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Production and changeover control of textile and PET recycling

Elias El Achkar *,1,2, Nicla Frigerio3,4

Department of Mechanical Engineering, Politecnico di Milano, p.za Leonardo da Vinci, 20156, Milano, Italy

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ABSTRACT

Circular economies have become a strong candidate for addressing environmental challenges by managing end-of-life products to reduce landfill waste. We herewith focus on the recycling of PET from plastic waste and textiles. This paper focuses on recycling PET from plastic waste and textiles and proposes a model for controlling plant operations, emphasizing Quality-Based Changeovers over cleaning to ensure production continuity. This paper also identifies technological and managerial challenges in PET recycling plants as raised in the related literature, such as the need for technology improvement, more effective collection routes and sorting processes, and devoted managerial strategies. Since a relevant industrial need is to manage the changeovers, we develop a model to control the operative management of the plant and to find the feedstock quality to be processed at a given time for profit maximization. A discrete event simulation model is built to represent the behavior of the system under an approximate state-based control policy, i.e. a two-threshold policy. Numerical results and sensitivity analysis highlight the impact of cleaning costs on system behavior, offering insights into optimal operational conditions.

1. Introduction

The demand for sustainable waste management has highlighted PET recycling as vital to circular economies. This paper focuses on providing an overview of PET recycling then delving into the problem of properly controlling production and the changeovers accordingly to feedstock quality. Using a discrete event simulation model, we address the challenges of varying feedstock qualities and propose Quality-Based Changeovers (QBC) to maintain continuous operations and maximize profitability. Our findings emphasize the need for advanced decision-making and provide recommendations to increase operational efficiency of the recycling plant.

Circular Economies (CE) have emerged as a viable approach to address issues demanding environmental awareness and sustainability, and the demand for novel and efficient models and methodologies tailored for circular manufacturing systems is on the rise. Effectively handling products at the end of their life cycle is essential for minimizing landfill waste. One widely discussed strategy involves appropriately managing the value retention of products.

Waste generation has become a huge concern, most notably that of post-consumer-plastic-waste (PCPW) and textile waste with PET content. The manufacturing of plastics is a resource-intensive industry and can lead to resource depletion. From 1950 to 2015, there is a compound annual growth rate of 8.4% in the global production of plastics due to the increase from the production of two metric tons in 1950 to 380 metric tons in 2015 (Geyer et al., 2017). This emphasizes the need to reconsider current waste management systems.

Recycling is an established value retention option (RO). It is defined as *"transforming a product or component into its basic materials or substances and reprocessing them into new materials"* (Ellen Macarthur Foundation, 2023). Its adoption has widely spread, and this is reflected in the increase in reference papers mentioning *recycling* (Okorie et al., 2018). Recycling is characterized by multiple process steps and multiple technologies and faces multiple challenges. The improvement of recycling can be in terms of effectiveness, i.e., enhancing the technological aspect of the process, and efficiency, i.e., enhancing the management of the methods. In this way, the development of circular manufacturing is augmented and this is what is driving this research.

This paper aims (i) to provide a comprehensive view of the challenges related to the operative management of a PET recycling plant through a systematic literature search and (ii) to analyze the problem of controlling a plant operating on two different quality feedstocks. A discrete event simulation (DES) model representing the controlled system is developed so that the response function for a given control

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* Corresponding author.
E-mail addresses: elias.elachkar@polimi.it (E. El Achkar), nicla.frigerio@polimi.it (N. Frigerio).

[1] Ph.D. student at the Department of Mechanical Engineering at the Politecnico di Milano.

[2] ORCID: 0009-0000-3432-9945.

[3] Assistant Professor of Manufacturing and Production Systems at the Department of Mechanical Engineering at the Politecnico di Milano.

[4] ORCID: 0000-0001-8146-9772.

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policy can be estimated. The impact of control parameters is analyzed in a set of scenarios as the control parameters vary.

2. Systematic literature review

In this literature review, the aim is to create a holistic view and understanding of the processes of CE and their complications and advancements. Notably, the ROs mentioned in this work are: *reuse, repurpose, recycle, and recover.* Based on this, a systematic search is performed with the following keywords, i.e., 'PET', 'polyethylene terephthalate', 'recycling', 'feedstock', '*polymerization', 'hydrolysis', 'circular economy', 'textile', 'fiber', combined in five combinations. The search obtains 585 papers, 400 of which are unique, which are then subsequently reduced to 32 publications with relevant content: 20 articles, two editorials, nine reviews, and one conference paper. While all concern PET recycling, 28 publications refer to PCPW and four to textiles. In terms of process, 20 publications refer to mechanical recycling, 20 to chemical recycling, and seven to biological recycling. Additional details related to the type of recycling process and input materials are provided in Table 4.

The following considerations are based on the described search while we report references for the most significant papers. Sections 2.3 and 2.4 respectively provide the identified challenges and the representative schema of virtuous recycling schemes as an output of this analysis.

2.1. Circular economies of plastics & textile wastes

In this section, the relation between the mentioned ROs and their role is explored, in the fields of PCPW and textile wastes.

CE are formed by their respective ROs; therefore, the selection of which RO to perform needs to be discussed. In the area of textile wastes, each of the four previously mentioned ROs is very prominent. The question then becomes, how can one determine which RO to perform? Indeed, key aspects are highlighted in terms of the hierarchy of the CE processes (Piribauer and Bartl, 2019). There is a prioritized rationale for selecting one RO over the other as represented in Fig. 1. In principle, when quality allows, precedence is granted to the higher level in the pyramid.

In the life cycle of PCPW, some ROs have less of an impact than others. Notably, *reuse* has only a few applications while *recycling* is fairly popular in this field. In assessing the performance of ROs, the aim is to promote sustainability and mitigate the adverse impacts of plastic waste generation on the environment. As for recycling, it can be noted that recycling is a step of a model of the stages of waste management (namely collection, sorting, recycling, and disposal), as seen in Nguyen et al. (2022). It is fundamental to analyze the interrelations between different economic sectors and the waste management stages.

