

## Sustainable sourcing including capacity reservation for recycled materials: A newsvendor framework with price and demand correlations



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### ABSTRACT

Critical raw materials like rare-earth elements are essential inputs for the production process of many electronic products, but also for environmentally-friendly green-energy technology products. The market for these materials faces high uncertainty associated with their supply. The use of recovered raw materials can help to mitigate the risk and simultaneously pave the way towards a circular economy. We investigate a sourcing strategy faced by a manufacturer considering the possibility to source critical raw materials from a supplier offering recycled material. As the recycling efficiency of these materials is still an ongoing research, and return flows from end-of-life products are highly volatile, we also rely on virgin material. We develop a single-period inventory model with procurement from a supplier offering recycled material according to a capacity reservation contract and a reactive supplier (spot market) offering virgin material. We consider uncertainties of demand, prices and recycling quantities as well as potential dependencies, in particular dependencies between prices for virgin and recycled materials and prices and demand. We provide results on the optimal policy structure and obtain a closed-form solution as a bound of the optimal procurement quantity. Our analysis gives us first insights on the effect of different economic parameters on the ordering decision. In an extensive numerical analysis we then study the impact of correlation on our results in order to derive managerial implications. We show that considering correlation when using such a sourcing strategy is especially important in environments with high demand uncertainty, high virgin material prices and yield uncertainty.

### 1. Introduction

Electric-vehicle production heavily depends on the supply of critical materials, for instance cobalt, as essential material for high-end rechargeable batteries. Mining of these materials is often concentrated to one region, e.g. cobalt or so called conflict materials such as tantalum, tin or tungsten stem mainly from the Democratic Republic of Congo, which makes especially European producers dependent on raw materials from that regions (Sydney Morning Herald, 2017). The European Raw Material Initiative (European Commission, 2014) focuses on such critical materials that are characterized by high economic importance on one side and high supply risk on the other side. Relevant industrial sectors that have demand for critical materials are for instance electrical and electronic equipment. Securing the supply for such materials is therefore essential to enable technological progress. Supply shortages

due to export restrictions, limited accessibility and availability as well as import dependency have the potential to create price volatility for these strategically important raw materials. Supply shortages are reflected in volatile virgin material prices (see e.g. the empirical Neodymium price development as depicted in Keilhacker and Minner, 2017).

The integration of return flows from end-of-life or end-of-use products back into the existing production network instead of or additionally to using material from the mine is one way how to increase the security of supply for these materials. According to Weetman (2017) there is a lot of potential for managing waste material streams, especially with regards to electrical and electronic equipment as there is high potential to contribute to the concept of a circular economy by means of recycling. In a circular economy, raw materials that can be recycled from waste streams are inserted back into the economy as new raw material inputs for production companies and can therefore close

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the material flow and prolong the useful life of a material. Value of materials are kept in the supply chain as long as possible and extend the classical make-use-dispose way of a linear economy in order to minimize waste (Ellen MacArthur Foundation, 2015). The EU Action Plan (European Commission, 2015) wants to raise awareness for the transition from waste to resources by boosting the market for secondary (recycled) raw materials. The circular economy concept in that context aims at reducing the consumption of raw materials (and energy) and tries to ensure more sustainable production and consumption through the circular flow of goods (see e.g. Ghisellini et al., 2016).

Reverse logistics cause additional complexities in inventory management approaches as the level of uncertainty is high due to uncertain product returns. A high degree of uncertainty in supply in terms of, amongst others, quantity of used products is involved in the returns by the consumers (e.g. Igin and Gupta, 2013). Due to the rapid development in technology, customers' desires for new product models is increasing and product life cycles are shrinking. Customers' willingness to return end-of-life products is, however, difficult to predict as customers have only limited incentives. Recyclers and subsequently manufacturers have to cope with stochastic return flows. Furthermore, for certain materials the quality of the recycling output is not known in advance of the recycling process, influencing the quantitative output for sale. The recycler, therefore, may not know in advance how much recycled quantity will be available to sell to the manufacturers. Consequently, it may be the case that not all orders can be fulfilled in full. In this paper, we will investigate such a situation from a manufacturer's perspective. The recycling quantity offered by the general recycler may be restricted and the company may not be able to fulfill all orders of the manufacturers completely. The presented situation is similar to a shortage gaming situation (see e.g. Cachon and Terwiesch, 2013).

For some raw materials like e.g. aluminum the recycling processes can be regarded as already quite mature and using recycled materials from waste streams is already established (Beall, 2015). For most of the critical materials, however, recycling processes are not that mature. Sorting and identification of end-of-life products with unknown quality and composition can be difficult, because different parts are mixed together in waste treatment plants which makes the sorting process there a lot more complicated and the resulting output quantity can vary. Quantity is therefore not always sufficient to replace primary material in large quantities (Beall, 2015). Rogetzer et al. (2018) show exemplarily by means of critical and conflict materials how a manufacturer can adapt its sourcing strategy by including some recycled material in its production process to contribute to the transition towards circular economy. The authors emphasize that for many critical materials recovery processes are still in development and material coming from the recycler may not be enough to fulfill the entire demand (Beall, 2015). An increase in recycling targets can be achieved by the introduction of new sorting technologies that enhance the output quality (Liu and Müller, 2012). Recycling rates for critical materials are still not enough to meet an economy's total demand (e.g. near-zero recycling rates for rare earth elements as shown in Gaustad et al., 2018) as, at the same time, also end-customer demand for high-tech products is continuously increasing. The demand for critical materials therefore cannot fully be met by recycling material alone; virgin material still plays a role.

For this paper, we use a scenario setting where recycling processes for critical materials are assumed to be already quite mature (similar to other materials like, for instance, aluminum) and demonstrate the impact of recycling on economy and environment. In a mature recycling process as it is the case for aluminum (Ferretti et al., 2007), for instance, material properties do not deteriorate during the process and the melting process produces secondary material of basically the same quality, it can therefore be assumed that secondary material can be used like primary material. Recycling of critical metals with very low material contents in returned or obsolete products and complex material compounds is, at the moment, not always favorable from an

environmental point of view. Usually, there are high amounts of energy required to produce primary material from the mine, whereas melting down waste, i.e. raw material contents in end-of-life products, needs only a fraction of the energy compared to the energy amount needed for mining primary material. Recycling used aluminum cans for beverages, for instance, saves 95% of the energy to produce an equal quantity of aluminum from bauxite (Rowe et al., 2017), reducing the ecological impact and improving resource efficiency throughout the life cycle of the product. Until recycling processes for critical materials develop and also become economically and environmentally feasible, it remains a potential future scenario. But, a manufacturer taking into account secondary material from a recycler as input source therefore contributes to environmental sustainability and the objectives of the circular economy, which are, according to the EU action plan (European Commission, 2015), (i) to optimize the use of virgin resources, (ii) to reduce pollution by increased recycling activities and (iii) to manage waste accordingly. The concept's idea is to produce more goods with less energy and fewer natural resources, less waste and pollution (Wong, 2017).

In this work we discuss how the integration of recycling material into the sourcing strategy, taking several uncertainties in this context into account, impacts a manufacturer's economic and environmental performance. We model a manufacturer's sustainable sourcing strategy operating in a single-period dual sourcing environment with one proactive supplier (a contract supplier) delivering recycled material with uncertain yield (due to issues in the recycling process the delivered quantity of the recycler to the manufacturer does not necessarily equal the reservation quantity) and a second reactive supplier delivering virgin material at an uncertain price reflecting the price volatility at the spot market. We assume a quantity reservation contract with uncertain exercise price reflecting recycling price volatility. The manufacturer's decision on capacity reservation has to consider the uncertainties as well as potential dependencies between them. Rising demand usually brings about high spot prices, we therefore assume demand and spot prices to be positively correlated. The same holds true for recycling prices and demand, where we also assume a positive correlation. Prices for these raw materials, i.e. recycling and virgin material prices, appear also to be correlated in a certain way, we therefore assume a positive correlation between the two prices. The goal is to get insights on such a sourcing strategy.

In particular, we address the following research questions:

- What is the impact of uncertainties with respect to demand, prices and yield of the recycler on the reservation quantities and costs of the manufacturer?
- What is the effect on the results when taking correlations between prices and between price and demand into account?

The remainder of this paper is organized as follows: In Section 2 we briefly review relevant literature. Section 3 describes the problem setting, the modeling framework and the mathematical problem and provides some analytical results. In Section 4 a detailed numerical analysis is carried out for an uncorrelated case and correlated settings. Finally, in Section 5, we provide managerial insights and recommendations. Section 6 provides a discussion of the results. Section 7 concludes the paper by summarizing the main findings and suggesting further research opportunities.

## 2. Related literature streams

The first strand of literature relevant to this paper is multiple sourcing inventory models. As this is a comprehensive stream, we refer to literature overviews presented, for instance, by Minner (2003) for more details. By means of dual or multiple sourcing options the dependency on a single supplier can be relaxed. Instead of using just one single supply source, companies can benefit from reduced supply

uncertainty if they have several supply sources in mind. Considering multiple supply sources in inventory models can reduce or even fully avoid the effects of shortage situations. For a current literature overview we refer to Yao and Minner (2017). A special case of multiple sourcing inventory models are dual sourcing models. They usually consider two supply sources, where one supplier is a cost-efficient but inflexible source usually located at a remote area, therefore having a long lead time. The second supplier is often rather flexible and able to deliver on quick response, either because of its proximity to the manufacturing company or the ability to make an emergency shipment. For this flexibility, the supplier usually charges a premium which is represented by a mark-up on top of the purchasing price (see Warburton and Stratton, 2005; Cachon and Terwiesch, 2013).

