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RESEARCH

The economic lot-sizing problem with remanufacturing and inspection for grading heterogeneous returns

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Abstract
We address an extension of the economic lot-sizing problem with remanufacturing in which returns are assumed dissimilar and an inspection activity is required in order to grade them into a finite number of pre-established nominal qualities of either remanufacturable or non-remanufacturable returns. There are set-up costs related to the production activities, including inspection. Separate inventories are assumed for incoming returns, inspected-and-graded returns and serviceable (new or remanufactured) products. Remanufacturing, discarding and inventory holding costs depend on the quality of the returns. The objective is to determine when and how much to inspect, remanufacture, discard and produce in order to meet the demand requirements on time, minimizing the sum of all the involved costs. For this problem we provide a mathematical programming formulation and suggest several lot-sizing rules based on different inspection and remanufacturing decisions. We also show the problem is NP-hard and provide a property about the form of its optimal solutions. An extensive numerical experimentation is conducted in order to analyse the behaviour of the lot-sizing rules suggested, considering different values for the problem parameters. The results obtained show that remanufacturing can offer economic benefits even in the case of an independent and relatively expensive inspection. In addition, we can conclude that the inspection of all incoming returns is in general the most cost-effective decision, even if not all of them are remanufactured.

Keywords Lot-Sizing Problem · Remanufacturing · Inspection · Heterogeneous returns · Mathematical Programming · Lot-sizing rules

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Introduction

In the economic lot-sizing problem with remanufacturing (ELSR), the demand requirements of a single product can be also satisfied by remanufacturing used products returned to the origin. This type of problem has gained the attention of academics because hybrid production-remanufacturing systems are common today, due to the benefits they offer to customers, manufacturers and the environment [3, 11, 28, 42]. Customers often pay less for remanufactured products with the same quality as the new ones, companies save production costs and the environment benefits from decreased use of raw materials, energy consumption and waste generation [12, 19]. Remanufactured products include automotive parts, heavy-duty engines, tires, aviation equipment, cameras, medical instruments, furniture, toner cartridges, copiers, computers, and telecommunications equipment, among others [21, 36, 37, 44]. Take-back legislations as well as certain market pressures act as drivers for the collection and recovery of used products also known as returns or cores [6, 7, 15, 33]. Remanufacturing is considered as a key supporting element for Circular Economy, term that refers to zero waste production systems in contrast to the traditional linear economy systems of take-make-waste [1, 14, 23]. Remanufacturing process often involves disassembly, inspection, sorting, cleaning, reprocessing, testing and reassembly. The operations involved in the process must guarantee a recovered product with at least the same quality and functionality as the newly manufactured one [21, 28, 36, 42].

One of the major challenges of the remanufacturing process is the non-uniform condition of the incoming returns, which directly affects the costs and operations of the recovery activities [16, 20]. The quality of the returns largely depends on the time and intensity of usage by customers [18]. In general, the remanufacturer has little control over the quality of incoming returns, and sometimes may not even apply additional charges for badly damaged or incorrect returns. Therefore, the inspection of returns is always necessary in one or more stages of the remanufacturing process. It results in high-quality remanufactured products, but may cause a decrease in remanufacturer profit [36, 37]. Poor inspection at the beginning of the remanufacturing process can lead to unnecessary processing later, or to unnecessary rejection of returns, resulting in a low recovery rate. Conversely, performing a proper inspection early in the process can lead to a reduction in total remanufacturing times. In this regard, in [37] it is reported that in the automotive remanufacturing industry, time savings of up to 20% can be achieved through proper inspection of the returns prior to processing. In [9] we present a recovery options analysis carried out on domestic electric storage water heaters (DESWH) for the Uruguayan manufacturer Rivomark (https://rivomark.com). The returns of this product require a detailed inspection to determine its condition regarding functional and safety requirements. Through inspection, returns are graded into one of a pre-established finite set of nominal qualities. Each one of them is related to a particular recovery route, i.e., the sequence of recovery tasks needed. We note that inspection should be focused on the storage tank, made of copper or steel, as it is the most critical component of a DESWH. Before that, through a detailed visual review it is determined whether or not a used DESWH requires destructive disassembly. Returns that require destructive disassembly are graded with a lower quality than those that do not, as more recovery tasks will be needed. In any case, both hydraulic and rust tests must be carried out on the storage tank. Among other tasks, the remanufacturing process may include reconditioning of the storage tank and the replacement of electrical and safety components.

In this paper we consider a hybrid production-remanufacturing system of a single item, with varying demand and return values over a finite and discrete-time planning horizon.

Incoming returns are assumed of heterogeneous quality and an inspection is required in order to grade them into a finite number of nominal quality levels of remanufacturable and non-remanufacturable returns. This kind of inspection is also called pre-inspection in the literature, as it is usually the first step in the remanufacturing process [36]. We assume that inspection is perfect, i.e., error free and all incoming returns can be graded into exactly one of the pre-specified quality levels. Set-up costs are assumed for the activities of the system, even for the inspection, and unit costs for holding inventories of incoming returns, inspected-and-graded returns and serviceable products, i.e., new or remanufactured products. The objective is to determine when and how much to produce, inspect, remanufacture and discard in order to satisfy the demand requirements on time, minimizing the sum of all the costs involved. We refer to this problem as the economic lot-sizing problem with remanufacturing, inspection and heterogenous returns (ELSRIH). As far as we know, the ELSR extension with heterogeneous returns and set-up costs for inspection has not been considered in the literature before.

