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► To cite this version:

Elodie Suzanne, Nabil Absi, Valeria Borodin. Towards circular economy in production planning: Challenges and Opportunities. *European Journal of Operational Research*, 2020, 10.1016/j.ejor.2020.04.043 . emse-02276514v1

HAL Id: emse-02276514

<https://hal-emse.ccsd.cnrs.fr/emse-02276514v1>

Submitted on 2 Sep 2019 (v1), last revised 29 Jun 2020 (v2)

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Toward circular economy in production planning: Challenges and Opportunities

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CMP – SITE GEORGES CHARPAK
CENTRE MICROELECTRONIQUE DE PROVENCE

April 2019

Working Paper EMSE CMP–SFL 2019/01

In the actual era of the international trade, global warming and depletion of Earth natural resources, the willingness to generate sustainable and competitive benefits determines us to stop thinking linearly (produce, consume and dispose) and to shift toward a circular approach by closing material loops. This last way of thinking falls within the concept of circular economy that, in turn, derives from reverse logistics. This paper proposes a comprehensive state-of-the-art around the circular economy and reverse logistics with a particular focus on mid-term production planning. The broad spectrum of reviewed publications is categorized and discussed with respect to the main recovery operations, namely: (i) disassembly for recycling, (ii) from product to raw material recycling, and (iii) by-products and co-production. For each of aforementioned recovery options, this paper elucidates the related definitions, reviews the mathematical formulations jointly with a structured overview of the solution methods, and discusses their industrial implications. Given the legislative pressure to mitigate environmental impacts caused by production operations, a special attention is paid to the greenhouse gas emissions and energy consumption. Finally, gaps in the literature are identified and future research opportunities are suggested.



Toward Circular Economy in Production Planning: Challenges and Opportunities

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Abstract

In the actual era of the international trade, global warming and depletion of Earth natural resources, the willingness to generate sustainable and competitive benefits determines us to stop thinking *linearly* (produce, consume and dispose) and to shift toward a *circular* approach by closing material loops. This last way of thinking falls within the concept of *circular economy* that, in turn, derives from *reverse logistics*. This paper proposes a comprehensive state-of-the-art around the topic of circular economy and reverse logistics with a particular focus on mid-term production planning. The broad spectrum of reviewed publications is categorized and discussed with respect to the main recovery operations, namely: (i) disassembly for recycling, (ii) from product to raw material recycling, and (iii) by-products and co-production. For each of aforementioned recovery options, this paper elucidates the related definitions, reviews the mathematical formulations jointly with a structured overview of the solution methods, and discusses their industrial implications. Given the legislative pressure to mitigate environmental impacts caused by production processes, a special attention is paid to the greenhouse gas emissions and energy consumption. Finally, gaps in the literature are identified and future research opportunities are suggested.

Keywords: Literature review, Circular economy, Reverse logistics, Operations Research, Production planning, Lot-sizing

1. Introduction

During the last decade, the expression *circular economy* experiences an increasing interest, particularly with the advent of environmental regulations around the world, including: in Europe, the Waste Framework Directive¹ (2008); in USA, the Enactment of the Resource Conservation and Recovery Act² (1984) and the Pollution Prevention Act³ (amended in 2002); in China, the Circular Economy Promotion Law⁴ (2008); in Japan, the Law for establishing a Material Cycles Society⁵; in Vietnam, the Environmental Protection Law⁶ (2005); in Korea, the Waste Control Act⁷ (amended in 2007) and the Act on Promotion of Resources Saving and Recycling⁸ (amended in 2008). A side effect of the rising popularity of the concept of circular economy among political, industrial and academic communities, is the lack of consistency around its definition and scope of action. Research streams originating from different scientific disciplines gave rise to various schools of thoughts of the circular economy. Among those adopted in production and operations management, let us mention e.g.: cradle-to-cradle (Kumar and Putnam, 2008; Baki et al., 2014), industrial ecology (Genovese et al., 2017).

Several academic efforts have been specially dedicated to clarifying and conceptualizing the term of *circular economy* (Kirchherr et al., 2017; Reike et al., 2018; Homrich et al., 2018). Although the expression *circular economy* still remains open, various definitions coexist. Based on the related state-of-the-art reviews, let us define the term of circular economy as follows:

Definition 1 (Homrich et al. (2018); Reike et al. (2018)). *The circular economy is an economic system that emerges to oppose the linear open-ended system (produce, consume, dispose), with the aim to accomplish sustainable development, simultaneously creating environmental quality, economic prosperity and social equity to the benefit of current and future generations.*

Aware of the business opportunities that the circular economy can procure, the European Commission makes significant efforts to support the transition to a more sustainable, low carbon, resource efficient and competitive economy. In this spirit, institutions such as the Scottish Institute for Remanufacture⁹ (United Kingdom) and the Institut de l'Économie Circulaire¹⁰ (France), have been created to help industrial actors adopting this concept in their production and supply chains.

Accordingly, to go further and in order to foster the generation of sustainable and competitive benefits, governments definitely want to stop thinking linearly for shifting toward a circular approach by: (i) eco-designing products, (ii) waste preventing, reusing and recovering, (iii) exploiting renewable energy resources. Falling within the circular economy, this way of thinking derives from the concept of *reverse logistics*, which is defined by the American Reverse Logistics Executive Council as: “the process of planning, implementing, and controlling the efficient, cost effective flow of raw materials, in-process inventory, finished goods and related information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal” (Rogers et al., 1999). Built on the three pillars of the sustainable development (namely, economic, environmental and societal), the ultimate goal of the adopted series of measures aims at reaching zero waste and extracting zero raw materials, by ranging from legislation to financial levers.