A second stream of literature relevant for this paper is inventory models that include multiple uncertainties and potential dependencies. Hong et al. (2014) consider two supply sources, where the first supply source is represented by a contract supplier with random yield. For the second supply source they assume a spot market with stochastic spot prices. They assume that demand, price and yield are normally distributed and furthermore consider correlations between them in a single-period procurement model using combined sourcing. They take the paper by Seifert et al. (2004), who also analyze a similar single-period problem and show benefits of using spot markets, as a comparison to their model. Merzifonluoğlu (2015) considers random customer demand, random spot prices and yield uncertainties in the context of a single-period newsvendor setting. The author also takes into account possible correlations between demand and spot prices and assumes all random variables to be normally distributed. In contrast to these papers we, however, do not restrict our analysis to the assumption of a multivariate normal distribution. For an overview about yield uncertainty, we refer to e.g. Yano and Lee (1995).

The application of real option arrangements such as spot markets, long-term procurement contracts (forward contracts) and options can be seen as risk management approaches for sourcing policies. However, to the best of our knowledge, there has been only limited applications of option concepts in inventory management. Burnetas and Ritchken (2005), as one exception, investigate the design of option contracts in supply chains that provide retailers with the flexibility in responding to unanticipated demand and prices and contribute to coordinating the supply chain. Martínez-de Albéniz and Simchi-Levi (2006), as another example, consider the impact of a supply option contract on the newsvendor where the newsvendor can buy options from multiple suppliers and has to pay a reservation price and an execution price for that. According to Chen and Parlar (2007) the literature on supply chain coordination by means of flexible supply arrangements for capacity reservation, especially in the manufacturing environment, is rapidly growing, which supports our problem setting. They introduce an extension of a single-period inventory model with stochastic demand where the newsvendor can buy options and determine the exercise price and quantity. Barnes-Schuster et al. (2002), for instance, discuss the role of options in a two-period model and consider demands to be correlated. Capacity reservation from the perspective of supply chain coordination is also topic in, for instance, Jin and Wu (2001). They analyzed capacity reservation contracts between a single supplier and multiple buyers with reservation fees deductible from the purchase price paid at delivery. Serel et al. (2001) examine the problem of combined purchase from spot market and capacity reservation. They considered a simple capacity reservation order up policy but they ignore spot market price uncertainty. Inderfurth and Kelle (2011) consider a combination of two alternative purchasing alternatives, one represented by a capacity reservation contract, the other by a spot market. They take into account uncertainty with regards to spot market prices and demand and their joint correlation effect. Luo and Chen (2017) investigate a two-stage supply chain with a capacity reservation contract facing deterministic market demand and random yield and the

presence of a spot market. They do not consider any correlations. The authors furthermore compare situations with and without implementing an option contract. Serel (2007) study a multi-period capacity reservation contract with a long-term supplier and consider uncertainty about the input quantity from the spot market. Kleindorfer and Wu (2003) point out that capacity reservation contracts are extensively used for purchasing commodity metals, which again fits to our problem setting. The pricing of option contracts has been investigated by Ritchken and Tapiero (1986) first and has been extended in several papers.

Rowe et al. (2017) discuss a sourcing strategy including recycled material. They consider one virgin material supplier and one offering recycled material, i.e. a dual sourcing situation, in a single-period scenario. They assume that each supplier sells products with an uncertain yield. The manufacturer in their setting must choose whether to source from a single supplier or from both suppliers. They show for a certain range of prices that the dual sourcing strategy increases the expected profit of the manufacturer compared to single sourcing. In contrast to Rowe et al. (2017) we, however, assume an environment with uncertain demand and uncertain prices for raw materials. Rogetzer et al. (2018) develop a single-period sustainable sourcing inventory model to derive order quantities for virgin and recycled raw materials and compare it to standard sourcing without recycling. The model includes uncertain demand, recycling prices and quantities from the recycler and related correlations and dependencies. In contrast to our approach, in which the recycler is the primary source, they assume recycling material to be the second supply source. These papers can be seen as a starting point for this paper.

A sustainable sourcing strategy in this research is expressed as the use of recycling material instead of or in addition to virgin material in order to contribute to more sustainability in supply chains for critical (and conflict) raw materials. Sustainability in this respect is usually characterized by three dimensions, the so-called triple bottom line approach (Elkington, 1998) including environmental, economic and social aspects. This paper is dealing with critical materials such as rare earth elements, which are materials that combine, according to the Raw Material Criticality Framework, the characteristics of, on the one hand, being highly important to the European economy and, on the other side, have a high risk associated to their supply (European Commission, 2010). The critical materials manufacturer, i.e. a general recycler, disassembles end-of-life/use-products to material level and pre-processes these materials from used products and components (Thierry et al., 1995) for further use. In such an open-loop supply chain, where material is involved that is recovered by parties other than the original producers (which would be a closed-loop then), secondary raw materials is provided which is ready for be used in any other product (Genovese et al., 2017). An overview about the current state of research in the area of closed-loop supply chains can be found in Guide Jr and Van Wassenhove (2009).

In conclusion, existing literature so far investigates occurring uncertainties only to limited extent (only price uncertainty, only demand uncertainty etc.) and often neglect dependencies between these uncertainties. Moreover, inventory models in that context are often expanded by an environmental component (see e.g. Rosič and Jammerneegg, 2013 or Arikan and Jammerneegg, 2014), but limited focus is put on the recycling aspect. Based on the gaps of the two strands of literature, this paper combines multiple sourcing strategies with uncertainties, correlations and sustainability issues and investigates a sourcing decision of a manufacturer that has to make a decision about how much capacity to reserve from a recycling company considering demand, recycling quantity and price uncertainties in the presence of a spot market. It contributes to the research streams on sustainable operations (see e.g. Jaehn, 2016), newsvendor models with yield and price uncertainties and circular economy. Table 1 summarizes the related literature and shows the research gap.

**Table 1**  
Summary of selected related literature.

	stochastic supply (S)	stochastic demand (D)	stochastic price of first supplier (P1)	stochastic price of second supplier (P2)	correlations	recycling	capacity reservation contract
Hong et al. (2014)	✓	✓		✓	✓(S, D, P2)		
Inderfurth and Kelle (2011)		✓		✓	✓(D, P2)		✓
Merzifonluoğlu (2015)	✓	✓		✓	✓(D, P2)		
Luo and Chen (2017)	✓			✓			✓
Rowe et al. (2017)	✓					✓	
Rogetzer et al. (2018)	✓	✓		✓	✓(S, D, P2)	✓	
Seifert et al. (2004)	✓	✓		✓	✓(D, P2)		
This paper	✓	✓	✓	✓	✓(D, P1, P2)	✓	✓

### 3. Problem setting and model

In this section we first describe the general problem setting that is going to be analyzed throughout the remainder of this paper. Then we discuss the model formulation and structural properties. Finally, we derive bounds on the optimal policy and present some comparative static results of the input parameters.

#### 3.1. Problem setting

Consider a European manufacturer of short life-cycle electronic components. For that we consider a single-period newsvendor inventory model with two supply sources. The manufacturer can source the raw material from a general recycler and from a virgin material supplier. As electronic waste is a rapidly growing issue and the manufacturer wants to keep pace with the time and is willing to be more sustainable, sourcing is primarily done from the recycling company. Based on the bill of materials we assume that one unit of the considered raw material, e.g. a critical material is needed for one unit of the final product. The steadily increasing demand for certain raw materials together with low overall collection rates may lead to situations where the recycler cannot provide sufficient quantity of recycled material. As we assume possible supply limitations at the recycler, we implement an uncertain yield recycling rate. If for quality reasons of the recycled material the necessary minimum amount of virgin material can be procured from the spot market as soon as demand of the final product is known. To emphasize the strategic importance of procuring recycled materials the manufacturer reserves capacity at the recycler. In such a real option contract this is done by paying upfront a unit reservation price that allows the manufacturer to buy at most the number of reserved units of the raw material at the so-called unit exercise price. The missing units of the material are then procured from the virgin material supplier at the spot market. The average price in a spot market is, however, higher than the average exercise price.

#### 3.2. Model formulation of sustainable sourcing strategy

The manufacturer in our case has to find the optimal reservation quantity at the recycler with uncertain yield, prices and demand that minimizes the overall expected cost. In Fig. 1 the sequence of events is shown. The manufacturing company decides on the reservation quantity  $q^r$  at the recycler before random demand  $D$  with distribution  $F_D$  and expectation  $\mu_D$  for a newsvendor product realizes. The manufacturer and the recycler agree on a fixed per unit reservation price for recycling material  $o$  and a random per unit exercise price  $X$  with expectation  $\mu_X$  in an options contract. The option or reservation price  $o$  has to be paid already when reserving capacity. It allows the recycler to start the recycling process by buying the necessary material. At this point in time the random yield rate  $Z$  with expectation  $\mu_Z$  and support  $[0,1]$  from the recycler and the random per unit virgin material price  $C_v$  with expectation  $\mu_{C_v}$ , where  $\mu_{C_v} > \mu_X$  and the random exercise price  $X$  are still

unknown. The quantity bought from the recycler is dependent on the realized yield rate  $z$ , the realized prices  $x, c_v$ , and the realized demand  $d$ . The realized exercise price  $x$  has to be paid when quantity is actually received from the recycler. According to the options contract, the manufacturer only has to pay the exercise price  $x$  for the part of  $q^r$  that is taken by the manufacturer, i.e.  $q^r z$ , and not for the entire amount reserved ( $q^r$ ). In case demand turns out to be small than  $q^r z$ , only  $xd$  is paid by the manufacturer. In case the realized virgin material price turns out to be smaller than the exercise price for recycled materials, the manufacturer does not exercise the options at the recycler, but buys the entire demand at the virgin material supplier at the (lower) price  $c_v$ . The manufacturer has to satisfy any demand that is not satisfied by the recycler from a virgin material supplier at price  $c_v$ . The notation used in this work is summarized in Table 2.