The main contributions of this paper are as follows. Firstly, we provide the definition and the mathematical model for the ELSRIH. We note that in order to obtain a mixed-integer linear programming (MILP) formulation for the problem, we had to establish a rounding rule for the non-integer values that result from applying the quality level fractions to the integer value of the number of returns. The rounding rule is proposed with the aim of avoiding as far as possible the loss of returns and maintaining the proportion of the qualities. We also provide an analysis about the form of the optimal solutions and the complexity order of the problem. Secondly, we propose nine lot-sizing rules (or inventory policies) for the ELSRIH, based on different inspection and remanufacturing criteria. These rules were implemented by extending the MILP formulation suggested for the problem. Thirdly, we present an extensive numerical experimentation in order to compare the solutions obtained from the lot-sizing rules suggested for the ESLRIH. For this analysis, we consider different values for returns ratio, set-up costs for inspection and quality level fractions.

The remainder of the present paper is organized as follows: Sect. 2 is devoted to the literature review about production systems with returns options, inspection and heterogenous returns. Section 3 of Methods provides the description, formulation and the lot-sizing rules suggested for the problem. We also provide in this section some theoretical properties related to the problem. In Sect. 4 of Results we present the design of the numerical experimentation conducted and the analysis of the results obtained. Section 5 finishes the paper with the main conclusions and certain guidelines for future research.

Literature review

The literature about hybrid production-remanufacturing systems is rather vast, even for the ELSR. Therefore, we focus here on problems with inspection and/or graded returns, considering first pure remanufacturing systems and then hybrid production-remanufacturing systems. For research works on ELSR we direct readers to [34, 35, 44] for those interested in mathematical formulations and exact methods, to [29, 31, 39, 40] for heuristic approaches, to [30] for the problem with product substitution and to [33] for the ELSR with recovery targets. In addition, we direct readers to [36–38] for research on the relationship between inspection and remanufacturing, and to [10, 46] for the problem of acquisition management of returns.

Pure remanufacturing systems

Tagaras and Zikopoulos [43] consider a pure remanufacturing system (PRS) with multiple locals for the collection and possibly sorting of returns, with stochastic demand and returns. A constant unit cost is assumed for the inspection activity. The optimal replenishment policy is analysed under the options of zero, central and local sorting. Ferguson et al. [8] suggest a profit model for a PRS with backlogging and graded returns but without inspection costs. A finite set of levels of nominal qualities are assumed for the remanufacturable returns, with known fraction values for each one of them. They show that under unit costs for holding inventory and remanufacturing it is optimal to remanufacture in descending order of quality: best quality returns are remanufactured first. They also found that the value of grading returns increases as the returns ratio increases. Denizel et al. [4] study a similar problem that [8] but including unit cost for grading returns. They found that the profit is mostly influenced by the remanufacturing costs rather than the quality of returns or the inspection costs. Mezghani and Loukil [22] suggest a profit model for a PRS in which the quality of the returns is defined by means of fuzzy expressions. A MILP formulation is suggested for the problem considering also a salvage price for the returns and backlogging. Zikopoulus [47] studies the performance of a particular inventory policy for a PRS with constant demand, in which the information about the condition quality of the incoming returns is either complete or incomplete. Two different remanufacturable qualities are considered (good and poor) and the inspection activity is not considered. He found that a complete information on the quality distribution for the incoming returns is more useful as its variability decreases. Nenes and Nikolaidis [25] also suggest a profit model for a PRS with suppliers offering graded returns (inspection activity is not considered). The problem considered is based on a real case of cell phones remanufacturer. A MILP formulation is suggested for the problem and evaluated by means of several numerical experiments in order to compare it against a single-period model. In Zikopoulus [48] a PRS is considered in which the remanufacturing costs and processing times depend on the quality of the returns, which are assumed remanufacturable of either good or poor quality. Costs for inspection are not considered. Liao et al. [17] carried out an extensive analysis about the effect of uncertainty on quantity and quality of returns on the PRS performance. Different optimization strategies are formulated and the uniqueness of the optimal solution for each one of them is demonstrated. However, the inspection activity is not considered in the analysis.

Hybrid production-remanufacturing systems

Aras et al. [2] consider a hybrid production-remanufacturing system (HPRS) with inspection and remanufacturable returns of either high or low quality. Inventory holding costs of remanufacturable returns are assumed independent of their quality and there is not cost related to the inspection activity. The system is analysed by means of a continuous-time Markov chain model. They found that the cost savings are amplified as returns quality decreases and return rate increases and that in general it is more profitable the prioritizing of high-quality returns. Konstantaras et al. [13] study an HPRS in which the incoming returns are inspected in order to determine the proper recovery option for them (refurbishing or remanufacturing). Unit cost is assumed for the inspection activity. Nenes et al. [24] analyse alternative inventory policies for a particular HPRS with stochastic demand and returns. The inspection is for grading the returns into reusable or remanufacturable items. Unit costs are assumed for the inspection. Dong et al. [5] consider a profit model for an HPRS with inspection for grading returns into specific groups of non-remanufacturable (1 group) or remanufacturable (3 groups) items. Raw materials, reuse of product components as well as processing times are considered for the remanufacturing activity. Unit costs are assumed for holding inventories and for the activities. A linear programming (LP) formulation is provided for the problem. In Mahapatra et al. [20] a profit model is suggested for a multi-product HPRS with heterogeneous quality returns. As in [4, 8], a limited number of nominal qualities is assumed, each one of them with a known fraction value. A constant unit cost is assumed for the inspection of incoming returns. Processing times, raw materials, safety stocks and costs for capacity readjustment are considered for production and remanufacturing. They found that grading returns is more valuable when the quality of returns is poor. Niknejad and Petrovic [26] analyse the optimization of a reverse logistic network for returns of heterogeneous quality. Inspection is considered for determining the recovery route of the incoming returns: disposal, repair or disassembly for obtaining components for the production of new products. Piñeyro [32] considers the ELSR with graded returns according to their quality but without inspection. A MILP formulation and several inventory policies are suggested for the problem. As in [4], it is noted that the total costs are mostly influenced by the remanufacturing costs instead other parameters. In Panagiotidou et al. [27] a stochastic HPRS with non-uniform returns is analysed by means of two different inventory models: procurement of new products before or after the inspection of incoming returns. A unit cost is assumed for the inspection. Sun et al. [41] study the economic lot scheduling problem in a remanufacturing system of a single item with constant demand and returns with heterogeneous quality. Particular settings are considered such as zero set-up cost for remanufacturing and at most only one remanufacturing type (remanufactured returns are of the same quality level) at certain period. Under the assumption of low-cost returns, they found that considering the grading of returns not only reduces the remanufacturing cost but also improve the efficiency of the whole system by reducing the ordering frequency.