A performance enhancement strategy should primarily focus on improving this model. The improvement of the model can be split into two areas. Specifically, on collection and sorting processes since they are essential to efficient recycling and waste reduction, in addition to advancements in recycling technology itself (Nguyen et al., 2022). This approach redefines plastic and textile waste as a valuable resource rather than a disposable substance.

2.2. PET recycling

In this section, the discussion is on the technological aspect of recycling. The idea is to highlight the recycling schemes with their pros and cons. Notably, the most used recycling methods are *chemical, biological, and mechanical recycling.*

Polymer to polymer chemical recycling is a physical and chemical transformation that converts the polymers of waste plastic into monomers and then back into polymers in the form of pellets. Chemical recycling of bottle-grade PET has an overall positive impact on the environment. Therefore, innovation in this field leads to a significant decrease in the manufacture of virgin PET and the high displacement of plastics from landfills and incineration to recycling (Cornago et al., 2021). This innovative recycling processes, that enable the production of virgin-equivalent PET, may lead to an improvement of at least 50% in 12 of the chosen 16 indicators, 75% in nine indicators, and a potential 5% reduction in CO_2 equivalent per kg of bottle-grade PET evaluated via Life Cycle Assessment (LCA) by (Cornago et al., 2021). Note that the chosen indicators are related to atmospheric impacts, impact on aquatic ecosystems, land impacts, ionizing radiation impacts, and human health impacts.

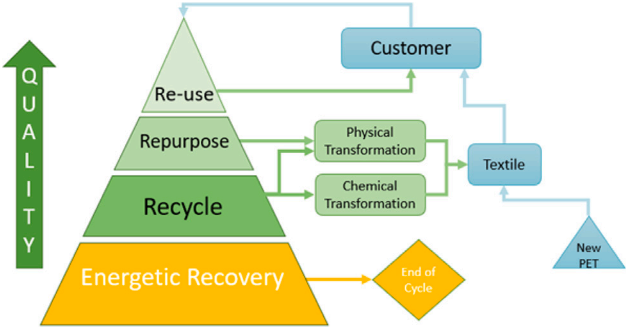

Fig. 1. Hierarchical model of certain retention options found in the textile industry.

Biological recycling relies on enzymes or microorganisms to assist in the decomposition of plastics rather than chemicals. Enzymes accelerate the decomposition of plastics, breaking them down into small molecules that microorganisms can digest. Despite this difference, biological and chemical recycling share the same goals. However, biological recycling is a less adopted technology. Of the 32 papers, biological recycling is referred to in seven, comparatively chemical recycling is referred to in 20. This can be associated with the difficulties inherent in methods that involve living organisms.

Mechanical recycling is melting plastic waste and transforming it into pellets to be reprocessed. Although the most common method, mechanical recycling is usually a downcycling process since it may lead to the detriment of material quality and an increase in losses in the cycle, which goes against CE. Mechanical recycling can become an upcycling process by controlling accurately the quality of the input of the recycling (Pinter et al., 2021). This is shown by studying the effect of multiple cycles of mechanical recycling on a certain amount of plastic on the quality of the PET and the recycled PET (rPET). For example, the results in Pinter et al. (2021) show that the quality of the rPET was not affected after 11 cycles. Nevertheless, quality control is challenging since it is usually done through collection and sorting (material-based and contaminant-based) which can be unreliable. Notably, the importance of collection and sorting is again highlighted.

From a technological point of view, chemical recycling is the most intriguing option of the three. Furthermore, this paper does not focus on improving the technical aspects of recycling but rather is content with highlighting the best scheme that is used for analysis.

2.3. Challenges

In the absence of CE, the Linear Production Model or "take-make-dispose" model is deemed unsustainable because it is reliant on the ongoing production of new products, which results in overconsumption and waste production. Notably, the footprint of plastic waste generation is due to increasing CO_2 emissions, consuming natural resources, and causing climate change. These problems can be exacerbated by a lack of awareness among consumers and their constant desire for new trends and new products. A list of the challenges while addressing the recycling option follows:

- Understanding the actual quality/composition of incoming product waste, Pinter et al. (2021). Indeed, this is an important area of focus, as the example of the quality of input product in mechanical recycling which dictated whether the process results in upcycling or downcycling;
- Properly sort and preprocess incoming products based on their quality/composition, Piribauer and Bartl (2019), Nguyen et al. (2022). This comes as a second phase to the previous point;
- Properly evaluating the value of incoming products or the impact of a certain recycling process on the overall cycle using LCA or Material Flow Analysis (MFA), Eygen et al. (2018);
- Estimating product's remaining value and remaining useful life, and thus obtaining an indicator that can aid in deciding whether efforts should be made to use an RO to cycle the waste or to proceed with direct disposal;
- Designing efficient integrated recycling schemes and tuning them properly when product composition changes. In their article, Nishijima et al. (2012) demonstrate how different recycling schemes can be integrated, with each scheme compensating for the weaknesses of others;
- Managing changeovers between waste types to improve efficiency, Brunaud et al. (2020).The varying waste qualities necessitate changeovers, thereby creating a need for operational control;
- Correctly routing product flows towards the best recycling process, Somoza-Tornos et al. (2021);

Sorting and collection are crucial in the plastic model cycle. However, many cities lack adequate infrastructure and comprehensive recycling plans, making it difficult for consumers to properly sort their waste. Separating various fiber types from one another and contaminants is one of the key issues in recycling. Moreover, assessing the quality of the waste and its potential recyclability is very time-consuming. Preprocessing material adds a step to the system and calls for more work and additional resources. Consequently, the overall cost of recycling may increase as a result of these activities, which frequently require manual work and specialized machinery. Other challenges faced in this field are quality-based changeovers (QBC). QBC are sequence-dependent changeovers that consider the dilution of quality and impurities in the modeling process (Brunaud et al., 2020). They are crucial in batch plants as they allow for the production of multiple products using the same machinery. By producing enough batches of the second product in a row, impurity levels can be reduced, returning the product to the desired quality standards. The idea of QBC is to minimize the use of chemical cleaning products, promoting environmental consciousness and alignment with CE principles. Plastic waste generation is interconnected in multiple areas and is an intricate problem to solve. Understanding the interactions between these industries is necessary for determining the major causes of plastic waste generation.