The manufacturer's cost ordering  $q^r$  units from the recycler are therefore given by

$$C(q^r) = q^r o + \begin{cases} dc_v, & c_v < x, \\ \min(d, q^r z)x + (d - q^r z)^+ c_v, & c_v \geq x, \end{cases} \quad (1)$$

where  $(y)^+ = \max(y, 0)$ . For varying virgin material price  $C_v$ , equation (1) is composed of two linear functions and therefore the expected cost from reserving  $q^r$  units at the recycler can be written as follows:

$$E(C(q^r)) = q^r o + E(\min(DX + (D - q^r Z)^+(C_v - X), DC_v)). \quad (2)$$

From equation (2) we can conclude that in an uncorrelated environment the optimal reservation quantity  $q^{r*}$  and  $E(C(q^{r*}))$  will only be dependent on the expected prices of the virgin material  $\mu_{C_v}$  and exercised recycled material  $\mu_X$  but not on the distribution of  $C_v$  and  $X$ .

The assumption of correlation between demand, price and yield uncertainty as well as the decisions whether to purchase from the recycler at all after realization of the uncertainties complicates the finding of the optimal decision. However, a numerical study enables us to discuss the optimal policy of such a newsvendor model and analyze the interaction of correlation in detail (see Section 4).

If we simplify some of our assumptions – such as correlation among the (some) uncertain variables, or the flexibility of using the spot market exclusively which is plausible since it will be unlikely that realized virgin material price  $c_v$  turns out to be lower than  $x$  – we are able to derive some analytical results and obtain a closed form solution. This will serve as a bound for the optimal policy that minimizes expected cost given in equation (2) and will give us first insights on the interaction of the different economic parameters in our model.

Let us first simplify our model and assume that sourcing from the recycler is always preferred over sourcing from the virgin material supplier, i.e. the buyer always purchases  $\min(d, q^r z)$  of the options and only relies on the spot market when  $d > q^r z$ . Then the expected cost in the simplified case are

$$\overline{E(C(q^r))} = q^r o + E(DX + (D - q^r Z)^+(C_v - X)). \quad (3)$$

Note that equation (3) is an upper bound of equation (2) where the difference between equation (3) and equation (2) is just

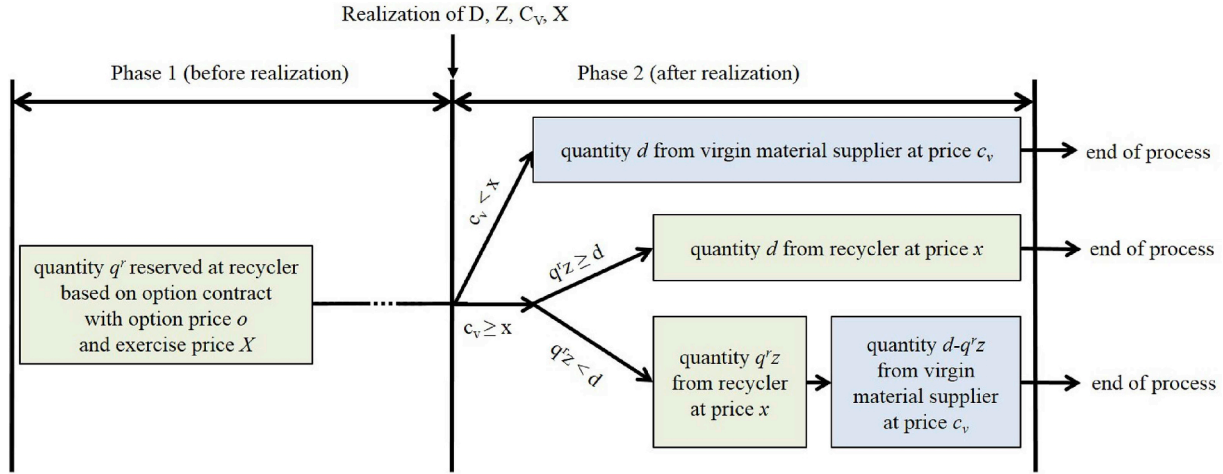


Fig. 1. Sequence of events.

Table 2

Notation.

Abbreviation	Description
Stochastic and deterministic parameters	
$D, d$	stochastic and realized demand
$F_D$	cumulative distribution function of $D$ with mean $\mu_D$
$Z, z$	stochastic and realized yield rate of recycler
$F_Z$	cumulative distribution function of $Z$ with mean $\mu_Z$
$C_v, c_v$	stochastic and realized price per unit of virgin material
$F_{C_v}$	cumulative distribution function of $C_v$ with mean $\mu_{C_v}$
$X, x$	stochastic and realized unit exercise price for recycling material
$F_X$	cumulative distribution function of $X$ with mean $\mu_X$
$f$	joint density function of $D, Z, C_v$ and $X$
$o$	unit option/reservation price for recycling material
Correlation coefficients	
$\rho_{C_v, D}$	correlation between $C_v$ and $D$
$\rho_{C_v, X}$	correlation between $C_v$ and $X$
$\rho_{X, D}$	correlation between $X$ and $D$
Decision variable	
$q^r$	reservation quantity at recycler
$\bar{q}^r$	reservation quantity at recycler (simplified case)
Cost	
$E(C(q^r))$	buyer's expected cost for reservation quantity $q^r$
$E(C(\bar{q}^r))$	buyer's expected cost for reservation quantity $\bar{q}^r$ (simplified case)

$$E(DX + (D - q^r Z)^+(C_v - X) - DC_v)^+.$$

The optimal reservation quantity  $\bar{q}^{r*}$  that maximizes equation (3) can be found by solving the following first order condition:

$$\frac{dE(C(\bar{q}^r))}{d\bar{q}^r} = o - \int_0^\infty \int_0^\infty \int_0^1 \int_{\bar{q}^r z}^\infty (c_v - x) z f(x, c_v, z, d) dd dz dc_v dx = 0. \tag{4}$$

Hence,  $\bar{q}^{r*}$  depends on the joint distribution  $f$  of the uncertain variables.

In an independent environment with a deterministic yield rate  $z$  the first order condition reduces to:

$$o - (1 - F_D(\bar{q}^r z))(\mu_{C_v} - \mu_X)z = 0 \tag{5}$$

From equation (5) the optimal reservation quantity  $\bar{q}^{r*}$  is given by:

$$\bar{q}^{r*} = F_D^{-1}\left(\frac{\mu_{C_v} - \mu_X - \frac{o}{z}}{\mu_{C_v} - \mu_X}\right) / z \tag{6}$$

From equation (6) we see that  $z \geq \frac{o}{\mu_{C_v} - \mu_X}$  has to hold since otherwise the ratio in equation (6) would be negative. Note that in the objective function the recycler specifies the unit option price  $o$  by

assuming perfect reliability, i.e.  $P(Z = 1) = 1$ . Thus, for the number of units  $q^r z$  that the recycler then actually delivers to the manufacturer, the effective unit option price is  $\frac{o}{z}$  depending on the yield rate  $z$ . As a consequence, in the numerator of the simplified case without correlation in equation (6) the price difference between virgin material and recycled material also includes this effective option price:  $\mu_{C_v} - \left(\frac{o}{z} + \mu_X\right)$ .

Conducting a comparative-static analysis with respect to the optimal reservation quantity  $\bar{q}^{r*}$  in equation (6) gives us first insights into the model. That is, the bound on the optimal procurement quantity  $\bar{q}^{r*}$  given in equation (6) is increasing in the expected price of the virgin material supplier  $\mu_{C_v}$ , decreasing in the expected recycling exercise price  $\mu_X$ , decreasing in the unit option/reservation price  $o$  of the recycler and is decreasing (increasing) in  $z$  if  $o < (>) z^2 f_D(\bar{q}^r z) \bar{q}^r (\mu_{C_v} - \mu_X)$ .

If the recycler is completely reliable (i.e.  $P(Z = 1) = 1$ ), it follows that

$$\bar{q}^{r*} = F_D^{-1}\left(\frac{\mu_{C_v} - \mu_X - o}{\mu_{C_v} - \mu_X}\right). \tag{7}$$

In this case, we need  $o + \mu_X \leq \mu_{C_v}$ . The unit opportunity cost of reserving too much capacity at the recycler are  $o$  as in a standard option contract (see for example Barnes-Schuster et al., 2002 or Burnetas and Ritchken, 2005). However, the unit opportunity cost of reserving too little quantity is equal to the (expected) price differential between the recycler and the spot market  $\mu_{C_v} - o - \mu_X$  as in a standard dual sourcing model (e.g. Warburton and Stratton, 2005; Cachon and Terwiesch, 2013).

#### 4. Numerical analysis

A numerical analysis is conducted in MATLAB to gain insights into the sustainable sourcing strategy that minimizes expected cost given in equation (2). In particular, it will be analyzed how demand, prices and quantity uncertainty at the recycler impact reservation quantities at the recycler and expected costs. First, the analysis is done for the uncorrelated case (Section 4.1) and afterwards we have a look at the influence of correlations on the results (Section 4.2).