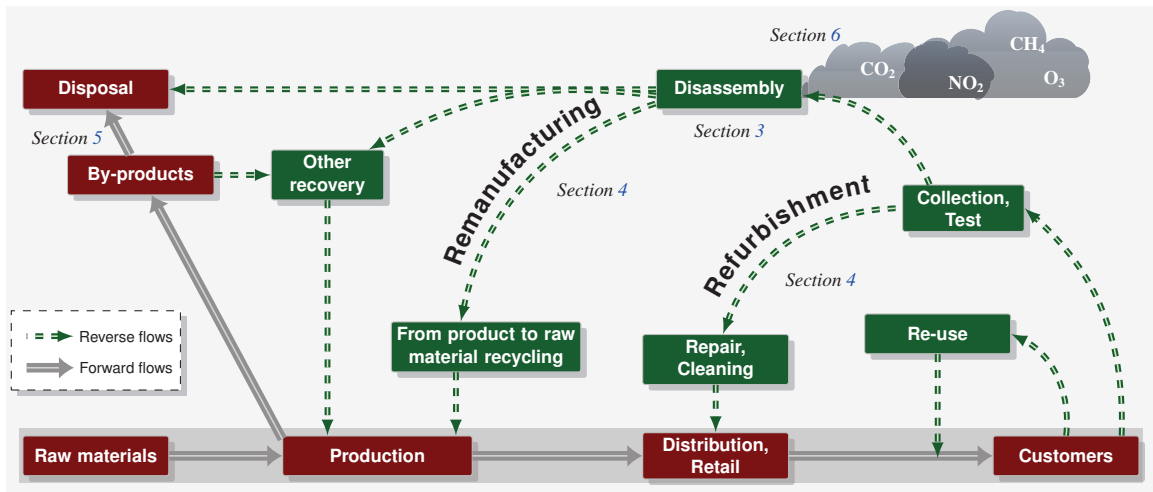


Figure 1: Reverse logistics: An overview

Since production processes have a high impact throughout a product life on supply, resource use and waste generation, let us distinguish four main topics dealing with the circular economy and delimit their scope in accordance with the reviewed papers:

- **Reverse logistics and waste management** refer to all environment-friendly operations related to the reuse of products and raw materials. For example, the European Commission established an order of priority of recovery operations (so-called *five step waste hierarchy*), starting with the preferred option of waste prevention, followed by preparing waste for reuse, recycling and other recovery (i.e. backfilling), with disposal (i.e. landfilling) as the last resort.

After its prevention, the reuse of waste is the next most desirable option in the hierarchy of waste management options, specified in the framework of the European Commission legislation. Reuse represents the using again without any structural changes of products that are not waste for the original purpose. This operation may require collection, but negligible or no processing. Reused products are generally sold in peer-to-peer, without any repairs or tests.

- **From product to raw material recycling:** Under Article 3 of the Waste Framework Directive¹, *recycling* means: “any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes”. In the literature, recycling options can be encountered under different terms, like reconditioning, repurposing, refurbishment, remanufacturing. By tending to superpose each other in their meaning, the definitions of these trending concepts are blurring and blending.

In production planning literature, two recycling terms stand mainly out, namely refurbishment and remanufacturing. *Refurbishment* emerges as a recovery process, by which waste are collected, tested, repaired, cleaned and resold as used products in working order, without having been disassembled. Refurbished products are often put back under warranty.

Meanwhile, *remanufacturing* is most frequently identified as a recovery operation of used products, including collection, repairing, disassembly and replacing of worn components for rebuilding products to the quality level of a newly manufactured ones. The main particularity of remanufacturing resides in product disassembly, the first and most important step in the markets for spare parts or re-processing operations in production.

- **Co- and by-products:** The notions of by-products and co-products recently emerge in supply chain optimization problems. Being of similar importance as a main product, *co-products* are generated together with a main product and have their own demand, whereas *by-products* are usually unexpected products issued from a manufacturing process and have less economic value than controllable production outputs.
- **Sustainability, greenhouse gas emissions and energy consumption:** Until not long ago, some researchers start to think about reducing greenhouse gases, by considering the carbon emissions generated during the production, transportation and remanufacturing operations in their models.

By superposing and cross-analyzing the different definitions of the same notions encountered in the literature, Figure 1 summarizes the industrial processes related to the circular economy and exhibits the links between them (see e.g. Govindan and Soleimani (2017); Kumar and Putnam (2008); Soleimani and Govindan (2014); Srivastava (2008); Thierry et al. (1995)).

Being written in the complementarity of the existing related surveys (see e.g. Ilgin and Gupta (2010); Subramoniam et al. (2009); Govindan and Soleimani (2017)), this paper puts the spotlight on production planning viewed through the prism of the circular economy. It seeks mainly: (i) to offer a representative overview of the predominant research and application topics/problems, (ii) to provide an unequivocal taxonomy and definitions of inherent industrial processes, and (iii) to discuss the findings of the reviewed studies, and (iv) to derive a number of gaps and avenues for future research.

2. Review methodology

Material collection. This literature review covers 122 papers, which reveal together the circular economy challenges and opportunities in mid-term production planning. Relevant material collection has been performed in several steps:

- In accordance with the scope of this review, we identified two sets of keywords, as indicated in Table 1. The first set corresponds to the keywords related to production planning, while the second one refers to the circular economy.
- All of 14 possible combinations of keywords from the first and second set have been applied to query Scopus database and Google Scholar.
- In the next stage, we checked the complete reference lists of all previously retrieved papers to identify relevant articles that cited them. After having removed conference papers, working papers and articles deemed out of scope, we reached a total of 89 papers distributed per topic as follows: 25 papers on *disassembly*, 40 papers on *remanufacturing*, 10 papers on *by-products* and/or *co-production*, 11 papers about *greenhouse gas emissions* and *carbon emissions*, and 7 papers on *energy*.
- In order to suitably contextualize the findings derived from the collection of 89 Operations Research oriented papers, we added 33 transdisciplinary general-purpose papers.

