hence, we have subsequently calculated the outcomes for 42 representative examples with our model to investigate more comprehensively the selection of a pool and certain suppliers. Thereby, we have identified three impact factors on order quantities and finally on profits that in parts counterbalance the impact of variation of demand described in the classical newsvendor model. The first impact factor is the suppliers' respectively pool's sustainability level that determines the end product price and thus profits. In contrast to the classical newsvendor model that says it would be optimal to have higher stocks with rising levels of uncertainty, our model has determined that the benefit of higher stocks does not always compensate the reduction of the end product price when switching to another, less sustainable pool. The second impact factor on the profits are fixed charges. Again contrariwise to the expectations of the classical newsvendor model, our model has found that the increase in stocks does not consistently offset the additional fixed charges that would incur if supplementary other suppliers in the same pool were procured from. The third impact factor is the coefficient of variation of demand ($\frac{\sigma}{\mu}$). Our model determined that if the coefficient of variation is greater than one and the average demand is greater than 20,000, it will be unprofitable to solely procure from supplier 1 as then the expected profits would be negative and the manufacturer would experience losses.

Eventually, the reduction of the salvage value to around one third of the original value in the second set of the examples has emphasized the need for our quantitative sustainable sourcing model: Although all suppliers with positive salvage values had to deal with the same relative reductions of their salvage values, they have not been avoided to the same extent.

5.2. Managerial implications

Besides the presented academic contributions, the model developed in this paper has also some managerial implications as shown by the representative examples.

First of all, our model can be used by a production manager of the described problem setting to select a mix of suppliers and determine order quantities to maximize the manufacturer's expected profit in the context of sustainability.

Furthermore, our model is not dependent on a specific definition of sustainability, which increases its applicability since sustainability seems to mean different things to different people as diverse surveys reveal, such as the study conducted by the MIT Sloan Management Review (Kiron et al., 2013). In order to use our model a manager simply needs to be able to rank suppliers from highest to lowest in terms of his own definition of sustainability.

Hence, our model can be used universally and contribute to achieve the ambitious targets of the climate change agreement of Paris in 2015.

5.3. Future research

Our single period model can be extended to a multi-period model to account for more realistic effects since vendor planning usually considers a higher granularity. Moreover, the robustness of the model should be enhanced: Further research is needed to explore more deeply the impact of various parameter changes on the optimal sourcing pattern and the manufacturer's expected profitability under the constraints of suppliers' sustainability levels. Finally, longer term research might study the setting of a long life cycle end product instead of our considered short life cycle product using our developed sustainable sourcing model formulation.

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Appendix

Appendix-Chapter IV 1: Data for Example 5.

Data for Example 5*

- $\mu = \{15000,15000,15000,15000,15000\}$
- $\sigma = \{15000,15000,15000,15000,15000\}$
- $P = \{\$110, \$105, \$102.50, \$100, \$100\}$
- $D = \{\$20\}$
- $R = \{\$90, \$85, \$82.50, \$80, \$80\}$
- $C = \{\$37.50, \$35, \$32.50, \$32.50, \$32.50\}$
- $V = \{\$7.50, \$2.50, \$0, -\$5, -\$10\}$
- $F = \{\$5000, \$5000, \$2500, \$1000, \$0\}$
- $L = \{10000,12500,15000,20000,20000\}$
- $S_1 = \{1\}$
- $S_2 = \{2,1\}$
- $S_3 = \{3,2,1\}$
- $S_4 = \{4,3,2,1\}$
- $S_5 = \{5,4,3,2,1\}$
- $Q_{11} = 20231.3$

  $Q_{21} = 19036.0, Q_{22} = 19303.4$

$Q_{31} = 19036.0, Q_{32} = 18558.0, Q_{33} = 18800.2$

$Q_{41} = 17219.8, Q_{42} = 18558.0, Q_{43} = 18053.2, Q_{44} = 18267.0$

$Q_{51} = 16045.3, Q_{52} = 17219.8, Q_{53} = 18558.0, Q_{54} = 18053.2, Q_{55} = 18267.0$

- $I_{11} = 3814$

  $I_{21} = 4817, I_{22} = 8380$

  $I_{31} = 5984, I_{32} = 7931, I_{33} = 8075$

  $I_{41} = 7159, I_{42} = 7931, I_{43} = 7634, I_{44} = 7759$

  $I_{51} = 6521, I_{52} = 7159, I_{53} = 7931, I_{54} = 7634, I_{55} = 7759$

- $E_{11} = \$314{,}617$

  $E_{21} = \$397{,}407, E_{22} = \$657{,}369$

  $E_{31} = \$493{,}691, E_{32} = \$645{,}389, E_{33} = \$666{,}209$

  $E_{41} = \$608{,}533, E_{42} = \$674{,}111, E_{43} = \$648{,}911, E_{44} = \$659{,}515$

  $E_{51} = \$586{,}917, E_{52} = \$644{,}350, E_{53} = \$713{,}764, E_{54} = \$687{,}083,$

  $E_{55} = \$698{,}310$

* For the parameters the subscripts are partly omitted and instead used to denote the entire vector.