The parameters used for this analysis are summarized in Table 3. The numerical setting for the base case is based on Rogetzer et al. (2018) and the numerical analyses in Rowe et al. (2017), Hong et al. (2014) and Luo and Chen (2017). Data for the numerical analysis was therefore mainly taken, wherever possible, from existing literature. For the following sensitivity analyses we use the base values as stated in column “base case” and vary them according to the parameter values

**Table 3**  
Summary of base parameter values.

Parameters	Base Case	Variations
option/reservation price per unit for recycling material $o$	2	
<b>Stochastic demand <math>D</math></b>		
Normal distribution $\mathcal{N}(\mu_D, \sigma_D)$	$\mathcal{N}(100,25)$	
Mean $\mu_D$	100	{5,...,40}
Standard deviation $\sigma_D$	25	{3,...,15}
Coefficient of variation $CV_D$	0.25	{0.05,...,0.40}
<b>Stochastic yield rate of recycler <math>Z</math></b>		
Standard beta distribution $\beta(\alpha, \beta)$	$\beta(18,2)$	
Shape parameter $\alpha$	18	{6,...,18}
Shape parameter $\beta$	2	{2,...,5}
<b>Stochastic price per unit of virgin material <math>C_v</math></b>		
Log-normal distribution $\mathcal{LN}(\mu_{C_v}, \sigma_{C_v})$	$\mathcal{LN}(15,3)$	
Expected recycling price $\mu_{C_v}$	15	{11,...,17}
Standard deviation $\sigma_{C_v}$	3	{3,...,15}
<b>Stochastic price per unit of recycling material <math>X</math></b>		
Log-normal distribution $\mathcal{LN}(\mu_X, \sigma_X)$	$\mathcal{LN}(8,3)$	
Expected recycling price $\mu_X$	8	{8,...,14}
Standard deviation $\sigma_X$	3	{1,...,15}
Correlation coefficient $\rho_{C_v,D}$	0	{0.35, 0.7}
Correlation coefficient $\rho_{C_v,X}$	0	0.7
Correlation coefficient $\rho_{X,D}$	0	0.7

stated in column “variations”, one variable at a time. We use the method of sample average approximation to estimate the expected cost with various uncertainties and potential dependencies. We therefore use a sample size of 100,000 scenarios and optimize for the reservation quantity of the recycler  $q^r$  using MATLAB-function *fminbnd*, which finds a minimum of a continuous problem function of one variable within a fixed interval. We conducted a one-sample *t*-test (see Law, 2007) to justify the choice of our simulation sample size. For sampling correlated demand, recycling prices and virgin material prices we use copulas (see e.g. Silberman et al., 2017). Copulas link univariate marginals to their full multivariate distributions where the dependence structure is fully expressed by the copula (see Nelson, 2006), i.e. we can use arbitrary marginals as we have in our assumptions. We use the Gaussian copula where the dependence structure between the stochastic variables is captured by the covariance matrix. To generate correlated random data from a copula we use the MATLAB-function *copulamd*, which returns random values generated from a bivariate Gaussian copula with linear correlation parameters.

Before carrying out an analysis for our model, i.e. considering equation (2), we briefly want to give a numerical insight into the simplified model (equation (3)) of an uncorrelated environment with a deterministic yield rate  $Z = E(Z)$  that was discussed in Section 3, i.e.

**Table 4**  
Cases for different values of  $\rho_{C_v,D}$ ,  $\rho_{C_v,X}$  and  $\rho_{X,D}$

Case	$\rho_{C_v,D}$	$\rho_{C_v,X}$	$\rho_{X,D}$
Uncorrelated case	0	0	0
Correlated case 1a	0.35	0	0
Correlated case 1b	0.7	0	0
Correlated case 2	0.7	0.7	0
Correlated case 3	0.7	0.7	0.7

the closed-form solution given in equation (6). In Fig. 2(a) we show exemplarily by varying the expected virgin material price that the reservation quantity  $\bar{q}^{r*}$  in such a simplified setting is relatively similar to the quantity reserved  $q^{r*}$  minimizing equation (2) in the base case, except for low expected virgin material prices. The expected costs in the simplified case  $\bar{E}(C(q^{r*}))$  shown in Fig. 2(b) are, however, higher than in the base case. When it comes to lower expected virgin material prices from the spot market, the difference in costs is notable. In the simplified situation the recycler is always preferred over sourcing from the virgin material, only the remaining parts not being able to be satisfied from the recycler are then bought at the spot market. The buyer relies only on the virgin material supplier when the realized quantity turns out not to be enough. For the base case, however, the manufacturer can still decide based on the realization of the yield whether to source from the recycler or from the virgin material supplier. If prices at the spot market turn out to be low, the buyer can go for the cheaper source, which results in more quantity reserved at the recycler (Fig. 2(a)) and lower expected total costs (Fig. 2(b)) in the base case in comparison to the simplified case.

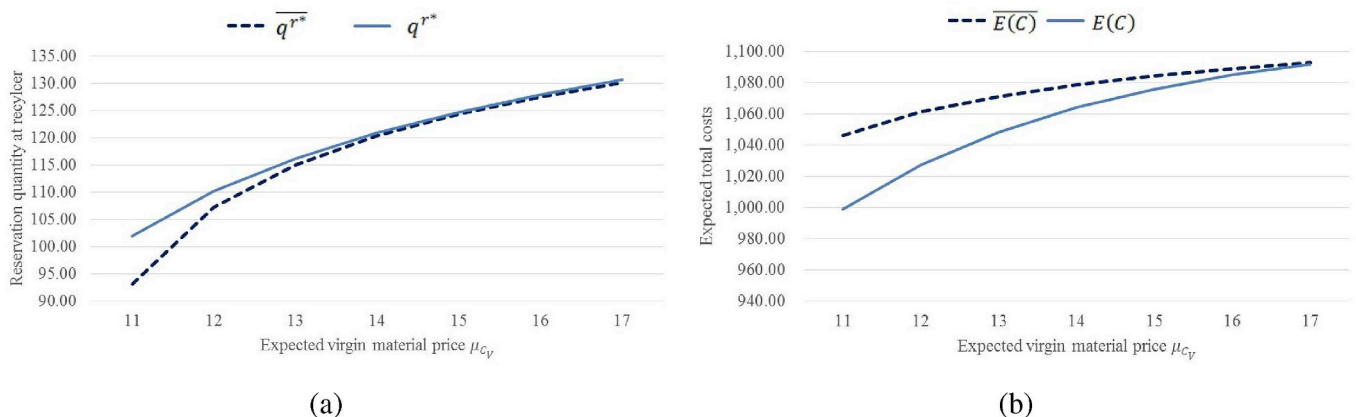
For the further analysis we distinguish between the cases listed in Table 4.

4.1. Uncorrelated case

For a first analysis, the manufacturer described in Section 3, is supposed to operate in an environment where no correlation between the stochastic parameters is assumed, i.e. all random variables are assumed to be independent (uncorrelated case, refer to Table 4). In such a setting we have a look at the impact of (i) demand uncertainty for the final consumer product (see Section 4.1.1), (ii) price uncertainty at the virgin material supplier and the recycler (see Section 4.1.2) and (iii) uncertainty at the recycler about the quantity to be delivered to the manufacturer (Section 4.1.3).

4.1.1. Effect of demand uncertainty on reservation quantity and cost

When varying the standard deviation of demand ( $\sigma_D$ ) resulting in different coefficients of variation  $CV_D$  we can see that in an uncorrelated setting with increasing standard deviation of demand the quantity that



**Fig. 2.** Comparing (a) optimal reservation quantities and (b) expected costs of simplified setting and base case varying  $\mu_{C_v}$ .

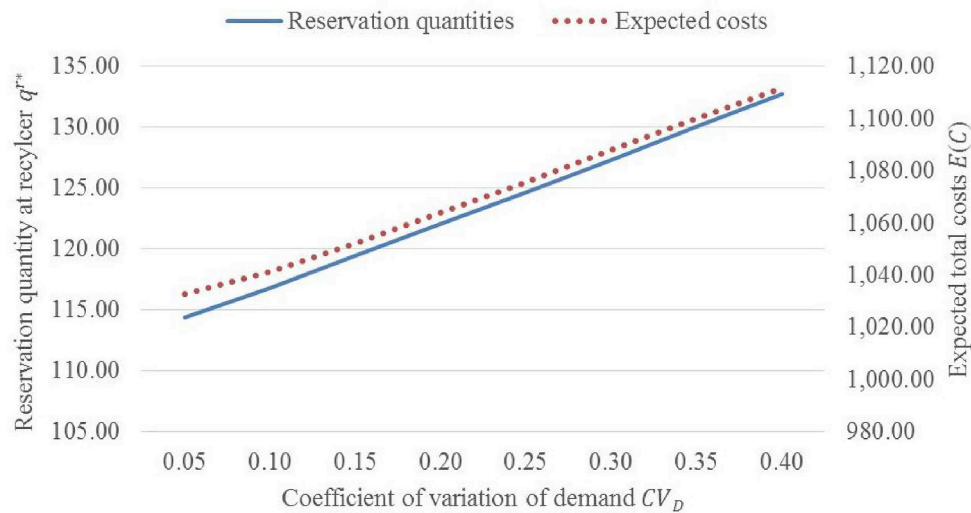


Fig. 3. Optimal reservation quantities and expected costs varying  $CV_D$

is bought from the recycler increases and the expected costs increase respectively (see Fig. 3). With more variability in demand for the final product, the manufacturer increases the reservation quantity at the recycler. Hong et al. (2014) also show the effect of increasing demand uncertainty in terms of decreasing profits and higher order quantities at the supplier.

4.1.2. Effect of price uncertainty on reservation quantity and cost

The price of virgin raw material is subject to high volatility (see also Reiner et al., 2014). As it is assumed in our setting that prices from the virgin material supplier are still uncertain at the time of reserving capacity at the recycler, we want to give an insight into the impact of that price uncertainty on the reservation quantities at the recycler and the related costs. It can be seen that, as expected, with higher expected value of the virgin material price the amount of recycling quantity reserved at the recycler increases and the overall costs also increase (see also Fig. 4). This effect of a spot price uncertainty can also be confirmed by Hong et al. (2014) who measure a decrease in order quantity (of virgin material at the spot market) with increasing coefficient of variation of the spot price. We have not taken the standard deviation of the virgin material price as a parameter for this case, as (for the uncorrelated case) we can see analytically (refer to equation (2) in Section

3) that this has no influence on the result.