2.4. Recycling routes

This section provides a representative schema of virtuous recycling routes for PCPW and textile feedstock with PET-content extracted from the literature analysis, as in Fig. 2. The schema is built on the hierarchical model in Fig. 1 and the prioritized ROs are maintained. The highlighted routes are dependent on the used technology, and state the paths of the products after disposal.

ROs and processes are represented in circles: reuse (RU), repurpose (RP), waste collection (CLCT), sorting (SG1: sorting by material, SG2: sorting by quality), mechanical recycling (MR), chemical recycling (CR), biological recycling (BR), and energetic recovery (ER). The landfill branch is represented in red. Light blue empty circles represent manufacturing processes.

Production, selling, and usage are represented as vast clouds (or orbits). Currently, such clouds are heavily PET demanding and are

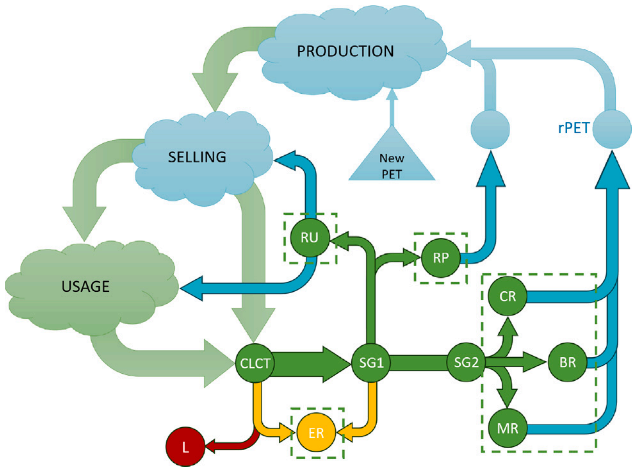

Fig. 2. Circular routes diagram.

saturated with PET-based products so that the flow of products from such clouds is not yet dependent on the rest of the cycle. Thus, the collection point (CLCT) represents a base from which all other routes begin. Afterward, a first sorting (SG1) occurs and routes the flows towards the different ROs, highlighted with dashed squares: energy recovery (ER), reuse/resell (RU), repurpose (RP), and recycling. RU is a process that implies the reuse of the waste without any transformation to the product, and thus is directed towards selling and usage. RP is a process that takes textile waste and repurposes it through a physical transformation by a production stage before selling and usage. On the flow directed towards the recycling options, SG2 serves as a key factor in achieving a more effective routing of products to CR, BR, and MR. The more advanced and reliable SG2 is, the more efficient the recycling can be, resulting in upcycling processes. The recycled material (rPET) is re-inserted in production (blue empty circle).

The proposed schema represents a virtuous flow diagram. However, it is true up to a certain extent. In many cases, the diagram is only partially implemented, featuring select recycling technologies and routes. Commonly, only mechanical recycling is available. In some cases, integrated schemes are used, where technologies are used cooperatively, and high waste efficiency is reached but the routes become very intricate. Nonetheless, the diagram can be considered as a representation of the current state and offers a good compromise between these two extremes.

3. Discussion on the identified problem

Among the challenges brought to light by the literature search, the sorting phase and the changeovers are the most frequently mentioned. Furthermore, from the industrial point of view, the operative management of the plant is critical, including batch sizing, allocation rules, system reconfiguration, and production control.

3.1. Problem description

The system is composed of multiple stages that process and handle feedstock in loads of a given weight. Since the quantity of PET-mass may vary in the feedstock, different quality labels are defined according to the amount of PET present in the feedstock, leading to multiple quality feedstocks simultaneously circulating the system which are stored in dedicated silos (or inventories). The identified problem searches for a balance between costs, number of changeovers, starvation, and blocking.

One of the main peculiarities of the problem is that the chemical recycling process operates on a fixed amount of PET-mass to be obtained as output. Therefore, depending on the quality, the reactor is loaded with a different amount of feedstock to obtain a certain nominal quantity of rPET. Since lower-quality feedstock requires a larger load, processing low-quality materials takes more time and is more costly. Therefore, the total production cost depends on the feedstock quality, whereas the revenue remains unaffected by the quality labels.

The first stage sorts the incoming feedstock and provides the quality label. However, the sorting might be unreliable so the quality label may change along the stages. The highest quality is always favored but it is also less frequent. To avoid starvation of the reactor and blockages along the system, the production of all quality feedstocks needs to be properly managed. Additionally, changeovers (such as QBC and cleaning) further complicate the problem. These changeovers are necessary to process different qualities of feedstocks sequentially and incur significant costs. Specifically, QBC adds an extra challenge since it requires a certain number of batches to dilute the remainder of the previous batch of a different type. Lastly, plant stages operate with different schedules: the manual processes do not operate continuously whereas the chemical recycling works in a semi-batch continuous manner.

The remaining work focuses on the production control problem of choosing which product variant or quality to produce at a given time in a chemical recycling plant to maximize profit.