Methods

In this section we provide first the problem description and its mathematical formulation (Sections 3.1 and 3.2, respectively). Then, in Section 3.3 we present an analysis about the complexity of the problem and the form of its optimal solutions. Finally, in Section 3.4 we present the definition of the lot-sizing rules suggested for the ELSRIH.

Problem statement

We consider the dynamic demand requirements of a single item over a finite and discrete time planning horizon that can be either satisfied by producing new items or by remanufacturing used items returned to origin. The returns are assumed of heterogeneous quality and an inspection activity is required in order to grade them into a finite number of nominal quality levels of either remanufacturable and non-remanufacturable returns. Each remanufacturable quality level is related to certain remanufacturing type, i.e., the tasks involved on the remanufacturing process, and then its cost, depend on the quality of the returns. The same behaviour is assumed for the discarding of non-remanufacturable returns. Remanufactured and new products are perfect substitutes despite the heterogeneous quality of the incoming returns. Thus, a single inventory is considered for serviceable products. However, separate inventories are assumed for uninspected as well as inspected-and-graded returns. Figure 1 shows a sketch of the flow of items for the inventory system of the problem.

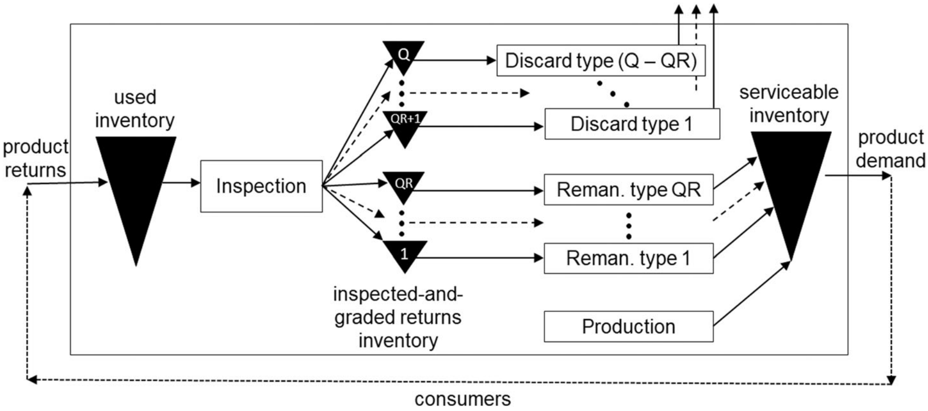

Fig. 1 Flow of items for the ELSRIH

Demand and returns quantities as well as cost values are assumed known in advance for each one of the periods within the planning horizon. We assume a stationary cost pattern similar to that used in the literature for lot-sizing problems with remanufacturing [31, 40, 45]: set-up costs for the activities and unit holding costs for carrying ending positive inventory form one period to the next. We assume that all incoming returns can be graded by means of a perfect inspection (free of errors) into one of the pre-specified quality levels. More precisely, we consider $0 < Q < \infty$ different levels of nominal qualities and $\alpha_q \geq 0$ for each level q in $\{\{1,...,Q\}\}$ in order to represent the portion of expected returns with quality level q, with $\alpha_1 + \alpha_2 + ... + \alpha_Q = 1$. Thus, when the inspection of a certain number $N > 0$ of returns is carried out in certain period t, a set-up cost is incurred, and $\alpha_q \times N \geq 0$ of either remanufacturable or non-remanufacturable returns of quality level q will be available at period t. We assume that a nominal quality q is better than $(q+1)$; sets $\{\{1,\ldots,QR\}\}$ and $\{\{(QR+1),\ldots,Q\}\}$ are considered for remanufacturable and non-remanufacturable qualities, respectively, with $1 \leq QR \leq Q$. Backlogging demand is not allowed and capacities for the activities and storage are assumed infinite. Lead times for the activities and initial inventory levels are assumed zero. The objective is to determine the quantities to be inspected, remanufactured, discarded and produced at each period in order to meet the demand requirements on time, minimizing the sum of all the involved costs. We refer to this problem as the economic lot-sizing problem with remanufacturing, inspection and heterogenous returns (ELSRIH).