Fig. 5 shows the impact of an uncertain exercise price of the recycling material on the reservation quantities at the recycler and the related costs. As expected, with higher expected value of the recycling material price the amount of recycling quantity reserved at the recycler goes down and the overall costs increase as virgin material is in general more expensive which leads to higher total costs.

4.1.3. Effect of quantity/yield uncertainty on reservation quantity and cost

As discussed earlier, the recycler might have to restrict the quantity that can be delivered to the manufacturer (“rationing”), due to too much overall demand for recycled materials or too less output from the recycling process. In this analysis we have a look at various beta-distributed yield rates (varying  $\alpha$  and  $\beta$ ) from the recycler (see Table 3), resulting in different expected yield rates  $\mu_Z$  (Fig. 6).

Additionally, two extreme cases are analyzed. In one extreme case the probability of receiving no quantity from the recycler ( $P(Z = 0)$ ) is 1. This would be comparable to a single sourcing strategy where the manufacturer sources only from the virgin material supplier, the resulting expected cost would be 1500. For reasons of comparison, we also look at the other extreme case, i.e. at the situation where the probability of receiving quantity from the recycler is  $P(Z = 1) = 1$ . This

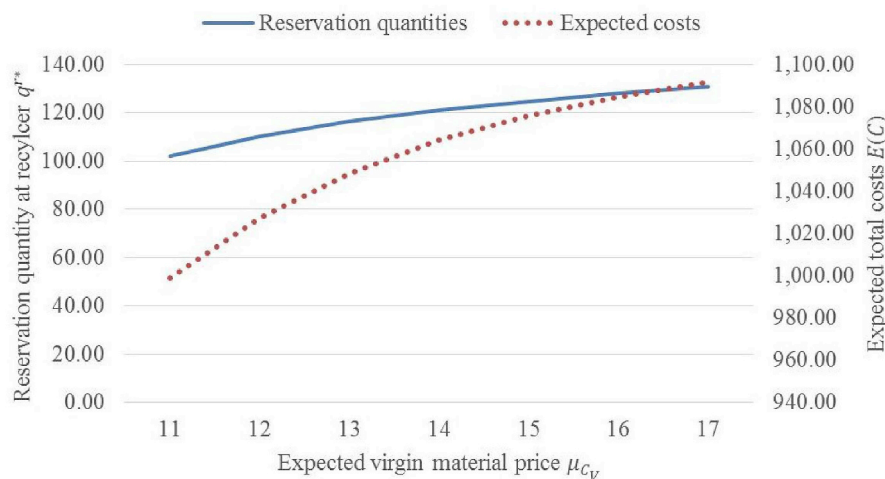


Fig. 4. Optimal reservation quantities and expected costs varying  $\mu_{C_V}$

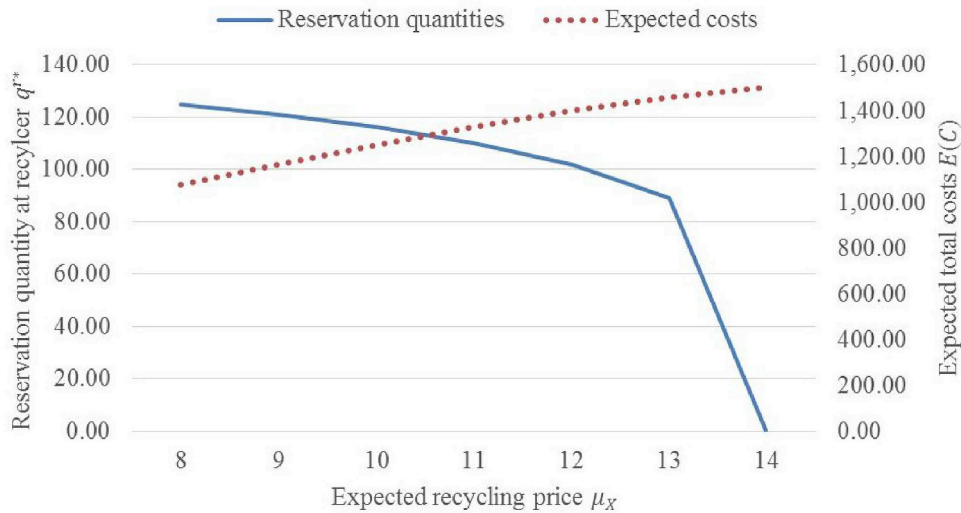


Fig. 5. Optimal reservation quantities and expected costs varying  $\mu_X$

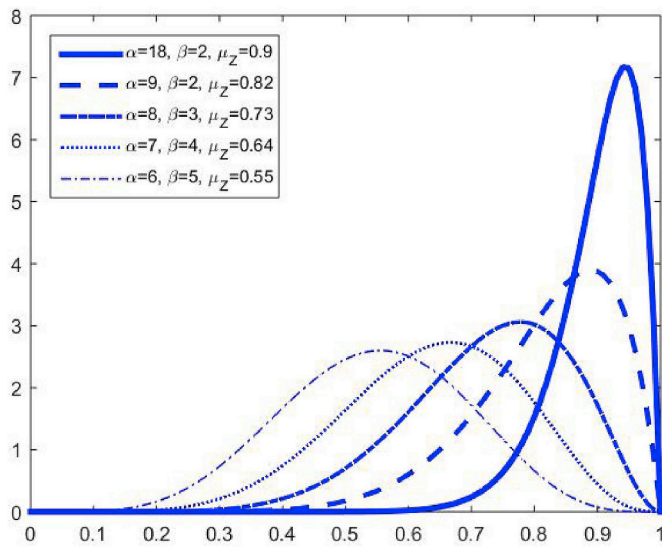


Fig. 6. Different beta-distributed yield rates of recycling quantities.

means that the manufacturer receives the entire amount reserved at the recycler. For the other cases it can be seen from Fig. 7 that the manufacturer sources proportionally more from the recycler when it comes to a lower mean of the recycling quantity in order to make sure that enough quantity is delivered. This phenomenon is referred to as shortage gaming and is known from the literature on the bullwhip effect (see e.g. Cachon and Terwiesch, 2013). Serel (2007) also supports that implication as he says that uncertain input markets lead to an increase in the share of inputs purchased in advance via long-term contracts.

4.2. Effect of correlation

In a next step of our numerical analysis we take correlation effects into account. We are particularly interested in the impact of correlation between virgin material and recycling prices  $\rho_{C_v, X}$ , the correlation between spot price and demand  $\rho_{C_v, D}$  and between recycling price and demand  $\rho_{X, D}$ . We assume positive correlation for these correlation values. This is summarized in Table 5.

In a first step we will add a positive correlation between virgin material price and demand  $\rho_{C_v, D}$  (see Section 4.2.1), where we will have a look on weak (correlated case 1a) and strong correlation values (correlated case 1b) followed by additionally taking a positive

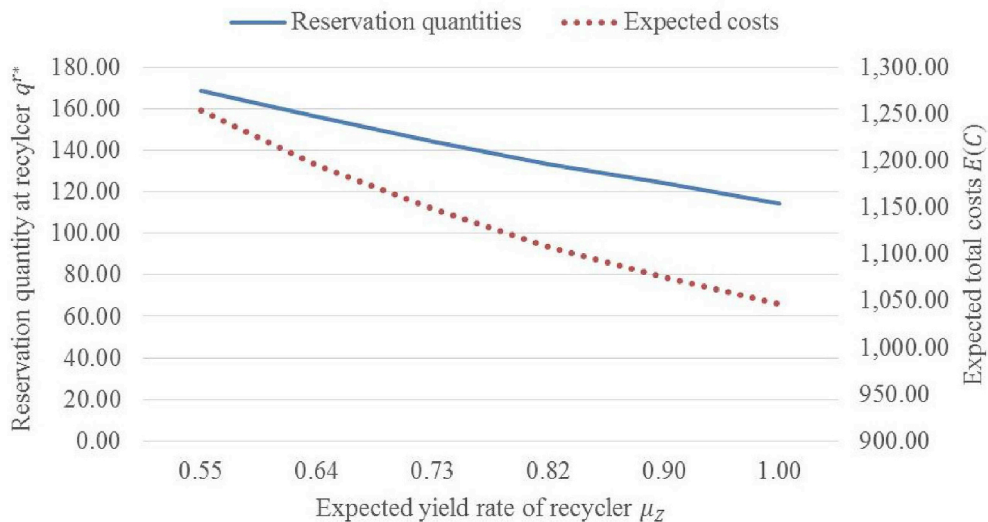


Fig. 7. Optimal reservation quantities and expected costs varying  $\mu_Z$



**Table 5**  
Correlation matrix.

	X	D	$C_v$
X	1		
D	+	1	
$C_v$	+	+	1

correlation between virgin material price and recycling price  $\rho_{C_v,X}$  (correlated case 2) into account (see Section 4.2.2) and on top adding a positive correlation between recycling material price and demand  $\rho_{X,D}$  (correlated case 3) in Section 4.2.3. Please refer again to Table 4 for the different cases.