Table 1: Keywords used in the literature search procedure

Keywords related to <i>production planning</i>	Keywords related to <i>circular economy</i>
1. Production planning	1. Disassembly
2. Lot-sizing	2. Remanufacturing
	3. By-product/byproduct
	4. Co-production/co-product/coproduit
	5. Carbon emissions
	6. Greenhouse gas emission
	7. Energy

Although many additional research efforts deserved consideration, we believe that the selected list of contributions offers a comprehensive state-of-the-art on production planning systems, which take into account the hot aspects of the circular economy.

Literature classification framework. A mid-term production planning decision support assists managers/firms in deciding how much and when (i) to produce and order new goods, (ii) to (dis-)assemble, and (iii) to (re-)manufacture. Apart from the option of preparing waste for re-use, three other loops support the circulation of production flows in industrial systems without entering the environment via the recovery of: products, materials and production residues, respectively (see Figure 1).

Table 2: Disassembly lot-sizing

Cap: Capacitated, D: Deterministic, ND: Nondeterministic, Ex: Exact, App: Approximate, Sol: Solver, R/B: Random or Benchmark, I: Industrial, G: Generic

Authors	Partial disassembly	Multiple products	Common parts	Multi-level demand	Cap	Type		Resolution			Instance		Application area
						D	ND	Ex	App	Sol	R/B	I	
Gupta and Taleb (1994)	✓					✓		✓			✓		G
Taleb et al. (1997)	✓		✓			✓			✓		✓		G
Taleb and Gupta (1997)	✓	✓	✓			✓			✓		✓		G
Neuendorf et al. (2001)	✓		✓			✓			✓		✓		G
Lee et al. (2002)	✓		✓		✓	✓				✓		✓	inkjet printers
Kim et al. (2003)	✓	✓	✓			✓			✓		✓		G
Lee and Xirouchakis (2004)	✓		✓			✓			✓		✓		G
Lee et al. (2004)	✓	✓	✓			✓				✓	✓		G
Kim et al. (2006a)	✓		✓		✓	✓			✓		✓		G
Kim et al. (2006c)	✓		✓		✓	✓			✓		✓		G
Kim et al. (2006b)	✓	✓	✓			✓			✓		✓		G
Langella (2007)	✓	✓	✓			✓			✓		✓		G
Qu and Williams (2008)		✓			✓	✓				✓	✓		automotive
Kim et al. (2009)	✓					✓		✓			✓		G
Barba-Gutiérrez and Adenso-Díaz (2009)	✓						✓		✓		✓		G
Kim and Xirouchakis (2010)		✓			✓	✓	✓		✓		✓		G
Prakash et al. (2012)	✓		✓			✓			✓		✓		G
Han et al. (2013b)					✓	✓				✓	✓		G
Sung and Jeong (2014)	✓				✓	✓			✓		✓		G
Ji et al. (2016)		✓	✓		✓	✓			✓	✓	✓	✓	valve factory
Fang et al. (2017a)		✓	✓		✓	✓	✓		✓		✓	✓	iron and stell
Habibi et al. (2017)					✓	✓				✓	✓		G
Tian and Zhang (2018)		✓			✓	✓			✓		✓		G
Liu and Zhang (2018)					✓	✓	✓		✓		✓	✓	valve factory
Kim et al. (2018)	✓	✓	✓	✓		✓			✓		✓		G

The reviewed publications are categorized and discussed with respect to these three recovery loops, namely: **(i)** disassembly for recycling in Section 3, **(ii)** from product to material recovery in Section 4, and, respectively, **(iii)** by-products and co-production in Section 5. To go further than these reverse logistics processes, Section 6 takes interest in the implications resulting from the consideration of greenhouse gas emissions and energy consumption in the production planning process.

Each of these sections: presents the context of the topic under study, elucidates the related definitions, reviews the mathematical formulations jointly with a structured overview of solution methods, and discusses the industrial implications. Section 7 consolidates the findings of this state-of-the-art and derives a number of opportunities for future research based on the identified gaps. Finally, Section 8 concludes this review paper.

3. Disassembly for recycling

The first crucial step in most processing operations of end-of-life/use products is disassembly. Allowing a selective retrieving of desired parts or components, it truly belongs to the area of environmentally conscious manufacturing and product recovery (Ilgin and Gupta, 2010). Disassembly appears in different recycling options (from product to raw material recycling), which results in planning problems with particular specifications.

From an engineering point of view, *disassembly* can be defined as a systematic and selective process of separating an item into components, subassemblies or other groupings (Ilgin and Gupta, 2010). Within the realm of operations management, quantitative disassembly problems can be classified into four generic types of problems:

- **Disassembly-to-order** (also called *disassembly leveling*): Determine the lot size of a mix of different types of end-of-life/use products to be disassembled for satisfying the demand of parts or components (see e.g. Kim et al. (2009, 2018)). Two optimization criteria are mainly considered in the literature, either minimizing the number of products to be disassembled, or the sum of costs related to the disassembly process. End-of-life/use products can have parts in common. The *parts commonality* means that products or subassemblies share their parts or components.
- **Disassembly lot-sizing** (also called *disassembly scheduling*): For a given disassembly structure, schedule the quantity of disassembling end-of-life/use products and their components in each period of a planning horizon in order to meet the demand of their parts or components (see e.g. Barba-Gutiérrez et al. (2008); Kim et al. (2009)). The considered optimization criterion seeks commonly to minimize the sum of a combination of costs: setup, penalty, overload, lost sales and inventory holding. Note that disassembly scheduling includes a timing of disassembling, unlike disassembly-to-order.