Mathematical formulation

We present below the notation used in this paper for the problem stated above:

- T: Number of periods of the planning horizon, with $0 < T < \infty$.
- Q: Number of quality levels for inspected returns, with $0 < Q < \infty$.
- QR: Number of quality levels of remanufacturable returns, with $0 < QR \leq Q$.
- D_t: Demand of serviceable items in period t, with $t = 1, \ldots, T$.
- R_t: Number of returns in period t, with $t = 1, \ldots, T$.
- K^p: Set-up cost of production.
- K_q^r: Set-up cost of remanufacturing the returns of quality q, with $q = 1, \ldots, QR$.

- K_q^d: Set-up cost of discarding the returns of quality q, with $q = (QR + 1), \ldots, Q$.
- K^i: Set-up cost of inspection for grading incoming returns.
- h^s: Unit cost of holding inventory for serviceable items.
- h^u: Unit cost of holding inventory of non-inspected returns.
- h_q^i: Unit cost of holding inventory of inspected returns of quality q, with $q = 1, \ldots, Q$.
- α_q: Fraction of returns of quality level q, with $q = 1, \ldots, Q$, $\alpha_q \geq 0$ and $\sum_{q=1}^{Q} \alpha_q = 1$.
- θ: A positive real number close enough to 1.
- B: A positive real number, with $0 < B < 1$.
- QF: Quality level chosen for rounding by difference, with $QF \in \{1, \ldots, Q\}$.
- M: Big number equal to $\max\left\{\sum_{t=1}^{T} D_t, \sum_{t=1}^{T} R_t\right\}$.
- x_t^p: Number of new items produced in period t, with $t = 1, \ldots, T$.
- $x_{q,t}^r$: Number of returns of quality q remanufactured in period t, with $q = 1, \ldots, QR$ and $t = 1, \ldots, T$.
- $x_{q,t}^d$: Number of returns of quality q discarded in period t, with $q = (QR + 1), \ldots, Q$ and $t = 1, \ldots, T$.
- w_t: Numbers of returns inspected in period t, with $t = 1, \ldots, T$.
- $x_{q,t}^i$: Numbers of inspected returns of quality level q in period t, with $q = 1, \ldots, Q$ and $t = 1, \ldots, T$.
- y_t^s: Inventory level of serviceable items in period t, with $t = 1, \ldots, T$.
- y_t^u: Inventory level of uninspected returns in period t, with $t = 1, \ldots, T$.
- $y_{q,t}^i$: Inventory level of inspected returns of quality level q in period t, with $q = 1, \ldots, Q$ and $t = 1, \ldots, T$.
- δ_t^p: 1 if production is carried out in period t, 0 otherwise, with $t = 1, \ldots, T$.
- $\delta_{q,t}^r$: 1 if remanufacturing of returns of quality level q is carried out in period t, 0 otherwise, with $q = 1, \ldots, QR$ and $t = 1, \ldots, T$.
- $\delta_{q,t}^d$: 1 if discarding of returns of quality level q is carried out in period t, 0 otherwise, with $q = (QR + 1), \ldots, Q$ and $t = 1, \ldots, T$.
- δ_t^i: 1 if inspection of returns is carried out in period t, 0 otherwise, with $t = 1, \ldots, T$..

Considering the parameters and variables of above, the ELSRIH can be formulated as the following MILP:

$$\mathrm{Min}\sum_{t=1}^{T}\left\{\begin{array}{c} \mathrm{K^p}\delta_t^p + \mathrm{K^i}\delta_t^i + \sum_{q=1}^{QR}\left(\mathrm{K_q^r}\delta_{q,t}^r\right) + \sum_{q=(QR+1)}^{Q}\left(\mathrm{K_q^d}\delta_{q,t}^d\right) \\ +\mathrm{h^s}\mathrm{y_t^s} + \mathrm{h^u}\mathrm{y_t^u} + \sum_{q=1}^{Q}\left(\mathrm{h_q^i}\mathrm{y_{q,t}^i}\right) \end{array}\right\} \tag{1}$$

subject to:

$$y_t^s = y_{(t-1)}^s - D_t + x_t^p + \sum_{q=1}^{QR} x_{q,t}^r, \quad \forall t = 1, \ldots, T \tag{2}$$

$$y_t^u = y_{(t-1)}^u + R_t - w_t, \quad \forall t = 1, \ldots, T \tag{3}$$

$$y_{q,t}^i = y_{q,(t-1)}^i + x_{q,t}^i - x_{q,t}^r, \quad \forall q = 1, \ldots, QR, \forall t = 1, \ldots, T \tag{4}$$

$$y_{q,t}^i = y_{q,(t-1)}^i + x_{q,t}^i - x_{q,t}^d, \quad \forall q = (QR + 1), \ldots, Q, \forall t = 1, \ldots, T \tag{5}$$

$$y_0^s = y_0^u = y_{q,0}^i = 0, \quad \forall q = 1, \ldots, Q, \ \forall t = 1, \ldots, T \tag{6}$$

$$x_{q,t}^i \le \alpha_q w_t + B, \quad \forall q = 1, \ldots, Q \wedge q \ne QF, \forall t = 1, \ldots, T \tag{7}$$

$$x_{q,t}^i \ge \alpha_q w_t + B - \theta, \quad \forall q = 1, \ldots, Q \wedge q \ne QF, \ \forall t = 1, \ldots, T \tag{8}$$

$$x_{QF,t}^i = w_t - \sum_{(q=1 \wedge q \ne QF)}^{Q} x_{q,t}^i, \quad \forall t = 1, \ldots, T \tag{9}$$