**4.2.1. Impact of correlation between demand and virgin material price  $\rho_{C_v,D}$**

In a first step we examine the joint effect of demand uncertainty and virgin material price uncertainty, i.e. spot market price uncertainty. It is assumed that virgin material prices and customer demands are positively correlated ( $\rho_{C_v,D} < 0$ ). Thus, when demand is high, the spot price is more likely to be higher than the price when demand is low (see also e.g. Merzifonluoğlu, 2015 or Seifert et al., 2004). When having a look at increasing correlation values of  $\rho_{C_v,D}$  it can be seen from Fig. 8 that the quantity that is reserved at the recycler as well as the costs increase when this correlation value is getting stronger. Not considering correlation effects could therefore underestimate the costs for the manufacturer. Consequently, the impact of demand and (virgin material) price correlation should be taken into account by the manufacturer in order to ensure a realistic ordering strategy.

Comparing the results from the uncorrelated with this correlated case, we display the difference in optimal reservation quantity at the recycler by  $\Delta q^{r*}(\%) = (q_{corr}^{r*} - q_{uncorr}^{r*})/q_{uncorr}^{r*} \times 100$ . Corresponding to the reservation quantities, the cost difference is displayed by  $\Delta C(\%) = (E(C)_{corr} - E(C)_{uncorr})/E(C)_{uncorr} \times 100$ . In Table 6(a) we see that with increasing standard deviation of demand and, hence, higher  $CV_D$  the quantity reserved at the recycler and the cost difference compared to the uncorrelated case are increasing when considering correlation. It is also important to consider correlation especially when virgin material prices are low. The lower the expected virgin material price, the greater is the difference in recycling quantities reserved and expected costs between the uncorrelated and the correlated case (Table 6(b)). Taking correlation between virgin material price and demand into account also has an effect especially in situations where the expected recycling price converges the virgin material price (Table 6(d)).

In addition, we conduct a full factorial design of possible combinations of problem parameters stated in the column “variations” in Table 3 to evaluate the cost differences when taking correlation  $\rho_{C_v,D} = 0.7$  into account compared to the uncorrelated case (Table 7).

We further have a look at the impact of strong ( $\rho_{C_v,D} = 0.7$ ) and weak ( $\rho_{C_v,D} = 0.35$ ) correlation values for selected parameters. From Table 8 the results of varying  $CV_D$  on reservation quantities and expected costs can be seen. It can be summarized that in an environment of more uncertain demand a stronger correlation between virgin material price and demand leads to higher reservation quantity at the recycler and subsequently higher expected costs.

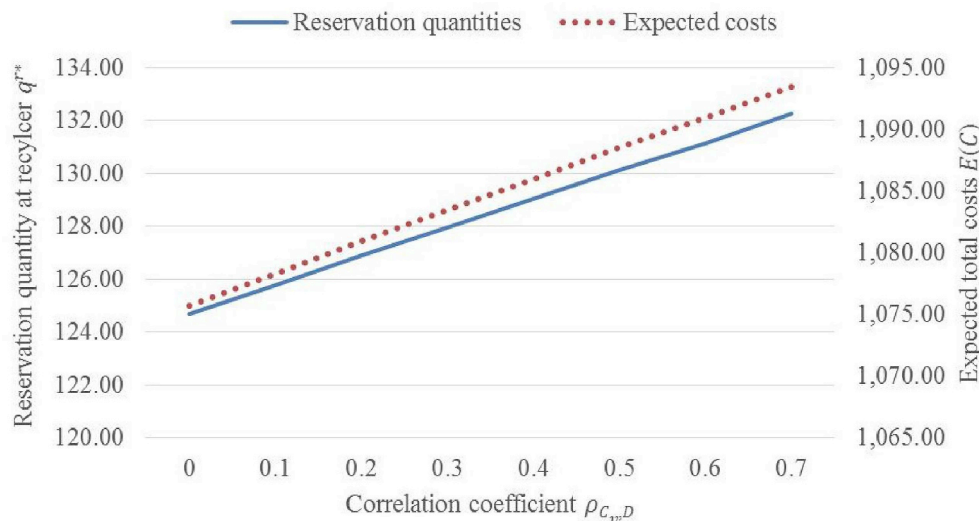
When having a look at the impact of weak and strong correlation values of  $\rho_{C_v,D}$  for different  $\mu_{C_v}$  on reservation quantities and expected costs, we can see from Table 9 that a strong correlation between demand and virgin material prices (correlated case 1b) leads to greater differences compared to low correlation (correlated case 1a). From the results it can be summarized that in situations where the virgin material prices are comparably low (i.e. the price difference to the recycler is small), a stronger correlation between virgin material price and demand leads to higher reservation quantity at the recycler and subsequently higher expected costs.

Considering high correlation values for  $\rho_{C_v,D}$  (correlated case 1b) results in higher reservation quantities and expected costs when having a look also at different yield rates from the recycler. According to Table 10 this effect is even stronger for situations with less probability of receiving the required quantity.

**4.2.2. Impact of correlation between virgin material and recycling price  $\rho_{C_v,X}$**

It is further assumed that both prices, i.e. the raw material price from the virgin material supplier  $C_v$  as well as the exercise price from the recycler  $X$  are correlated. Similar to Reiner et al. (2014) who assume a newsvendor setting with, on the one hand, a contract price characterized by low mean and low variance, on the other hand, a high price volatility of the spot market price with high mean and high variance, it is assumed that recycling and virgin material prices appear to behave similar in a certain ratio and distribution of the prices. The prices for virgin and recycling material are then considered to be highly positively correlated ( $\rho_{C_v,X} = 0.7$ ). This correlation could be even higher in practice, i.e. up to perfectly correlated, but the effects are already visible when taking the selected correlation coefficient of 0.7.

Correlation case 2 leads to higher reservation quantities at the recycler and subsequently to higher expected costs compared to the uncorrelated setting. Fig. 9 shows the (a) optimal reservation quantities



**Fig. 8.** Comparison of optimal reservation quantities and expected costs for different  $\rho_{C_v,D}$

**Table 6**

Comparison of optimal reservation quantities  $q^{r*}$  and expected costs  $E(C)$  for different (a)  $CV_D$ , (b)  $\mu_{C_v}$ , (c)  $\mu_Z$  and (d)  $\mu_X$  taking correlation  $\rho_{C_v,D} = 0.7$  into account.

$CV_D$	$\Delta q^{r*}$	$\Delta E(C)$	$\mu_{C_v}$	$\Delta q^{r*}$	$\Delta E(C)$	$\mu_Z$	$\Delta q^{r*}$	$\Delta E(C)$	$\mu_X$	$\Delta q^{r*}$	$\Delta E(C)$
<b>0.05</b>	1.28%	0.37%	<b>11</b>	12.99%	3.49%	<b>0</b>	0.00%	3.52%	<b>8</b>	6.08%	1.65%
<b>0.10</b>	2.59%	0.70%	<b>12</b>	10.31%	2.81%	<b>0.55</b>	6.91%	2.53%	<b>9</b>	6.97%	1.77%
<b>0.15</b>	3.72%	1.02%	<b>13</b>	8.30%	2.31%	<b>0.64</b>	6.65%	2.23%	<b>10</b>	8.28%	1.95%
<b>0.20</b>	4.92%	1.34%	<b>14</b>	6.98%	1.93%	<b>0.73</b>	6.55%	2.01%	<b>11</b>	10.26%	2.21%
<b>0.25</b>	6.08%	1.65%	<b>15</b>	6.08%	1.65%	<b>0.82</b>	6.15%	1.82%	<b>12</b>	12.80%	2.54%
<b>0.30</b>	7.18%	1.95%	<b>16</b>	5.26%	1.43%	<b>0.90</b>	6.08%	1.65%	<b>13</b>	17.50%	2.97%
<b>0.35</b>	8.16%	2.25%	<b>17</b>	4.67%	1.26%	<b>1</b>	5.82%	1.50%	<b>14</b>	0.00%	3.52%
<b>0.40</b>	9.11%	2.56%									

and (b) expected costs for the uncorrelated setting compared to correlated case 2. It can be seen that in an environment, where both correlations (i.e.  $\rho_{C_v,X}, \rho_{C_v,D} = 0.7$ ) are assumed to be strong, the reservation quantity and related expected costs are highest. The effect/difference is strongest for e.g. situations with small virgin material prices.

Comparing correlated case 2 to the uncorrelated setting (no correlation) gives insights into the difference in optimal reservation quantities and expected costs. An analysis is – similar to Section 4.1 – done for the parameters  $CV_D, \mu_{C_v}, \mu_Z$  and  $\mu_X$  to see the development of results for varying uncertainties. With higher uncertainty in demand more quantity is reserved at the recycler compared to the uncorrelated case, also resulting in higher expected costs. Moreover, lower virgin material prices (and hence a smaller cost differences compared to the recycling prices) in correlated case 2 leads to higher reservation quantities at the recycler in comparison to the uncorrelated case. In situations with higher yield uncertainty, the manufacturer also reserves more quantity at the recycler when it comes to an environment like in correlated case 2.

When analyzing in detail the development of reserved quantities and expected costs when varying the expected recycling prices it can be observed that with an increase in the recycling price the reservation quantity at the recycler goes down (Fig. 10(a)). As soon as the recycling price converges to the virgin material price, the reservation quantity strives for a quantity of zero. This development is also visible when having a look at the expected costs (Fig. 10(b)). With an increase in recycling prices the overall costs also go up. For this analysis we can also see that correlated cases 1 and 2 results in higher quantities and higher costs, respectively, than the uncorrelated case.

Having a look at another aspect of increasing price uncertainty at the recycler, namely an increasing standard deviation of the recycling price, shows that in correlated cases 1 and 2 the reservation quantities at the recycler and the related expected costs are higher compared to the uncorrelated case (Fig. 11(b)). The higher the uncertainty with regards to the recycling price ( $\sigma_X$ ), the more quantity is reserved at the recycler (Fig. 11(a)).

This insight is also confirmed by Hong et al. (2014), who also have a look at a positive correlation between demand and spot prices and can observe smaller profit (i.e. higher costs) in a strongly correlated environment.