3.2. Background on other approaches

To the authors' knowledge, the scientific literature does not analyze the described problem and does not focus on recycling plants. Nevertheless, relevant approaches are described as follows:

Markov Decision Process (MDP) models can be used to find optimal state-based control policies. For example, a make-to-stock remanufacturing system is analyzed with MDP to determine the optimal policy to decide whether to fulfill the demand with a new product, to fulfill it with a remanufactured product, or to reject the demand, as seen in Liu and Papier (2022). However, the results obtained are approximate when the problem does not match with MDP assumptions, which is the case for the system under analysis. Also, the paper does not consider changeovers.

Queueing theory is also frequently applied, as in Zhang et al. (2023). The authors model the system under analysis with an M/M/1 queue controlled by threshold policies. The two policies that are optimized are an N-policy and a hysteretic threshold policy. Both policies are based on setting thresholds that, if crossed trigger the required actions, N-policy necessitates one threshold, while a hysteretic policy requires two. The identified problem features production rate changes, setups and setup costs, planning and control, and parameter optimization. As per MDP, the results obtained are approximate when the problem does not match with model assumptions and these queueing models cannot represent the system under analysis.

Analytical models can be developed to represent controlled production systems. As an example, a remanufacturing system is studied in Fathi et al. (2015) with the use of an approximate analytical method. The system handles both manufactured and remanufactured products, the latter returning from two different markets. A threshold-based acceptance policy is optimized to maximize profit. Differently from the system at hand, the approach represents the system as a single stage fed by multiple buffers and does not consider changeovers. Therefore, it cannot be applied to represent the current problem.

4. Problem formulation and assumptions

The system is composed of three sequential stages, namely sorting, preprocessing, and chemical recycling (Fig. 3). The production system is assumed to be always fed feedstock to be recycled, and the obtained rPET is always sold at a price of $\alpha = 1.17$ [\$/kg]. The sorting stage $i = SG$ processes batches with a fixed weight M of feedstock, resulting in two quality feedstocks, i.e., high Q_H and low Q_L, based on the percentage of usable PET content and related contaminants. A batch is assumed to be sorted as Q_H with a given probability, p_H. The preprocessing stage $i = P$ processes batches with a fixed weight M to remove metal parts and shred the feedstock. At stage P, with a probability PDG (Probability to Downgrade), a load that is previously labeled as Q_H at SG can be downgraded to Q_L since the output of SG is not certain and can lead to a wrong assessment. The chemical recycling process stage $i = C$ operates in a semi-batch manner, loading the reactor with loads of feedstock of a given quality. Significant changeovers are required to switch from Q_H to Q_L and vice versa. Two options are available:

1. Cleaning: The process is interrupted and stage C is cleaned so that the traces of Q_L are below the allowable tolerance level, similarly from Q_H to Q_L;
2. Quality Based Changeover (QBC): The process is uninterrupted, and stage C produces QBC_{reps} loads of Q_H with less efficiency until the traces of Q_L are below the allowable tolerance level.

The execution of QBC is the preferable choice in the industry. Thus, we assume QBC is executed unless there is not enough quantity in the input buffers to allow the QBC to happen. In the latter case, cleaning is performed.

Since the reactor in stage C works on loads with a fixed mass of PET m, different quantities of Q_H and Q_L feed stage C. Assume that the mass percentage content of PET in Q_j is $Purity_j$. Stage C is loaded with $m_j = m \cdot \frac{1}{Purity_j}$ of $Q_j | j = H, L$. As the PET content decreases, the quantity of material to load the reactor increases.

Buffers of limited capacity $B_{\max}$ are located between stages and are devoted to a single quality, thus four buffers are included in the system, i.e. $B_{ij} | i = P, C; j = H, L$. The buffer level is denoted with $b_{ij} \in [0, B_{\max}]$.

Stages $i = SG, P$ are mostly manual and work on a single shift (i.e. eight hours, seven days/week), whilst stage C is designed to work without interruptions. The sorting and pre-processing times (T_{SG}, T_P) are assumed to be random variates, and the time to perform chemical process t_c is assumed as deterministic due to the nature of the processes. Note that a list of abbreviation is in Table 3.

4.1. Control policy

The control problem consists of selecting the type of quality to be processed in stages $i = P, C$ at a given time. Because of the complexity of a state-based control policy, an approximated two-threshold-based control policy is used in this work. This policy refers to a policy mechanism that uses two thresholds to manage a system's state; thus a form of "memory" is introduced to the system by using two thresholds for switching in different directions, creating a hysteresis effect.[5] Even though the resulting policy might be myopic, the effectiveness of the control is shown in the remainder of this paper.

In this study, the action is either to produce from high quality $(a_i = Q_H)$ or from low quality $(a_i = Q_L)$ for $i = P, C$. The state variables are the current produced quality at stage i (i.e., q_i) and the buffer level of Q_H at stage i (i.e., b_{iH}), since this product is more profitable. The two-threshold policy is applied for the two stages $i = P, C$ resulting in four control parameters (two thresholds per stage). We define vector $\boldsymbol{u}$ as the vector of control parameters so that the solution of the control problem is encoded in $\boldsymbol{u} = [\lambda_P, \theta_P, \lambda_C, \theta_C]$, where λ_i represents the threshold that triggers the production of Q_H when the observed buffer level b_{iH} rises above this point, while θ_i represents the buffer level that triggers the production of Q_L when the observed value b_{iH} falls below this threshold for their respective stages. The control policy maps the

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[5] An example of two-threshold control policy, or hysteretic control policy, is the temperature control in buildings.

Fig. 3. Conceptual Model Diagram.

Table 1
List of parameters used in the equations and their values.