- **Disassembly sequencing:** Find the best order of disassembly operations, while optimizing the costs related to the life-cycle of the end-of-life/use products (see e.g. [Han et al. \(2013a\)](#); [Lambert \(2003\)](#)).
- **Disassembly line balancing:** Assign disassembly tasks to qualified workstations, while respecting the precedence relations. The objective usually aims at minimizing the number of workstations, the idle time of workstations, the cycle time, etc. or a combination of these parameters (see e.g. [Kalaycilar et al. \(2016\)](#)).

For comprehensive reviews on disassembly systems in their broad application, the interested reader is referred to [Lambert \(2003\)](#); [Kim et al. \(2007\)](#); [Ilgin and Gupta \(2010\)](#).

3.1. Mathematical formulations

Two classes of problems revolve around production planning in disassembly systems, namely disassembly-to-order and disassembly lot-sizing. Table 2 analyzes the identified papers focusing particularly on the class of disassembly scheduling problems, which can allow:

Distinct structure and number of product types. Both cases of single and multiple product types have been addressed in the literature (see Table 2). Note that it is not so much the number of product types, but rather their structure which increases the problem complexity. Two product structures can be distinguished: **(i) assembly type**, where each child item has at most one parent, i.e. a given product type does not allow parts commonality (see Figure 2(a)), and **(ii) general type**, otherwise (see Figure 2(b)).

With or without parts commonality. Owing to interdependencies among different parts or components of end-of-life/use products, disassembly lot-sizing problem with parts commonality becomes more complex. Both versions with or without parts commonality have been addressed in the literature for a single or multiple product types (see Table 2).

Multi-level demand. Relatively little research addresses problems which integrate both disassembly-to-order and scheduling decisions ([Kang et al., 2012](#); [Kim et al., 2018](#)). These two interrelated problems are separately treated in the literature.

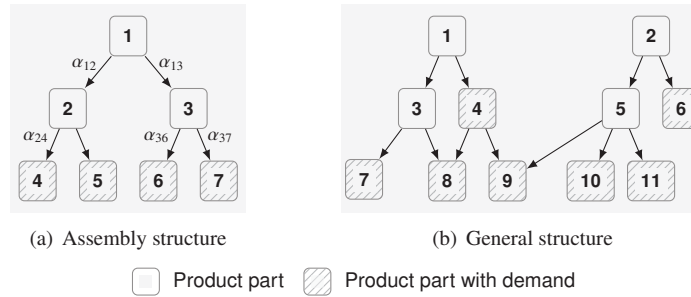


Figure 2: Disassembly Bill Of Materials (d-BOM), where α_{ij} is the quantity of part j obtained from one unit of its parent i , $i \in \{1, 2\}$, $j \in \{2, 3, \dots, 11\}$.

Partial or complete disassembly. No information about parent-child matching between items is required in complete disassembly setting, the root-leaf relationship being sufficient (see e.g. [Kim et al. \(2007\)](#); [Habibi et al. \(2017\)](#); [Liu and Zhang \(2018\)](#)). Against the complete disassembly planning, partial disassembly setting involves mainly two questions: **(i)** to what depth the products have to be disassembled in each period of time horizon?, and **(ii)** in the case with parts commonality, which disassembly sequence has to be performed?

Capacited or uncapacitated. Similar to production planning problems in assembly systems, the resource capacity constraint is an important consideration due to its industrial soundness. As Table 2 witnesses, both uncapacitated and capacitated disassembly lot-sizing problems are treated in the recent literature.

Consider a given disassembly Bill Of Materials (d-BOM) with an assembly structure as illustrated in Figure 2(a). All items are numbered level by level: $1, 2, \dots, \ell, \ell + 1, \dots, n$, where 1 represents the root index and ℓ is the index of the first leaf item. All indices greater or equal to ℓ correspond to leaf parts. The disassembly of one unit of parent i results in α_{ij} units of part j . Denote in parentheses (i) the parent of a part i .

For this basic d-BOM, [Kim et al. \(2007\)](#) formalized a generic version of the disassembly lot-sizing problem which aims: to determine the disassembly quantity and timing X_{it} of all parents i ($\forall i < \ell$) in order to meet the demand of leaf

parts d_j ($\forall j \geq \ell$) over a planning time horizon $1, 2, \dots, T$. Let the objective function be cost-based and include two costs unrelated to disassembly timing. A fixed setup cost f_i is required if any disassembly operation of part $i < \ell$ is performed in period t . This condition is verified via the indicator variables Y_{it} , $\forall t \in \llbracket 1, T \rrbracket, \forall i \in \llbracket 1, \ell - 1 \rrbracket$.

In order to satisfy the demand of leaf-items, partial disassembly is allowed during the planning horizon. An inventory holding cost h_i is thus incurred, when I_{it} parts of type i are stored from period t to period $t + 1$ to meet future demands, $\forall t \in \llbracket 1, T \rrbracket, \forall i \in \llbracket 2, N \rrbracket$. The available quantity of the root-item is supposed unlimited. A generic version of the disassembly lot-sizing problem is given below:

$$\min \sum_{t=1}^T \left[\sum_{i=1}^{\ell-1} f_i Y_{it} + \sum_{i=2}^N h_i I_{it} \right] \quad (1)$$

s.t.