**Table 7**

Cost difference  $\Delta C(\%)$  of the sustainable sourcing strategy considering correlation  $\rho_{C_v,D} = 0.7$  compared to the uncorrelated case.

$\mu_Z$	$\mu_{C_v}$	$\sigma_{C_v}$	$CV_D$			$\mu_Z$	$\mu_{C_v}$	$\sigma_{C_v}$	$CV_D$			
			0.05	0.25	0.40				0.05	0.25	0.40	
0.90	11	3	0.72%	1.95%	5.40%	0.55	11	3	0.97%	4.71%	7.50%	
		8	1.70%	7.91%	12.25%			8	2.28%	10.69%	16.69%	
		15	2.63%	12.10%	18.58%			15	3.58%	15.86%	24.19%	
	15	3	0.32%	0.32%	2.25%		15	15	3	0.53%	2.38%	3.59%
		8	0.91%	4.05%	14.68%				8	1.40%	6.19%	14.90%
		15	1.73%	7.68%	11.74%				15	2.49%	10.82%	16.14%

**Table 8**

Comparison of results for weak and strong correlation values for different  $CV_D$

	$\rho_{C_v,D} = 0.35$		$\rho_{C_v,D} = 0.7$	
	$\Delta q^{r*}$	$\Delta E(C)$	$\Delta q^{r*}$	$\Delta E(C)$
<b>0.05</b>	0.32%	0.17%	1.28%	0.37%
<b>0.10</b>	0.62%	0.32%	2.59%	0.70%
<b>0.15</b>	0.91%	0.47%	3.72%	1.02%
<b>0.20</b>	1.19%	0.61%	4.92%	1.34%
<b>0.25</b>	1.46%	0.75%	6.08%	1.65%
<b>0.30</b>	1.73%	0.89%	7.18%	1.95%
<b>0.35</b>	2.00%	1.03%	8.16%	2.25%
<b>0.40</b>	2.28%	1.17%	9.11%	2.56%

**Table 9**

Comparison of results for weak and strong correlation values for different  $\mu_{C_v}$

	$\rho_{C_v,D} = 0.35$		$\rho_{C_v,D} = 0.7$	
	$\Delta q^{r*}$	$\Delta E(C)$	$\Delta q^{r*}$	$\Delta E(C)$
11	8.92%	1.80%	12.99%	3.49%
12	6.50%	1.35%	10.31%	2.81%
13	4.91%	1.06%	8.30%	2.31%
14	3.90%	0.88%	6.98%	1.93%
15	3.30%	0.75%	6.08%	1.65%
16	2.87%	0.66%	5.26%	1.43%
17	2.40%	0.59%	4.67%	1.26%

**Table 10**

Comparison of results for weak and strong correlation values for different  $\mu_Z$

	$\rho_{C_v,D} = 0.35$		$\rho_{C_v,D} = 0.7$	
	$\Delta q^{r*}$	$\Delta E(C)$	$\Delta q^{r*}$	$\Delta E(C)$
0	0.00%	0.00%	0.00%	0.00%
0.55	3.79%	1.22%	6.91%	2.53%
0.64	3.53%	1.07%	6.65%	2.23%
0.73	3.48%	0.95%	6.55%	2.01%
0.82	3.44%	0.85%	6.15%	1.82%
0.90	3.30%	0.75%	6.08%	1.65%
1	3.07%	0.67%	5.82%	1.50%

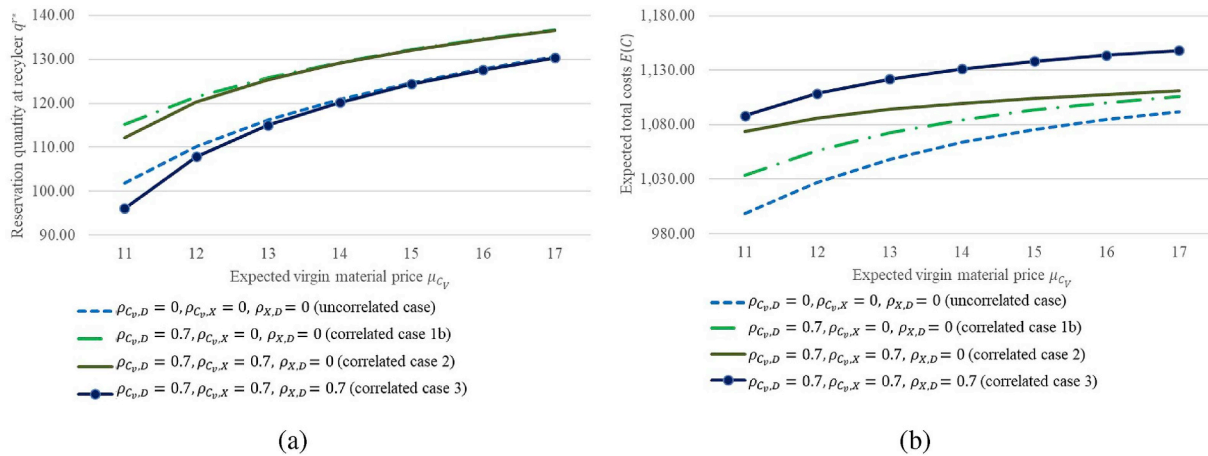


Fig. 9. Comparison of (a) optimal reservation quantities and (b) expected costs for different settings varying the expected recycling price  $\mu_{Cv}$ .

4.2.3. Impact of correlation between recycling price and demand  $\rho_{X,D}$

Similar to the correlation between virgin material price and demand, also a correlation between recycling material price and demand  $\rho_{X,D}$  is assumed to be positive. When having a look at the impact of considering also this correlation (correlated case 3), it can be seen from Figs. 9(a) and 10(a) that the quantity reserved at the recycler is even less compared to the uncorrelated case and that therefore leads to higher expected total costs (see Figs. 9(b) and 10(b); even higher than in correlated case 2). Especially visible is that impact when having a closer look on Fig. 11, where the standard deviation of the recycling price is varied. From Fig. 11(a) one can see that including the correlation between recycling price and demand into the analysis leads to strong effects on the quantity that is reserved at the recycler. In the setting of the paper this even leads to less quantities reserved at the recycler compared to the uncorrelated case and resulting in even higher expected total costs compared to correlated case 2.

5. Managerial insights

From the numerical analyses in Section 4 some managerial conclusions can be drawn. The results from our analysis are depicted by two key figures for the focal company, i.e. the manufacturer, which show the success of the company in total costs (economic figure) and resource consumption (ecological figure), i.e. the reservation quantity of recycled materials at the recycler.

From the findings of the uncorrelated case it can be observed that uncertainties, especially with respect to demand, price and quantity at

the recycler influence a manufacturer's sourcing behavior. With more variability in demand for the final product, the manufacturer increases its reservation quantity at the recycler which increases the expected cost. An increase in the expected price of virgin material leads to an increase in the quantity reserved at the recycler, as the objective is cost minimization. Quantity/yield uncertainty at the recycler also impacts a manufacturer's sourcing strategy. The recycler may ration the quantities delivered to the manufacturers. In such settings and especially when it comes to situations where the expected quantity is low the manufacturer has to reserve more at the recycler to still receive the required quantity for production. Highly uncertain market conditions (demand, prices and yield) should motivate manufacturers to secure more capacity at the recycling supplier.

From the analysis of correlated case 1 considering strong demand and virgin material price correlation we can draw the following conclusion: Strong demand and virgin material price correlation leads to an increase in the expected costs and a decrease in the quantity sourced from the virgin material supplier, while the reservation quantity at the recycling supplier increases. This result is similar to the managerial conclusions drawn by Merzifonluoglu (2015) who investigate demand and spot market price correlation. Furthermore, not considering correlation can lead to wrong cost estimations in various situations. Large cost differences compared to the uncorrelated case are observed in situations with high standard deviations of the virgin material price, high standard deviations of demand and low virgin material prices (see full factorial design in Table 7). The stronger the correlation between demand and virgin material prices, the more intense this effect. These

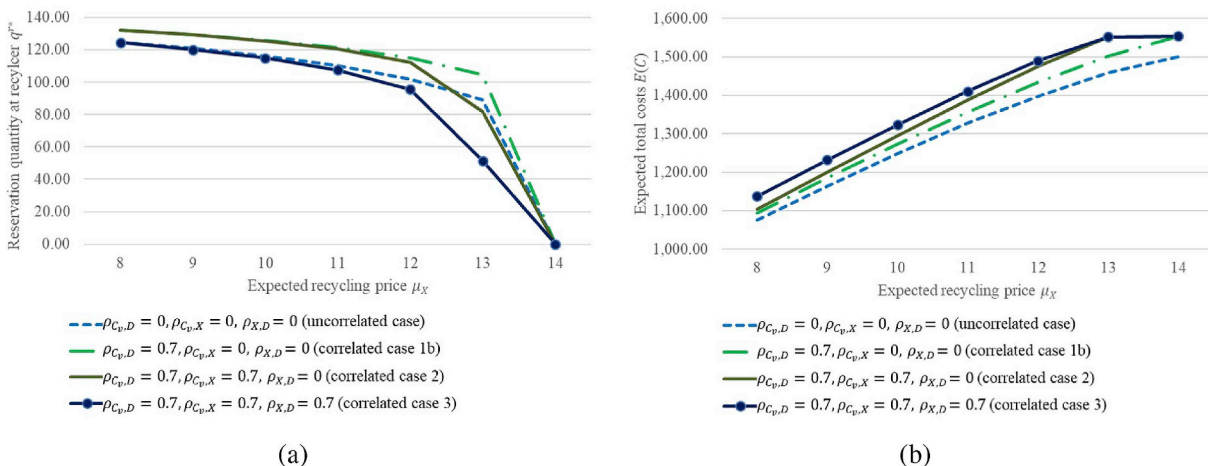


Fig. 10. Comparison of (a) optimal reservation quantities and (b) expected costs for different settings varying the expected recycling price  $\mu_X$ .