Parameter	Value
Sorting time [h]	$T_{SG} \sim$ Weib $\mu = 5.56; \sigma = 4.448$
Preprocessing time [h]	$T_P \sim$ Weib $\mu = 5.56; \sigma = 4.448$
Chemical processing time [h] (Q_H)	$t_{c,H} = 1.67$
Chemical processing time [h] (Q_L)	$t_{c,L} = 2.08$
Cleaning time [h]	0.83
C_{id}	0.334
$\%C_{cl}$	0.5
$\%C_S$	10%
$\%C_P$	10%
$\%p_H$	40%

control action $a(q_i, b_{iH})$ at stage $i = P, C$ according to the state variables and the control parameters as follows:

$$a(q_i, b_{iH}) = \begin{cases} Q_H & \text{if } q_i = Q_H \text{ and } b_{iH} \geq \theta_i \\ Q_L & \text{if } q_i = Q_H \text{ and } b_{iH} < \theta_i \\ Q_H & \text{if } q_i = Q_L \text{ and } b_{iH} > \lambda_i \\ Q_L & \text{if } q_i = Q_L \text{ and } b_{iH} \leq \lambda_i \end{cases} \tag{1}$$

If stage i starves of a certain product quality, it is assumed that the production switches to the other available quality.

4.2. *Objective function*

The optimization problem follows:

$$\max_{\boldsymbol{u}} \ \Pi(\boldsymbol{u}) \tag{2}$$

$$\lambda_i > \theta_i \quad \forall i = P, C \tag{3}$$

$$0 \leq \lambda_i \leq B_{\max} \quad \forall i = P, C \tag{4}$$

$$0 \leq \theta_i \leq B_{\max} \quad \forall i = P, C \tag{5}$$

The optimal control $\boldsymbol{u}^* = [\lambda_P^*, \theta_P^*, \lambda_C^*, \theta_C^*]$ solves the provided problem. The domain of the control variables is in Eq. (4) and (5). Additionally, the control feasibility implies $\lambda_i > \theta_i$ as in Eq. (3). The objective function in Eq. (2) is to maximize the profit $\Pi(\boldsymbol{u})$ computed as:

$$\Pi(\boldsymbol{u}) = \#LoadChem \cdot m \cdot \alpha - \sum_k COST_k \tag{6}$$

Since the obtained rPET does not depend on feedstock quality, the production revenue does not depend on Q_j, and the production of Q_H is trivially preferred. Nevertheless, the availability of Q_H is limited, and Q_L must also be processed to avoid blocking of stage SG, P and starvation in stage C. In Eq. (6), four cost factors are considered: the costs of processing the feedstock, i.e., $COST_i | i = SG, P, C$, and the cost of performing cleanings, $COST_{cl}$. Stockout costs and inventory holding costs are assumed to be negligible. In details:

$$COST_C = t_{\text{id}} \cdot \frac{C_{id}}{t_{c,H}} \cdot C_{C,H} + \sum_{k=1}^{\#Load_H} \beta_{Hk} \cdot C_{C,H} + \sum_{k=1}^{\#Load_L} \beta_{Lk} \cdot C_{C,L} \tag{7}$$

$$\beta_{jk} = \begin{cases} QBC_{scaling\,factor} & if\ QBC\ occurs \\ 1 & otherwise \end{cases} \tag{8}$$

$$COST_{SG} = \%C_S \cdot COST_C \tag{9}$$

$$COST_P = \%C_P \cdot COST_C \tag{10}$$

$$COST_{cl} = \#Cleaning \cdot \%C_{cl} \cdot C_{C,H} \tag{11}$$

The cost for the chemical process $COST_C$ in Eq. (7) is composed by the cost of keeping the reactor idle for time t_{id} and the cost of processing the feedstock Q_H and Q_L. For Q_H the unitary cost is $C_{C,H}$ and the unitary cost for Q_L is scaled according to the purity: $C_{C,L} = C_{C,H}/Purity_L$. Coefficients $\beta_{jk} | j = H, L$ are used as scaling factors to increase the cost of the chemical processing as a QBC occurs for the kth load. The reactor experiences a loss in efficiency as the QBC is happening, and this is translated to an increase in cost assumed as 10% (or $QBC_{scaling\,factor} = 1.1$).

The costs of stages SG, P are proportional to $COST_C$, respectively $\%C_S$ for sorting and $\%C_P$ for pre-processing (Eq. (9)–(10)). The cost for performing cleanings is in Eq. (11) where the cost of each cleaning is the proportion $\%C_{cl}$ of $C_{C,H}$.

5. Numerical results

Referring to the description in Section 4, we assume $B_{\max} = 4000$ kg, $p_H = 0.4$, $M = 1000$ kg, $m = 100$ kg, $Purity_H = 1$ and $Purity_L = 0.8$ so that $m_H = 100$ kg and $m_L = 125$ kg. As a consequence, one batch of feedstock translates in 10 and eight loads at stage C for Q_H and Q_L, respectively. The values of other parameters used in the model are given in Table 1 according to the literature and conforming to industrial experience to represent realistic scenarios. A set of 12 scenarios (as seen in Table 2) is designed to explore the control problem with a full factorial design with three factors, namely:

1. $QBC_{reps} \in \{16, 24, 32\}$ [load];
2. $C_{C,H} \in \{65, 75\}$ [\$/load];
3. $PDG \in \{0.03, 0.15\}$.

Factor selection is based on literature, knowledge, and industrial experience.

The complete enumeration of solutions is executed to obtain the response function $\Pi(\boldsymbol{u})$ for each scenario. Also, we computed the number of cleanings $\#C$, the number of $\#QBC$, and the number of changeovers $\#S = \#C + \#QBC$ for each candidate solution $\boldsymbol{u}$. Specifically, each scenarios requires the evaluation of 8200 candidate solutions $\boldsymbol{u}$.

The DES model of the system is implemented in ARENA 2022. After a set of preliminary analyses, the selected simulation length is 1050 days, where each run is replicated 10 times. The warm-up is calculated as 412 h. On a laptop with an Intel Core i7-6500U (2.50 GHz base speed) and 8 GB of RAM, each scenario requires six hours of computation time.