$$M\delta_t^p \ge x_t^p, \quad \forall t = 1, \ldots, T \tag{10}$$

$$M\delta_{q,t}^r \ge x_{q,t}^r, \quad \forall q = 1, \ldots, QR, \forall t = 1, \ldots, T \tag{11}$$

$$M\delta_{q,t}^d \ge x_{q,t}^d, \quad \forall q = (QR+1), \ldots, Q, \forall t = 1, \ldots, T \tag{12}$$

$$M\delta_t^i \ge w_t, \quad \forall t = 1, \ldots, T \tag{13}$$

$$x_t^p, y_t^s, y_t^u, w_t \ge 0, \delta_t^p, \delta_t^i \in \{0, 1\}, \quad \forall t = 1, \ldots, T \tag{14}$$

$$y_{q,t}^i \ge 0, x_{q,t}^i \in \mathbb{Z}^+ \cup \{0\}, \quad \forall q = 1, \ldots, Q, \forall t = 1, \ldots, T \tag{15}$$

$$x_{q,t}^r \ge 0, \delta_{q,t}^r \in \{0, 1\}, \quad \forall q = 1, \ldots, QR, \forall t = 1, \ldots, T \tag{16}$$

$$x_{q,t}^d \ge 0, \delta_{q,t}^d \in \{0, 1\}, \quad \forall q = (QR+1), \ldots, Q, \forall t = 1, \ldots, T \tag{17}$$

The objective function (1) is defined as the sum of all the involved costs for the problem. Constraints (2) to (5) are the inventory balance equations for serviceable, incoming returns and inspected-and-graded returns, respectively. Constraint (6) specifies that the initial inventory levels must be zero. Constraints (7) and (8) are for obtaining the integer number of inspected returns of quality q in certain period t, i.e. $x_{q,t}^i$, with the aim of avoiding the loss of returns and maintaining as much as possible the proportion established by the quality level fraction α_q. In this sense, parameter $B = 0.5$ is used for rounding the real number equal to $(\alpha_q w_t)$, and θ = 0.99999 for obtaining its integer floor value. In addition, Eq. (9) are for obtaining the inspected returns of the chosen quality $QF = Q$ by means of the difference between the total number of inspected returns and the sum of the inspected returns of the rest of the qualities. Constraints (10) to (13) establish that a set-up cost is incurred whenever a positive amount is produced, remanufactured, discarded or inspected, respectively. Constraints (14) to (17) state the set of possible values for the decision variables.

Problem analysis

We provide in this section, two properties about the form of the optimal solutions and the order of complexity of the ELSRIH.

Property 1 about ELSRIH optimal solutions Under the assumption of low-cost for the returns, i.e. $h_q^i \geq h^u$ for all $q = 1, \ldots, Q$, there is an optimal solution of the ELSRIH for which it is fulfilled that if there is inspection in certain period, then there must be a recovery activity (remanufacturing or discard) in the same period. Consider a feasible solution for the problem with: $\delta_j^i = 1$ and $\delta_{j,q}^r = \delta_{j,q}^d = 0$, for all quality levels q and some period j. Assume that there is a period k and a quality level q, such that k is the first period after j with: $\delta_{k,q}^r + \delta_{k,q}^d \geq 1$. Thus, we can obtain a new solution by transferring forward the inspection from period j to the next period k, saving at least $(h_q^i - h^u)(k-j) \geq 0$ units of cost. On the other hand, if period k does not exist, then we can save at least $(h_q^i - h^u)(T-j) + K^i \geq 0$ units of cost by eliminating the inspection in period j.

Property 2 about ELSRIH complexity We note that the ELSR, i.e. the problem without inspection and heterogenous returns, can be considered a particular case of the ELSRIH formulated above in (1) – (17). Let us consider the ELSR with remanufacturing set-up cost equal to K^r and all the other necessary parameters and variables defined as those for the ELSRIH but without considering inspection and heterogenous returns. Then, we can define an ELSRIH instance for which $Q = QR = QF = 1$ and $\alpha_1 = 1$, i.e. only one quality level of remanufacturable returns and without non-remanufacturable returns. In addition, we define $K_1^r = K^r/2, K^i = K^r/2$ and $h_1^i = h^u$. Thus, an optimal solution for this ELSRIH will be also optimal for the ELSR. Therefore, as expected, solving the ELSRIH is at least as difficult to solve as the ELSR. Since the ELSR is an NP-hard problem even in the case of stationary costs as we assumed here [34], we can conclude that it is also the ELSRIH.

Lot-sizing rules for the ELSRIH

We suggest in this section nine lot-sizing rules (or inventory policies) for the ELSRIH, based on different criteria for the inspection and remanufacturing activities. Some of them can be considered an extension of those proposed in [32] for the problem without the inspection activity. The lot-sizing rules are implemented by means of adding certain linear constraints to the formulation of (1)-(17) of above for the ELSRIH, which we refer to hereinafter as the original formulation.