$$I_{i,t-1} + \alpha_{(i),i} X_{(i),t} = I_{it} + d_{it} \quad \forall t \in \llbracket 1, T \rrbracket, \forall i \in \llbracket \ell, N \rrbracket \quad (2)$$

$$I_{i,t-1} + \alpha_{(i),i} X_{(i),t} = I_{it} + X_{it} \quad \forall t \in \llbracket 1, T \rrbracket, \forall i \in \llbracket 2, \ell - 1 \rrbracket \quad (3)$$

$$I_{i,0} = 0 \quad \forall i \in \llbracket 2, N \rrbracket \quad (4)$$

$$X_{it} \leq M Y_{it} \quad \forall t \in \llbracket 1, T \rrbracket, \forall i \in \llbracket 1, \ell - 1 \rrbracket \quad (5)$$

$$I_{it} \geq 0 \quad \forall t \in \llbracket 1, T \rrbracket, \forall i \in \llbracket 2, N \rrbracket \quad (6)$$

$$X_{it} \geq 0 \quad \forall t \in \llbracket 1, T \rrbracket, \forall i \in \llbracket 1, \ell - 1 \rrbracket \quad (7)$$

$$Y_{it} \in \{0, 1\} \quad \forall t \in \llbracket 1, T \rrbracket, \forall i \in \llbracket 1, \ell - 1 \rrbracket \quad (8)$$

The set of equalities (2)-(3) expresses the flow conservation constraints. As constraints (4) specify, the initial inventory level of each part is null. Constraints (5) involve a setup cost in each period if any disassembly operation is realized in that period. The definition domains of all variables are stated in constraints (6)-(8). Note that besides the cost-based objective function (1), another optimization criterion considered in the literature seeks to minimize the

number of products to be disassembled i.e. $\sum_{i=1}^T X_{1i}$, see e.g. [Gupta and Taleb \(1994\)](#); [Taleb et al. \(1997\)](#).

3.2. Complexity and solution methods

As much emphasized in the literature, disassembly planning cannot be assimilated as a reverse production planning problem. By design, the assembly process converges to a single demand source (final product), while the disassembly process diverges to multiple demand sources (parts or components). Due to the divergent disassembly structure, the complexity of related problems grows drastically with the number of product types to be disassembled ([Prakash et al., 2012](#)). Note that the well-known zero-inventory property ([Wagner and Whitin, 1958](#)) does not hold in the case of disassembly scheduling, and the classical lot-sizing algorithms cannot be directly applied to solve the disassembly scheduling problem ([Kim et al., 2007](#)).

[Kim et al. \(2009\)](#) proved that the uncapacitated disassembly lot-sizing problem with assembly product type (1)-(8) is NP-hard. Together with the complexity result, [Kim et al. \(2009\)](#) are the only authors who propose an exact branch-and-bound approach for the cost-based disassembly lot-sizing problem. Before this work, [Gupta and Taleb \(1994\)](#) developed an exact algorithm based on reverse materials requirement planning (MRP), which minimizes the number of disassembled products.

Due to the combinatorial nature of decisions involved by partial disassembly or parts commonality, various heuristic solution methods have been developed to tackle the different extensions of the basic problem (1)-(8) pointed out in Table 2, namely: partial disassembly, bounded capacity, multi-level demand and parts commonality. Among these methods, general and special-purpose approximative approaches can be founded: hybridized MIP combined with Lagrangian relaxation ([Ji et al., 2016](#)), constructive heuristics ([Barba-Gutiérrez et al., 2008](#); [Sung and Jeong, 2014](#); [Kim et al., 2018](#)), metaheuristics ([Prakash et al., 2012](#); [Tian and Zhang, 2018](#)).

Facing uncertainties, little but varied approaches can be found in the literature to deal with them: chance-constrained programming ([Liu and Zhang, 2018](#)), stochastic programming without recourse ([Kim and Xirouchakis, 2010](#)) and fuzzy reverse MRP ([Barba-Gutiérrez and Adenso-Díaz, 2009](#)).

3.3. Industrial implications and discussions

With respect to disassembly scheduling, [Kim et al. \(2007\)](#) provided a state-of-the-art on the generic problem (1)-(8) and its generalizations. Based on this prior work, let us review the advances achieved since then, in terms of the research directions identified by [Kim et al. \(2007\)](#):

- *Problem extensions:* Among all problem extensions suggested by [Kim et al. \(2007\)](#), only the capacitated problem with general product structure and complete disassembly has been addressed in the literature by [Ji et al. \(2016\)](#).

Note that the following problems remain still open: capacitated problem with general product structure and partial disassembly, problems with setup time, problems with storage capacity, problems with defective returns and problems with backlogging.

- *Consideration of non-deterministic parameters:* Since the review of Kim et al. (2007), several studies dealt with nondeterministic demand and yield of the reusable product parts (Barba-Gutiérrez and Adenso-Díaz, 2009; Kim and Xirouchakis, 2010; Liu and Zhang, 2018). Two formats of uncertain data representations have been used: fuzzy sets (Barba-Gutiérrez and Adenso-Díaz, 2009) and probability distributions (Kim and Xirouchakis, 2010; Liu and Zhang, 2018).

Further research efforts deserve to be devoted to handling related uncertainties, e.g.: product quality, quantity of defective parts, setup time. Given the high prevalence of uncertainty in upstream and downstream flows of the disassembly operations, it could be interesting to supply the planning decisions with valuable knowledge derived by data mining of some available raw data.

- *Embedding of other related decisions:* Without a special established taxonomy, there also exist generalized disassembly problems, which integrate various disassembly aspects, such as routing and lot-sizing (Habibi et al., 2017), lot-sizing and pricing (Tian and Zhang, 2018; Qu and Williams, 2008), leveling and scheduling (Kang et al., 2012),.
- *Integration with other activities in recovery systems:* Besides reassembly, the disassembly operation is an inherent activity of remanufacturing systems. The integrated decision-making on both disassembly and reassembly operations seems to remain unexplored.