5.1. *Control of the preprocessing*

The results obtained in all evaluated scenarios show that the optimal control parameters for controlling stage $i = P$ are $\lambda_P^* = B_{\max}$ and $\theta_P^* = 0$. Thus, the optimal control indicates to start producing Q_L only when B_{PH} empties (i.e., $b_{PH} = 0$) and to switch to Q_H when B_{PH} is full (i.e., $b_{PH} = B_{\max}$). Additionally, for when $B_{PL} = 0$ a direct switch is triggered to Q_H to avoid starvation. Since optimal for all scenarios, the remaining analysis is reported for the values $\lambda_P^* = B_{\max}$ and $\theta_P^* = 0$.

Table 2
Results obtained as optimal profit $\Pi(\boldsymbol{u}^*)$ per scenario. Additionally, the profit obtained with benchmark policy $u_{bc} = [B_{max}, 0, B_{max}, 0]$ is reported as well as the difference $\Delta = \Pi(\boldsymbol{u}^*) - \Pi(\boldsymbol{u}_{bc})$. Factors characterizing the scenario design, the mean and 95%CI over 10 replications are reported.

Scenario	QBC_{reps} [load]	$C_{C,H}$ [\$/load]	PDG	$\Pi(\boldsymbol{u}^*)$ [\$]		$\Pi(\boldsymbol{u}_{bc})$ [\$]		Δ[\$]
S1	16	65	0.03	345 912.35	±1.38%	341 263.60	±1.02%	1.36%
S2	16	65	0.15	329 372.15	±1.05%	328 009.76	±0.46%	0.42%
S3	16	75	0.03	163 943.42	±1.96%	158 961.09	±2.19%	3.13%
S4	16	75	0.15	147 117.58	±2.34%	145 950.60	±0.99%	0.80%
S5	24	65	0.03	343 844.28	±1.04%	330 873.62	±1.09%	3.92%
S6	24	65	0.15	321 466.65	±1.41%	316 546.55	±1.01%	1.55%
S7	24	75	0.03	161 748.00	±2.21%	146 726.05	±2.47%	10.24%
S8	24	75	0.15	138 841.85	±3.32%	132 678.82	±2.43%	4.65%
S9	32	65	0.03	359 452.78	±0.87%	319 470.13	±1.60%	12.52%
S10	32	65	0.15	339 179.75	±0.91%	307 203.44	±0.81%	10.41%
S11	32	75	0.03	180 589.40	±1.71%	133 942.58	±3.92%	34.83%
S12	32	75	0.15	160 122.45	±1.94%	122 206.10	±2.05%	31.03%

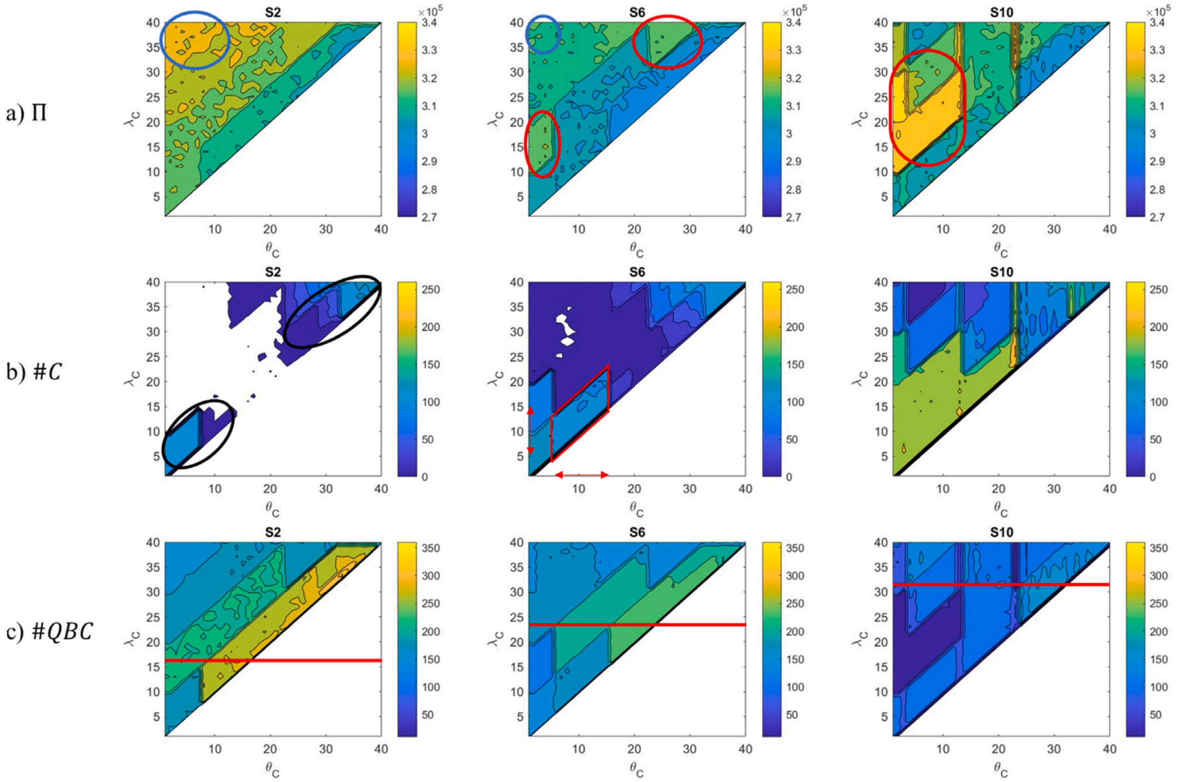

Fig. 4. Contour plots of (a) Π (first row), (b) $\#C$ (second row), and (c) $\#QBC$ (third row) obtained for scenarios S2 (first column), S6 (second column), and S10 (third column). Values are reported for $\lambda_P^* = B_{\max}$, $\theta_P^* = 0$ while varying control parameters θ_C (x-axis) and λ_C (y-axis). The mean over 10 replications is reported.