No Inspection (NoInsp) Inspection is not carried out at any period within the planning horizon. The following constraint is added to the original formulation:

$$\sum_{t=1}^{T} w_t = 0 \tag{18}$$

Full Inspection (FullInsp) All incoming returns within the planning horizon are inspected (but not necessarily remanufactured). The following constraint is added to the original formulation:

$$\sum_{t=1}^{T} w_t = \sum_{t=1}^{T} R_t \tag{19}$$

Inspection and Recovery (I&R) This is the application of Property 1 of Sect. 3.3 about the form of the optimal solutions of the ELSRIH. If inspection is carried out in certain period, then remanufacturing or disposal of at least one level of quality of returns is also carried out in the same period. The following constraints are added to the original formulation:

$$\delta_t^i \le \sum_{q=1}^{QR} \left(\delta_{q,t}^r\right) + \sum_{q=(QR+1)}^{Q} \left(\delta_{q,t}^d\right), \forall t = 1, \dots, T \tag{20}$$

Inspect at Each Period (IEP) If the number of incoming returns in certain period is positive, then all of them are inspected. The following constraints are added to the original formulation:

$$y_t^u = 0, \forall t = 1, \dots, T \tag{21}$$

Zero Outgoing Inventory of Used items (ZOU) If inspection is carried out in certain period, it must include all available returns. The following constraints are added to the original formulation.

$$M \times \left(1 - \delta_t^i\right) \ge y_t^u, \forall t = 1, \dots, T \tag{22}$$

Zero Inventory of Remanufacturable items (ZIR) Zero inventory of inspected-and-remanufacturable returns (i.e. all returns inspected in certain period that are of remanufacturable quality, are remanufactured in the same period). The following constraints are added to the original formulation.

$$y_t^q = 0, \forall q = 1, \dots, QR, \forall t = 1, \dots, T \tag{23}$$

Zero Final Inventory of Remanufacturable items (ZFIR) The final inventory of inspected-and-remanufacturable returns must be zero (i.e. all returns inspected that are of remanufacturable quality, are remanufactured within the planning horizon). The following constraints are added to the original formulation.

$$y_T^q = 0, \forall q = 1, \dots, QR \tag{24}$$

Full Remanufacturing (FullRem) All incoming returns within the planning horizon are inspected, and all inspected-and-remanufacturable items are remanufactured. We note that this lot-sizing rule is the joint version of the lot-sizing rules *FullInsp* and *ZFIR* of above. Therefore, it can be implemented by adding the constraints of (19) and (24) to the original formulation.

Zero Outgoing Inventory of Used and Remanufacturable items (ZOUR) If inspection (remanufacturing) occurs in certain period it must involves all the available incoming returns (inspected-and-remanufacturable items of the same quality). We note that this lot-sizing rule is a restricted version of the lot-sizing rule *ZOU*. Therefore, it can be implemented by adding to the original formulation the constraints of (22) in addition to the following.

$$M \times \left(1-\delta^{r}_{q,t}\right) \geq y^{i}_{q,t}, \forall q = 1, \ldots, QR, \forall t = 1, \ldots, T \tag{25}$$

Results

In this section we present the design and the results of the numerical experiments carried out for the analysis of the ELSRIH under different values of returns ratio, set-up costs of inspection, and quality level fractions. To perform the analysis, we compare the optimal solutions obtained from the original formulation of Section 3.2 against those obtained from the lot-sizing rules suggested in Section 3.4.

Design of the numerical experimentation

The instances generated for the numerical experiments are based on the benchmark set introduced in [39] and used also in [31, 40]. We assume that remanufacturing is economically attractive: costs related to the returns are at most equal to the cost related to the new items. In addition, we assume that the set-up costs for remanufacturing and discarding decrease as the quality of returns increases, and the opposite for the inventory holding costs as in [4, 8, 32, 48], i.e., $K^r_1 \leq \ldots \leq K^r_Q \leq K^p$, $K^d_1 \leq \ldots \leq K^d_Q \leq K^p$ and $h^s \geq h^i_1 \geq \ldots \geq h^i_Q \geq h^u$. We also assume that the set-up cost of inspection is at most equal to the set-up cost of remanufacturing, i.e., $K^i \leq K^r_1$. We consider a planning horizon of 22 periods (number of weekdays in a month) for all the instances. A normal distribution with mean 100 is considered for the demand values, and means 10, 30, 50, 70 and 90, for the returns. Variances of 10% and 20% for both demand and returns values are considered. The set-up cost of production is set to 2000. The set-up cost for inspection can be 50, 200 and 500. Four nominal qualities are considered for the inspected-and-graded returns, with levels 1 to 3 for the remanufacturable returns and level 4 for the non-remanufacturable returns (1: best, 2: better, 3: good, 4: poor). The set-up costs of remanufacturing for qualities 1 to 3 are 500, 1000 and 1500, respectively; and the set-up cost for discarding the returns of quality level 4 is 500. The inventory holding cost for serviceable items is 1, for incoming returns 0.1, and for inspected-and-graded are 0.8, 0.5, 0.2 and 0.1 for qualities 1 to 4, respectively. The quality level fractions considered for qualities 1 to 4 are (0.1, 0.2, 03, 0.4), (0.25, 0.25, 0.25, 0.25) and (0.4, 0.3, 0.2, 0.1), in order to represent scenarios of low-, equal- and high-quality returns, respectively. For each one of the $5 \times (2^2) \times (3^2) = 180$ different settings, 10 instances were generated, which results in 1800 instances in total.

Analysis of the results

The original formulation (1)–(17) for the ELSRIH and those from applying the lot-sizing rules of (18)–(25) were coded in AMPL and solved using CPLEX 12.8.0.0 running on a PC with CentOS Linux 7, 8 CPUs Intel Core i7-6700, 3.40 GHz, 64-bit, and 24 GB of RAM.