From an industrial perspective, several real-life applications have been discussed in the literature (see Table 2). These case studies notably underline the importance and the relevance to combine optimization approaches with sensitivity and/or what-if analysis for supporting the decision-making process in complex industrial frameworks (Qu and Williams, 2008; Ji et al., 2016; Liu and Zhang, 2018).

4. From product to raw material recycling

In this section, let us discuss the production planning systems including the following recycling operations: (i) the conversion of worn-out goods into new or as good as new ones, and (ii) the flow back of material obtained during disassembly into production as valuable material. These recovery operations fall within the concept of *remanufacturing*. Various terms can be enumerated, that are often confused with remanufacturing, such as restoring, reconditioning, repurposing, refurbishment. No clear-cut definitions and distinctions between these recovery options exist in the literature. One thing is certain, *remanufacturing* becomes a standard term for an industrial recovery process of returned products, which requires several processing operations including often the disassembly operation.

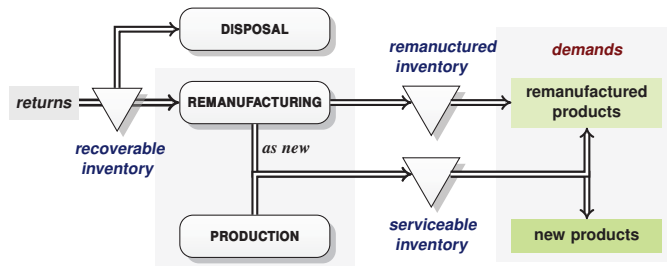


Figure 3: Production system including remanufacturing

Manufacturing and remanufacturing are two alternative and competing production ways, which share the same industrial environment and often lead to the same serviceable products. Accordingly, production planning systems for remanufacturing raise new questions for production and inventory management, the well-posedness of which heavily depends on the systems settings. In the production planning literature, the classic lot-sizing problem has been extended with a remanufacturing option under different settings with or without final disposal options, as depicted in Figure 3. A significant part of the identified articles operates on production systems, where manufactured and remanufactured products are identical, and assimilated as *serviceable products* (see e.g. Teunter et al. (2006)). Another part distinguishes the newly produced from remanufactured products in customer demand (see e.g. Fang et al. (2017b); Baki et al. (2014)).

Table 3: Lot-sizing with remanufacturing options

Time-dep: Time-dependent, Cap: Capacitated, D: Deterministic, ND: Nondeterministic, Ex: Exact, App: Approximate, Sol: Solver, R/B: Random or Benchmark, I: Industrial, G: Generic

Authors	Separated demands	Time-dep parameters	Setups		Cap	Type		Resolution			Instance		Application area
			Joint	Separated		D	ND	Ex	App	Sol	R/B	I	
Richter and Sombrutzki (2000)		✓		✓		✓		✓	✓		✓		G
Golany et al. (2001)		✓				✓		✓			-	-	G
Richter and Weber (2001)		✓		✓		✓		-	-	-	-	-	G
Yang et al. (2005)		✓				✓		✓	✓		✓		G
Teunter et al. (2006)			✓	✓		✓		✓	✓		✓		G
Li et al. (2006)		✓		✓		✓		✓	✓		✓		G
Li et al. (2007)		✓		✓	✓	✓		✓	✓		✓		G
Li et al. (2009)							✓	✓			✓		G
Pan et al. (2009)		✓			✓	✓		✓			✓		G
Piñeyro and Viera (2009)		✓		✓		✓			✓		✓		G
Denizel et al. (2010)		✓			✓	✓	✓	✓			✓		G
Piñeyro and Viera (2010)	✓	✓		✓		✓		✓			✓		G
Zhang et al. (2011)		✓		✓	✓	✓		✓			✓	✓	steel
Schulz (2011)				✓		✓		✓			✓		G
Zhang et al. (2012)	✓	✓		✓	✓	✓		✓			✓		G
Tao et al. (2012)						✓	✓	✓			✓		G
Sahling (2013)			✓	✓	✓	✓				✓	✓		G
Han et al. (2013b)	✓	✓			✓	✓				✓	✓		G
Naeem et al. (2013)				✓	✓	✓	✓	✓			✓		G
Baki et al. (2014)				✓	✓	✓			✓		✓		G
Chen and Abrishami (2014)	✓	✓		✓		✓		✓			✓		G
Li et al. (2014)				✓		✓		✓			✓		G
Retel Helmrich et al. (2014)		✓	✓	✓		✓				✓	✓		G
Cai et al. (2014)							✓				✓		G
Parsopoulos et al. (2015)				✓		✓		✓			✓		G
Piñeyro and Viera (2015)				✓		✓		✓			✓		G
Sifaleras and Konstantaras (2015)				✓		✓		✓			✓		G
Sifaleras et al. (2015)				✓		✓		✓			✓		G
Cunha and Melo (2016)		✓	✓	✓		✓				✓	✓		G
Hilger et al. (2016)				✓	✓	✓	✓	✓			✓		G
Macedo et al. (2016)		✓	✓	✓		✓	✓			✓	✓		G
Cunha et al. (2017)		✓		✓		✓				✓	✓		G
Fang et al. (2017a)	✓	✓		✓		✓	✓	✓			✓	✓	iron and steel
Giglio et al. (2017)		✓		✓	✓	✓		✓			✓		G
Sifaleras and Konstantaras (2017)				✓		✓		✓			✓		G
Koken et al. (2018a)	✓				✓	✓		✓			✓		G
Koken et al. (2018b)	✓				✓	✓		✓			✓		G
Kilic et al. (2018)				✓		✓	✓	✓			✓		G
Ali et al. (2018)		✓		✓		✓				✓	✓		G
Zouadi et al. (2018)				✓		✓		✓			✓		G