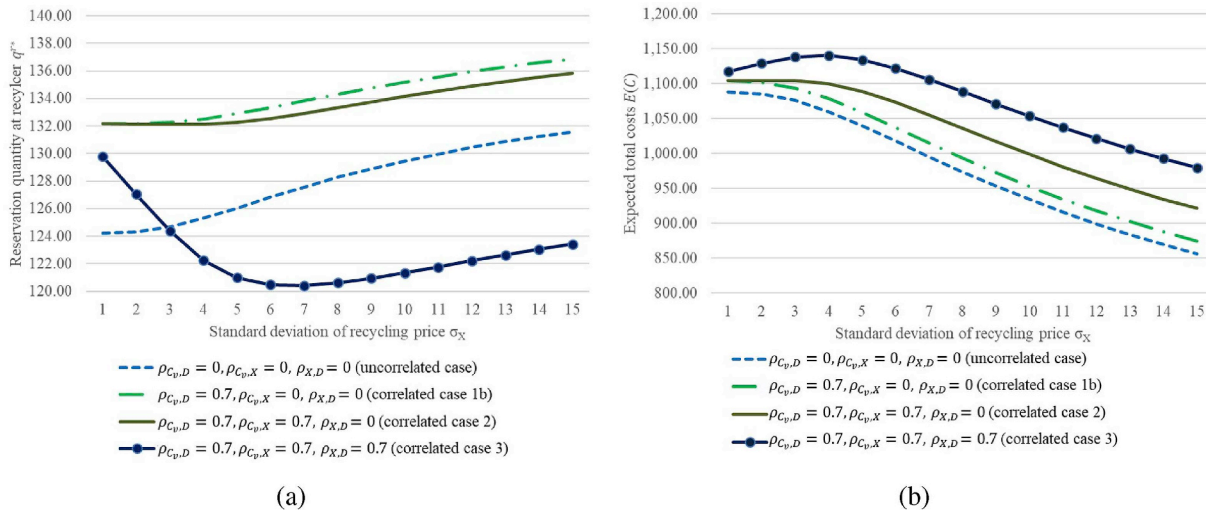


Fig. 11. Comparison of (a) optimal reservation quantities and (b) expected costs for different settings varying the standard deviation of the recycling price.  $\sigma_X$

results are becoming even more obvious when we assume a smaller quantity to be received from the recycler. Not taking into account correlation would underestimate overall expected costs.

The analysis of *correlated cases 2 and 3*, in which the positive price and demand correlations are studied, supports our previous statement and emphasize the importance of taking correlation into account in order not to reserve wrong quantities and/or underestimate costs that might occur. This differences in quantities and cost are larger for high variability in demand, low virgin material prices (and high recycling prices, respectively) and low yields from the recycler.

To summarize from our numerical results, the suggested sustainable sourcing approach including recycled materials is especially suitable (in terms of economic and environmental goals) for manufacturer that are confronted with the following situations:

- **Demand uncertainty:** In a situation where the actual demand that is realized might significantly differ from the expected demand, which is the case for high uncertainty in demand represented by a high coefficient of variation of demand, it is beneficial for the manufacturer to decide to reserve more quantity at the recycler than to (at a later point in time) have to order remaining material from the more expensive spot market source. Having this alternative sourcing option allows the manufacturer to react appropriately in such a setting.
- **Price uncertainty:** The more expensive virgin material (high expected virgin material prices) at the spot market turns out to be in contrast to the recycled material price, the more quantity is reserved at the (cheaper) recycling material supplier who then starts with the recycling process based on the reservation quantity. High expected recycling prices lead to a decrease in quantity reserved at the recycler, therefore leads to a higher probability of buying more at the expensive spot market, which leads to higher costs. This effect is intensified when correlation is taken into account.
- **Yield uncertainty:** In situations where the probability of receiving a higher amount of quantity from the recycler (high yield rate from recycling processes) is high(er), the manufacturer does not intentionally have to reserve more quantity than needed at the recycler beforehand (no need for shortage gaming). In situations with limited yield, however, the manufacturer should make sure not to reserve too little quantity from the recycler to receive the required amount in the end and benefit from the comparatively lower recycling prices and in order not to have to use the more expensive emergency source delivering virgin material.
- **Correlations:** In an environment where demand is correlated with

prices of raw material the effect of uncertainty in demand, yield and prices is even more visible. The same holds true for an environment where prices of virgin and recycled materials are correlated. Increased correlation increases the expected total costs and the total reservation quantity at the recycling supplier.

### 6. Discussion

Uncertainties with respect to supply and demand are main concerns supply chains have to face in complicated, fast-changing environments of today. These are challenges such as fluctuating raw material input quantities, uncertain demand for the final product or random prices at a reactive supply source on the spot market, just to name a few. Having a (sustainable) dual sourcing strategy in mind, in which the manufacturer can have a second supply source to rely on in cases of unexpectedly high demands, supply shortages or other unforeseen incidents, proves to be a good way to avoid shortage situations (see also Yao and Minner, 2017). Apart from considering demand and spot price uncertainties, companies have become more attentive to the issue of recycling (Rowe et al., 2017). Especially in the area of critical materials (e.g. rare earth materials) only minor significance has been attributed to recycling of these materials so far as they are usually only required in small quantities. As demand for these raw materials is constantly growing, because they are part of many products in the electronics industry, the Seventh Framework of the European Union has put focus on the technical feasibility of recycling of critical materials. As the procurement of these materials is associated with considerable risks and can be problematic in the sense of social sustainability (especially for conflict materials), it is especially important for these materials to have not only primary material from the mine but also alternative sourcing options available. An additional challenge when considering recycling are the obstacles that Thierry et al. (1995) mention in their paper which hinder higher implementation of these materials, namely the differences in quality (i.e. yield uncertainty) and costs (i.e. price uncertainty) between recycled and virgin materials. Including random yields (to depict uncertain quantities) from recycling processes makes the model realistic and the manufacturer aware of the fact that he might not always receive the full amount ordered. Our model gives insights for the recycler of critical materials, as it provides appropriate assurance that there is a certain amount of demand for the recycling material and that the company is not producing recycled material without having customers. This demand is visible from the results of the analysis. We can therefore see that (given the case of a positive technical aspect of recycling) it is doable from an economical point of view, visible from the results of our

analysis. Even though the focus of our study is on the manufacturer, it has also implications on the upstream part of the supply chain, e.g. the raw material suppliers and can be applied to other industries as well where a manufacturer utilizes recycled materials, such as the aluminum or plastics industry, for instance, where recycling processes are already quite mature. The presented model we have discussed in this paper can be a useful contribution for different sourcing strategies regarding recycled materials, particularly for products where recycling practices are already established, such as polymers and plastics. For such materials the economic feasibility is already given and the recycling procedures already show their benefits. For critical materials, e.g. tungsten, tantalum etc. we are aware that quantities are at the moment not reasonable enough to make a clear statement with respect to the distinction between virgin and recycling materials in terms of quality/purity and prices, but see that the potential of recycling is there. Our model therefore should give an idea of the potential when using recycled materials in the sourcing process for critical materials.

## 7. Conclusions

This paper had the goal to analyze a sourcing strategy for critical materials with virgin raw materials and recycling raw materials applying a single-period inventory model. We discuss how the integration of recycling material into the sourcing strategy impacts a manufacturer's economic and environmental performance considering several uncertainties and potential correlations between them.

### 7.1. Summary

We develop a single period inventory model under uncertain demand in order to derive optimal reservation quantities from a proactive contract supplier offering recycled materials with uncertain yield according to capacity reservation (option) contract and a reactive supplier (spot market) offering virgin materials at an uncertain price reflecting the price volatility at the spot market. We provide results on the optimal policy structure and obtain a closed form solution as a bound of the optimal reservation quantity at the recycling supplier. It gives us first insights on the effect of different economic parameters on the ordering decision. By means of a sensitivity analysis we then numerically discuss the impact of demand uncertainty, recycling quantity uncertainty at the recycler and price uncertainty at the virgin material supplier and the recycler. We also study the effect of taking correlation between price and demand uncertainties into account.

### 7.2. Findings

From our study we can conclude that ignoring correlations could underestimate the costs and reservation quantities. We show that considering correlation when using such a sourcing strategy is especially important in environments with high demand uncertainty, volatile raw material prices and situations with yield uncertainty in order not to underestimate costs and reservation quantities. Second, from an ecological point of view, the manufacturer contributes to the concept of circular economy as the total input of virgin raw materials in the production process is (partly) replaced by recycling material. Consequently, the input of virgin material is reduced which contributes to the objectives of the EU action plan for a circular economy (European Commission, 2015) and, hence, waste reduction.

### 7.3. Outlook

As recently the technical feasibility of recycling has been answered in a positive way and the economic feasibility of recycling of critical materials is, according to our results, given, a next step would be to apply this model to a case and feed the model with real data. Extending the model to a multi-period setting in order to include feedback effects

would also provide valuable managerial insights. For further analyses, taking other dependencies into account could be of interest. Dependencies between stochastic recycling quantity and stochastic recycling price are for instance considered already in Rogetzer et al. (2018), but not yet in this analysis. This correlation is assumed to be negative. Similar to Hong et al. (2014) another correlation could be taken into account, namely between virgin material prices and yield recycling rates. Another possible research direction would be to also include the recycler with his decision about the recycling price into the model. This would imply a game-theoretic analysis.

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