Table 1 reports the number of solutions obtained from the lot-sizing rules according to different ranges of cost error percentage, that is calculated as:

$$cost\_error\_percentage = \frac{100 * (LSR\_optimal\_cost - OF\_optimal\_cost)}{OF\_optimal\_cost},$$

where *LSR_optimal_cost* and *OF_optimal_cost* are the objective values of the optimal solutions obtained from the lot-sizing rule and the original formulation, respectively. We note that the solutions obtained from *NoInsp* are the same of those obtained from *ZFIR*. In addition, we note that all the solutions of both *IEP* and *FullRem* have a cost gap greater than 10%. The detailed information about the cost gaps for each one the lot-sizing rules is provided in Table 2, and the information of the running times is provided in Table 3.

General remarks

From Tables 1 and 2 we can extract the following general observations for the lot-sizing rules suggested for the ELSRIH.

Remark 1 We note that the lot-sizing rule *I&R* achieves the optimal solutions, as it is the application of Property 1 about the form of the optimal solutions of the ELSRIH. In addition, when examining the solutions obtained, we could see that not all inspected returns in a certain period are remanufactured or discarded within the planning horizon, but at least a part of them.

Remark 2 It is interesting to note that in general, the full inspection rule provides solutions with a lower cost than those with the null inspection rule. In fact, most of the solutions obtained from *FullInsp* (over 98%) have a cost gap lower than 5%. In addition, the highest error gap of *FullInsp* (5.46%) is significantly lower than that of *NoInsp* (22.48%). This means a major flexibility of the full inspection rule. However, we note that the null inspection rule achieves a greater number of optimal solutions than the full rule in the case of low number of returns and high set-up costs for inspection, which is not a surprise (see Table 1).

Remark 3 Since the solutions for the lot-sizing rules *ZIR* and *NoInsp* are the same, we can conclude that under a separate set-up cost scheme for the remanufacturing types, the rule of remanufacturing all the inspected-and-remanufacturable returns as soon as possible is not a suitable option. However, from the results obtained for the lot-sizing rule *ZFIR*, the option of remanufacturing all the inspected-and-remanufacturable returns but within the planning horizon may lead to near optimal solutions.

Remark 4 It is economically favourable the inspection of all the available returns in certain period (*ZOU*) as well as the remanufacturing of all the available inspected-and-graded returns of the same quality in certain period (*ZOUR*). In fact, over the 50% of the solutions obtained from the lot-sizing rules *ZOU* and *ZOUR* are optimal and the maximal cost gap is 3.20% and 3.86%, respectively. However, we note that *ZOU* slightly surpasses *ZOUR*, as expected since

Table 1 Number of solutions per cost gap ranges

Cost Error	*NoInsp*	*FullInsp*	*I&R*	*IEP*	*ZOU*	*ZIR*	*ZFIR*	*FullRem*	*ZOUR*
0–0.0001%	677	9	1800	0	930	677	732	0	891
0.0001–5%	566	1771	0	0	870	566	987	0	909
5.0001–10%	360	20	0	0	0	360	81	0	0
10.0001–15%	127	0	0	94	0	127	0	1	0
15.0001–20%	59	0	0	270	0	59	0	420	0
≥20.001%	11	0	0	1436	0	11	0	1379	0

Table 2 Performance of the lot-sizing rules

All instances	*NoInsp*	*FullInsp*	*I&R*	*IEP*	*ZOU*	*ZIR*	*ZFIR*	*FullRem*	*ZOUR*
AVG	3.69	2.18	0.00	49.16	0.32	3.69	1.46	21.72	0.40
MIN	0.00	0.00	0.00	11.44	0.00	0.00	0.00	14.63	0.00
MAX	22.48	5.46	0.00	96.97	3.20	22.48	7.86	29.37	3.86
D variance									
10%	3.82	2.18	0.00	49.02	0.31	3.82	1.46	21.64	0.40
20%	3.56	2.18	0.00	49.30	0.32	3.56	1.47	21.80	0.41
R variance									
10%	3.70	2.17	0.00	49.18	0.32	3.70	1.45	21.69	0.41
20%	3.69	2.19	0.00	49.14	0.31	3.69	1.48	21.74	0.40
R mean									
10	0.01	2.21	0.00	47.34	0.00	0.01	0.01	20.52	0.00
30	1.09	2.26	0.00	51.06	0.08	1.09	1.09	21.47	0.09
50	2.90	2.11	0.00	50.47	0.27	2.90	2.41	22.01	0.32
70	5.58	2.05	0.00	49.36	0.43	5.58	2.12	21.98	0.55
90	8.88	2.26	0.00	47.60	0.80	8.88	1.68	22.59	1.06
K^i									
50	5.23	0.70	0.00	18.75	0.37	5.23	1.97	20.20	0.45
200	3.81	1.83	0.00	41.55	0.33	3.81	1.53	21.38	0.43
500	2.05	4.00	0.00	87.18	0.25	2.05	0.89	23.57	0.33
Quality scenarios									
low	1.01	2.25	0.00	47.50	0.06	1.01	0.26	20.91	0.12
equal	3.35	2.16	0.00	49.48	0.26	3.35	1.16	21.65	0.35
high	6.72	2.13	0.00	50.50	0.63	6.72	2.97	22.59	0.74

the latter is a restricted version of the former. This behaviour is similar to that observed in [32] for the problem without inspection and [29] for the ELSR.

Remark 5 The extreme rules of inspection whenever it is possible (*IEP*) as well as remanufacturing all the remanufacturable returns regardless of their quality (*FullRem*), are not able to achieve good quality solutions for the ELSRIH. This behaviour for *FullRem* was also observed in [32] for the problem without inspection. The poor performance for these lot-sizing rules is not a surprise considering the separate set-up scheme for the activities.