4.1. Mathematical formulations

In seeking to better define industrial contexts, the academic community investigated different variants of the lot-sizing problem with remanufacturing options (LSR). Apart from the classical capacitated and uncapacitated cases of the lot-sizing problem, let us review the main remanufacturing-oriented characteristics of this problem, which tend to define a nomenclature within the scientific community:

Joint or separated setups. Both configurations have been studied in the literature, namely when:

- Manufacturing and remanufacturing are performed in two separate processes, each having its own setup costs. This problem is commonly called *lot-sizing with remanufacturing and separate setups*.
- Manufacturing and remanufacturing share the same production routes and have one joint setup cost. Defined on this assumption, the problem is known as *lot-sizing with remanufacturing and joint setups*.

As Table 3 clearly shows, academic problem definitions favor production configurations with separated setup and tend thus to be close to real-life settings.

Stationary or time-dependent parameters. Special cases of LSR with stationary parameters have been not neglected and a number of useful analytical results has been derived for them. For example, [Teunter et al. \(2006\)](#) proposed a polynomial-time dynamic programming algorithm for the LSR with joint setups and stationary costs.

Inventory management. As illustrated in Figure 3, the integration of products returns and remanufacturing-related goods into production environment affects the traditional inventory management ([Ilgin and Gupta, 2010](#)). In this respect, decisions related to the recoverable (of products return), serviceable (of identical manufactured and remanufactured products) and remanufactured inventories are inherent to LSR problems for a suitable coordination between the regular policies of procurement and remanufacturing.

With or without products substitution. In contrast to the classical lot-sizing problem, one of the main specificities of LSR lies on the demand, that can be fulfilled from a single stream of serviceable products or be fitted into two categories of newly produced and remanufactured ones. Even if no distinction is commonly made between manufactured and remanufactured products, there exist some studies that considered the market divided into new and remanufactured segments (Koken et al., 2018a,b; Zhang et al., 2011; Chen and Abrishami, 2014). To go further, Piñeyro and Viera (2010) allowed the substitution of remanufactured products by the new ones for absorbing the fluctuations in the quantity of product returns.

The general form of the lot-sizing problem with remanufacturing, time-dependent parameters and separated setups can be formally defined as done in Retel Helmrich et al. (2014). Let the planning horizon be spread over T periods. Denote by d_t the demand for serviceable products and r_t the amount of returns, $\forall t \in \llbracket 1, T \rrbracket$. The related industrial process involves the following costs: unit production costs for manufacturing (remanufacturing) p_t (\hat{p}_t), setup costs for manufacturing (remanufacturing) f_t (\hat{f}_t), unit holding costs for serviceable products h_t and returns \hat{h}_t , $\forall t \in \llbracket 1, T \rrbracket$.

Let X_t (\hat{X}_t) be the amount of manufactured (remanufactured) products and Y_t (\hat{Y}_t) the binary indicator for manufacturing (remanufacturing) in period $t \in \llbracket 1, T \rrbracket$. Variables I_t and \hat{I}_t are used to express the inventory levels of serviceable products and returns, respectively. Making use of the above notations, the LSR problem with time-dependent parameters and separated setups can be formulated as follows:

$$\min \sum_{t=1}^T (p_t X_t + \hat{p}_t \hat{X}_t + f_t Y_t + \hat{f}_t \hat{Y}_t + h_t I_t + \hat{h}_t \hat{I}_t) \quad (9)$$

s.t.

$$\hat{I}_{t-1} + r_t = \hat{I}_t + \hat{X}_t \quad \forall t \in \llbracket 1, T \rrbracket \quad (10)$$

$$I_{t-1} + \hat{X}_t + X_t = I_t + d_t \quad \forall t \in \llbracket 1, T \rrbracket \quad (11)$$

$$I_0 = \hat{I}_0 = 0 \quad (12)$$

$$\hat{X}_t \leq \sum_{i=t}^T d_i \hat{Y}_i \quad \forall t \in \llbracket 1, T \rrbracket \quad (13)$$

$$X_t \leq \sum_{i=t}^T d_i Y_i \quad \forall t \in \llbracket 1, T \rrbracket \quad (14)$$

$$\hat{X}_t, X_t, \hat{I}_t, I_t \geq 0 \quad \forall t \in \llbracket 1, T \rrbracket \quad (15)$$

$$\hat{Y}_t, Y_t \in \{0, 1\} \quad \forall t \in \llbracket 1, T \rrbracket \quad (16)$$

The objective function (9) minimizes the sum of production, setup and holding costs associated to manufacturing and remanufacturing processes. The sets of equalities (10)-(11) express the flow conservation constraints. Both serviceable and returns inventories are initialized via constraints (12). Constraints (13)-(14) track the manufacturing and remanufacturing setups. Binary and nonnegative requirements are imposed in constraints (15)-(16).

4.2. Complexity and solution approaches

The uncapacitated lot-sizing problem with remanufacturing, joint setups and stationary parameters is polynomial and can be solved by a dynamic programming algorithm running in $O(T^4)$ (Teunter et al., 2006). Some special cases of the LSR problem with joint and separate setup costs preserve the zero-inventory property and can be solved in polynomial time (Golany et al., 2001; Richter and Sombrutzki, 2000; Richter and Weber, 2001).

The following uncapacitated LSR problems have been proven to be NP-hard: (i) LSR with separate setups for stationary cost parameters (Retel Helmrich et al., 2014), (ii) LSR with joint setups in general (Retel Helmrich et al., 2014), (iii) LSR with general and stationary concave-cost structures (Golany et al., 2001; Yang et al., 2005). As the capacitated lot-sizing problem, the LSR problem with bounded capacity remains NP-hard. A number of interesting complexity results and useful properties for the capacitated LSR problem with different cost structures has been found by Pan et al. (2009).