5.2. Control of the chemical recycling

The results obtained show that the shape of the response function varies according to the scenario and the optimal control parameters λ_C^* and θ_C^* depend on the specific scenario (there might also be multiple equivalent solutions). Fig. 4 provides the results obtained and includes nine sub-graphs: S2, S6, S10 by column and profit $\Pi(\boldsymbol{u})$, the number of cleanings $\#C$, and the number of $\#QBC$) by row. S2, S6 and S10 are selected as representatives of the overall design of experiments. Each graph is the contour plots reported for $\lambda_P^* = B_{\max}$, $\theta_P^* = 0$ and for all combinations of the control parameters of stage $i = C$ with the x-axis representing θ_C and the y-axis representing λ_C. A behavior and area analysis is performed to characterize the optimal areas.

5.2.1. Behavior analysis

Shape of the graphs: The contours are only present on the top half of the graph. This is due to the constraint $\lambda_i > \theta_i$ that limits the feasible solutions to everything strictly above the $\lambda_C = \theta_C$ line. All scenarios show parallel diagonal lines in the response functions. This feature is related to the discretization of entities of mass M in stage P to entities of mass m in stage C, leading to different amounts of feedstock processed at each stage, with one batch from stage P equaling M/m loads from stage C. Such discretization appears in Fig. 4.a-S6, where a parallelogram is highlighted in red.

Total number of changeovers: The number of changeovers $\#S$ for all scenarios trivially increases with the decrease in the difference $\lambda_C - \theta_C$, i.e., $\#S$ is the highest along the lines parallel and close to the first bisector of the graph. Consequently, the closer the thresholds are to each other the higher the frequency of changeovers, and thus an area where $\#S$ is minimal is at the top left of the graphs.

The number of Cleaning: The two changeover options are significantly affecting the profit. Cleaning is performed whenever the amount of feedstock does not allow QBC to happen. This situation occurs frequently, i.e., $\#C$ is high, in two cases. The first case is depicted in Fig. 4.(b)-S2 in the bottom left area circled in black (also note the red line is reported in Fig. 4.c-S2 for $\lambda_C = QBC_{reps}$) and occurs when $\lambda_C < QBC_{reps}$. Examining the policy, specifically at the higher threshold λ_C, reveals that a changeover is selected when $b_{iH} > \lambda_C$, resulting in

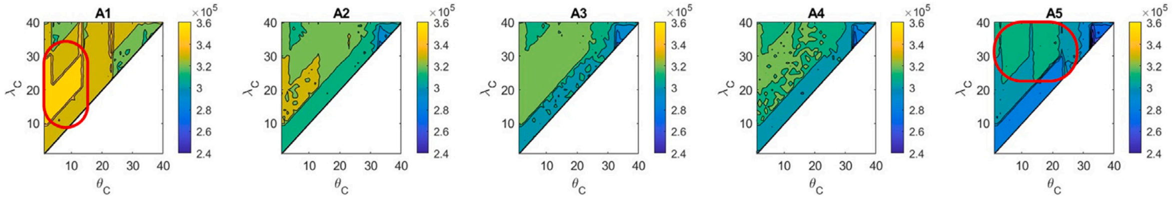

Fig. 5. Contour plots of the profit $\Pi(\boldsymbol{u})$ for λ_P^* and θ_P^* while varying control parameters λ_C (x-axis) and θ_C (y-axis). The five graphs represent results obtained in scenarios A1 to A5. The mean over 10 replication is reported.

$b_{iH} < QBC_{reps}$, and consequently $B_{C,H}$ does not have enough material to perform QBC when transitioning from Q_L to Q_H. The second case is when $\lambda_C - \theta_C$ is small with too frequent changeovers and the policy does not allow B_{CL} to accumulate enough Q_L for a QBC while switching from Q_H to Q_L, as seen in the top right area circled in black Fig. 4.(b)-S2. As QBC_{reps} increases, the two identified areas expand and merge (Fig. 4.(b)-S6-S10).

The number of QBC: From Fig. 4.c, the $\#QBC$ increases with the increase of λ_C and θ_C, and the decrease of $\lambda_C - \theta_C$ (Fig. 4.c)-S2 yellow contours). The red horizontal line reported in Fig. 4.c for $\lambda_C = QBC_{reps}$ is a feature for all scenarios and the area below such a line represents a combination of control parameters where QBC is prevented from Q_L to Q_H and cleaning is executed. Indeed, the $\#QBC$ shows complementary behavior with respect to the $\#C$.

5.2.2. Optimization zones

The results obtained in the analyzed scenarios show two areas of optimality with equivalent solutions for the control policy. The *primary area* corresponds to the trivial control policy of producing Q_L only when B_{CH} empties, i.e., $\lambda_C = B_{\max}$ and $\theta_C = 0$. This policy coincides with a minimal $\#S$. The *primary area* is optimal in S2 (circled in blue in Fig. 4.a) where QBC_{reps} is low. The *secondary area* is optimal in S10 (circled in red in Fig. 4.a). Such a non-trivial location of the control policy indicates that reducing the total number of changeovers (having $\#S$ minimal) is not optimal, whereas the optimal policy should find a balance between cleaning and QBC costs. When the cost of performing $\#QBC$ increases because of the increased QBC_{reps}, cleaning is more advantageous, and it should be preferred to QBC. The intermediate scenario S6 has multiple clusters of equivalent solutions. The change in locations of the optimal area coincides with the increase of the QBC_{reps}, thus the *primary area* diminishes and the *secondary area* becomes more prominent. This highlights the impact of the changeover options and costs.

5.3. Optimality and sensitivity analysis

Table 2 includes the optimal profit $\Pi(\boldsymbol{u}^*)$ obtained in scenarios S1-S12. Additionally, the table includes the comparison between the profit obtained with the optimal control $\boldsymbol{u}^*$ and the profit obtained with the trivial policy $\boldsymbol{u} = [B_{max}, 0, B_{max}, 0]$ to highlight the need of properly selected the control policy, above all when QBC is significant (S9-S12).