Results of the sensitivity analysis

From Table 2 we first note that the variances of 10% and 20% on the demand and returns do not have a significant impact on the behaviour of the lot-sizing rules. Regarding the variations on the returns ratio, we can observe that as the number of returns increases the performance of *NoInsp* (and also *ZIR*) worsens. This can be explained because the two lot-sizing rules do not take advantage of the economic benefits offered by the recovery of returns, which in addition causes high inventory levels of them. Similar to the latter effect, but to a lesser extent and on the inventory of serviceable items, may explain the slightly improvement observed for the lot-sizing rules *ZOU*, *ZOUR* and *FullRem*. In the case of the variations on the set-up cost of inspection, as it increases, the impact on the total cost of a low (high) or even zero (full) level of inspection is expected to be low (high). This explains the performance enhancement (worsening) for the lot-sizing rules *NoInsp*, *ZIR* and *ZFIR* (*IEP* and *FullRem*) as the set-up cost of inspection increases. For the lot-sizing rules *ZOU* and *ZOUR*, the improvement in their performance as the set-up cost of inspection increases, may be explained by a decrease on the number of inspections, even if they involve all the available returns.

Finally, considering the variations on the quality level fractions, we note that as the proportion of returns of good quality increases, the performance of the lot-sizing rules with no inspection (i.e. *NoInsp* and also *ZIR*) worsens, as expected. For those lot-sizing rules with positive inspection, the performance deterioration as the quality of returns increases, can be explained to a greater or lesser extent by the trend to maintain high inventory levels of the most expensive inspected-and-remanufacturable returns. However, it is interesting to note that this negative effect is reversed in the case of the lot-sizing rule *FullInsp*. This enhancement may be explained by the greater flexibility of *FullInsp* for the inspection and remanufacturing than the other lot-sizing rules with positive inspection.

Analysis of the running times

From Table 3, we can note that the running times of AMPL/CPLEX for solving the original formulation (*OF*) of the ELSRIH are in average 70 s. Since the lot-sizing rules suggested are implemented as restricted version of the ELSRIH original formulation, their running times may be longer. However, only a little increase in the running times is observed for several of the lot-sizing rules, even for some of them we can observe a significant reduction. This is the case of *NoInsp*, *IEP* and *ZIR* as they only involve problems for determining the optimal production plan, and then, easier to solve than the ELSRIH.

Conclusions

In this paper we have addressed the economic lot-sizing problem with remanufacturing, inspection and heterogenous returns (ELSRIH) under stationary cost pattern. The main difference with respect to similar problems considered in the literature, is that we assume that a set-up cost is incurred whenever a positive inspection is carried out in certain period within the planning horizon. In addition, inspected returns are graded into a set of pre-established nominal qualities of either remanufacturable or non-remanufacturable returns, according to a fraction value related to each one of them. We note that the problem considered in this paper is based on a research carried out for a Uruguayan manufacturer of electric water heaters, which are one of the most commonly devices for water heating in many countries around the world [9].

We suggest a MILP formulation and several lot-sizing rules for the ELSRIH. In order to obtain a MILP formulation for the problem we had to face the problem of rounding the non-integer expressions that result from applying the quality level fractions on the number of returns. We analyse the problem, and show that it is NP-hard since it is at least as difficult to solve as the ELSR, i.e. the problem without inspection and with homogenous returns. In addition, we show that under the assumption of low-cost returns, there is an optimal solution for the problem in which inspection is carried out in certain period if and only if a certain recovery type is also carried out. Nine different lot-sizing rules are suggested for the problem, based on different criteria for inspection and

Table 3 Running times in seconds for the original formulation (*OF*) and the lot-sizing rules

	OF	*NoInsp*	*FullInsp*	*I&R*	*IEP*	*ZOU*	*ZIR*	*ZFIR*	*FullRem*	*ZOUR*
AVG	70.20	0.47	74.45	55.22	2.87	65.05	3.36	85.52	72.01	72.79
MIN	0.91	0.21	1.02	1.03	0.39	0.68	0.56	0.97	1.03	0.67
MAX	361.95	1.27	1146.59	368.83	12.02	547.21	26.78	607.05	560.86	678.76

remanufacturing. An extensive numerical experimentation was carried out in order to analyse the lot-sizing rules under different values of returns ratio, set-up cost of inspection and quality level fractions. Considering the results obtained from the numerical experimentation we can draw the following conclusions: (1) it is optimal to inspect and remanufacture in the same period, i.e. inspect as late as possible; (2) a full inspection rule is in general more profitable than a null one; (3) the inspection in certain period should involve all the available returns, and this is also true for the remanufacturing but only for those returns of the same level of quality; and (4) only one remanufacturing type should be carried out in certain period.

Considering the complexity of the problem, it would be interesting to suggest and evaluate time-effective solving procedures for the ELSRIH, such as extending the well-known Silver-Meal heuristic as in [39, 45] or using a metaheuristic approach as in [31, 40] for the ELSR. Whatever the case, the findings of this paper about the form of the optimal solutions and the effective lot-sizing rules can provide a great support. We note that in practice, a hybrid production-remanufacturing system as that to be implemented in Rivomark, include capacity constraints and several final products. Therefore, extend the problem formulation in order to consider more realistic assumptions is also other interesting option for future research.

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Authors' contributions The three authors contributed equally to this paper.

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