An ANOVA analysis is made to evaluate the significance of the design parameters over the optimal solution $\boldsymbol{u}^*$. The results showed that all the factors are significant with a p-value < 0.001 and that interactions are not significant. A multi-comparison test is made to find the scenario reaching the highest profit, which is S9 with $QBC_{reps} = 32$, $CPC_H = 65$, and $PDG = 0.03$. Thus, to have a low cost $C_{C,H}$ is a trivial result as to have a low PDG: the better the mix is sorted, the lower PDG and the better the operation of the overall system. The finding that a high QBC_{reps} contributes to higher profits is non-trivial. Although increasing the number of QBC repetitions can lead to higher changeover costs, the results imply that the benefits of multiple repetitions outweigh these costs, likely due to the decrease in overall changeovers required.

Table 3
List of abbreviations and their meaning.

Abbreviations	Meaning
QBC	Quality Based Changeovers
PET	Polyethylene Terephthalate
rPET	Recycled Polyethylene Terephthalate
PDG	Probability to Downgrade
Q_H	Quality feedstock High
Q_L	Quality feedstock Low
$C_{C,H}$	Unitary cost for Q_H
QBC_{reps}	Number of loads required to perform a QBC
SG	Sorting Stage
P	Preprocessing Stage
C	Chemical recycling Stage
$[\lambda_C, \theta_C]$	Thresholds of the policy at stage C
$[\lambda_P, \theta_P]$	Thresholds of the policy at stage P
Weib	Weibull Distribution

As discussed in Section 5.2.2, when there exists a non-trivial solution of the control policy, the optimal location is related to the cleaning and QBC costs and the balance between them. Therefore, a sensitivity analysis is performed to further study the impact of the cleaning cost. New scenarios A1 to A5 are design as variations of S9 with increased cleaning cost. Specifically, $QBC_{reps} = 32$ [load], $C_{C,H} = 65$ [\$/load], $PDG = 0.03$ and the cleaning coefficient $\%C_{cl}$ is respectively 0.5, 2.5, 3, 3.5, and 5 for A1, A2, A3, A4 and A5. Results are in Fig. 5. It can be noted that: As the QBC becomes the cheaper option (from left to right), the optimal control migrates from the *secondary area* (A1) to a new *secondary area* (A5), where switches are performed mostly with QBC. In an intermediate situation (A3) where the costs of the two options are about the same, the optimal control is in the *primary area*.

6. Conclusions and future developments

This work explores the recycling of materials from products at their end-of-life, one of the key value retention options in circular economies. It provides insights into production control in PET recycling plants. Key findings include the development of a model that uses QBC to maintain production continuity and optimize performance, decision-making strategies for product variant selection, and system reconfiguration based on feedstock quality. The discrete event simulation highlighted the balance between cleaning costs and QBC for maximizing profitability. The implications of this study shows that QBC may enhance production efficiency, improved sorting and preprocessing lead to better recycling rates, and properly selecting the feedstock quality boosts system performance.

Numerical results show that there exists a non-trivial control that significantly affects the profit. This policy is also greatly affected by the properties of the system. Indeed, the ANOVA analysis shows that the level of the QBC_{reps} that maximizes the profit is counterintuitive. Also, two areas of optimality have been identified and described, as system parameters may vary. The primary area is located where the overall number of changeovers is minimal; the *secondary area* migrates according to the cost of changeover options, i.e., cleaning and QBC.

Table 4
Categorization of the articles found in the literature search.

Article	Mechanical recycling	Chemical recycling	Biological recycling	PCPW	Textiles
Gironi and Piemonte (2011)	x			x	
Carniel et al. (2021)	x	x		x	
Nishijima et al. (2012)	x	x		x	
Kim et al. (2022)			x	x	
Pellis et al. (2023)	x		x	x	
Beghetto et al. (2023)	x	x		x	
Cornago et al. (2021)	x	x		x	
Hossain et al. (2022)	x	x	x	x	
Chea et al. (2023)	x	x		x	
Singh et al. (2021)	x	x	x	x	
Hidalgo-Crespo et al. (2022)				x	
Kumar et al. (2021)				x	
Welle (2011)	x	x		x	
Millette et al. (2019)				x	
Jang et al. (2020)	x	x		x	
Lonca et al. (2020)				x	
Somoza-Tornos et al. (2021)	x	x		x	
Kasmi et al. (2023)	x	x		x	
Lee et al. (2023)		x			x
Mastellone et al. (2017)				x	
Eygen et al. (2018)	x	x		x	
Antonopoulos et al. (2021)	x	x		x	
Tiso et al. (2021)	x	x	x	x	
Lu et al. (2022)		x		x	
Uekert et al. (2022)	x	x	x	x	
Datta and Kopczyńska (2016)	x	x		x	
Haupt et al. (2017)				x	
Velis (2018)					x
Piribauer and Bartl (2019)	x	x	x		x
Papamichael et al. (2023)		x			x
Pinter et al. (2021)	x			x	
Nguyen et al. (2022)				x	

Practitioners are encouraged to adopt more efficient changeover strategies to boost their plant's profitability and efficiency. The paper's findings highlight the importance of balancing cleaning costs with QBC to maximize profits, offering a clear pathway for operational improvements.

Future research should focus on developing efficient optimization algorithms, developing state-based control policies, and exploring diverse quality feedstocks to further enhance recycling operations. Additionally, future efforts will be devoted to incorporating the dynamic selection of the changeover option (cleaning or QBC) into the model. The mentioned future efforts offer a great opportunity to delve into what this field has to offer.

CRediT authorship contribution statement

Elias El Achkar: Writing – original draft, Supervision. **Nicla Frigerio:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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