Very few studies have been dedicated to developing exact methods to solve the difficult variants of the deterministic LSR problem. In this regard, let us mention the work of Li et al. (2006), who developed an exact dynamic programming algorithm for the LSR problem with separated setups and product substitution. Sahling (2013) combined the column generation with a truncated branch-and-bound method to obtain high-quality solutions. Ali et al. (2018) conducted a polyhedral analysis of the LSR with separated setups based on two reformulations and derived important properties related to their strength. On the flip side, an abundance of literature proposes heuristic solution methods such as: constructive (Baki et al., 2014), based on relaxations (Chen and Abrishami, 2014), adaptation of the part period balancing and Silver–Meal heuristics (Zouadi et al., 2018), metaheuristics (see e.g. Li et al. (2014); Koken et al. (2018a,b)), etc.

Despite the predominance of deterministic models, several research efforts have been undertaken to cope with non-deterministic problem settings. Various sources of uncertainties are separately or jointly considered in: (i) setup costs, (ii) demands, (iii) quantity, quality or yield of products returns. To deal with them, classical stochastic programming paradigms have been used: approaches based on the expected value (Hilger et al., 2016; Denizel et al., 2010), two-stage programming (Macedo et al., 2016), stochastic dynamic programming (Naeem et al., 2013; Cai et al., 2014; Tao et al., 2012).

The competitiveness of heuristic solution approaches is commonly measured in an empirical way via numerical experiments. Instances reproducibility and performance comparability are thus key aspects for the field of operations research. In this respect, note that Sifaleras et al. (2015) and Sifaleras and Konstantaras (2017) created benchmark data for two lot-sizing problems: (i) multi-product case with remanufacturing, and (ii) with product returns and recovery. These instances are available on <http://users.uom.gr/~sifalera/benchmarks.html>.

4.3. Industrial implications and discussions

The management of production planning with remanufacturing differs from management activities in traditional production systems in several aspects: (i) the integration of return flows, the quantity, quality and timing of which are difficult to predict, (ii) the coordination between manufacturing and remanufacturing routes and multiple simultaneous inventory management and, (iii) the production streams down-flow. As appears from Table 3, lot-sizing with remanufacturing is an increasingly active area of research since the 2000s.

Prior to this work, Guide Jr (2000) have identified multiple complex characteristics of remanufacturing. Considerable progress has been made since then, notably in terms of: (i) models/methods to aggregate production planning models that consider returned products and balance returns with demand, while managing the associated inventories (see Table 3), (ii) models/methods to help in planning what parts and components to recover in disassembly (see Section 3), (iii) investigations related to traditional purchasing activities versus purchasing for remanufacturing (Cai et al., 2014). Moreover, research efforts have been also spent to integrate into LSR problems, non-conventional but inherent aspects including: acquisition pricing (Cai et al., 2014), carbon emission constraints (Zouadi et al., 2018), supplier selection (Zouadi et al., 2018).

Several research topics on production planning with remanufacturing are open for further analysis and studies:

- There is an evident lack of exact solution methods for the LSR problem and its variants.
- The coordination between disassembly, remanufacturing and reassembly should be considered, while evaluating different management policies between these strongly correlated industrial processes.
- From an academic point of view, production planning with remanufacturing has received a lot of interest. Meanwhile, a weak link with industrial applications may be perceived. Besides the real-life application encountered in the steel industry (Zhang et al., 2011), no real-life case studies are conducted in the literature to the best of our knowledge.

5. By-products versus co-products

A wide range of industrial production processes generates several products in a single production run with different quality levels, economic values, environmental impacts, and waste or non-waste statuses. This phenomenon is known in the literature as *co-production* and can be: (i) deliberated or non-deliberated; (ii) controlled or uncontrolled (see Table 4).

The depletion of scarce natural resources and the abundance of waste accumulation in landfills lead our and future generations to seek pathways for converting unavoidable production outputs into useful and high added-value products. Besides the technological feasibility, making industry processes less wasteful raises new legislative, economic, environmental and management questions.

Given the industrial specificities varying across sectors and continuously evolving production technology, no clear and universal distinction between non-waste and waste products can be drawn. Apart from the rigorous definition of waste, the texts of environmental and waste legislations use notions such as by-products or secondary material, while explaining their meaning in a more or less detailed manner. For example, the Circular Economy Promotion Law⁴ (China) mentions the by-products without giving an explicit definition. Under the Resource Conservation and Recovery Act² (USA), “a by-product is a material that is not one of the primary products of a production process and is not solely or separately produced by the production process [...] The term does not include a co-product that is produced for the general public’s use that is ordinarily used in the form in which it is produced by the process”. The Waste Framework Directive¹ (Europe) pays special attention to the specification of the term *by-product*. Notably, Article 3 of this directive

Table 4: By-products versus co-products

D: Deterministic, ND: Nondeterministic, Ex: Exact, App: Approximate, Sol: Solver, R/B: Random or Benchmark, I: Industrial, G: Generic

Authors	Type of product(s) under study	Type		Resolution			Instance		Application area
		D	ND	Ex	App	Sol	R/B	I	
Bitran and Leong (1992)	"... multiple products produced simultaneously or products with <i>by-product</i> ."		✓		✓		✓		G
Bitran and Gilbert (1994)	"... a <i>co-production</i> process is one in which a family of several different products is produced simultaneously."	✓			✓			✓	semiconductor
Bitran and Leong (1995)	"Units not meeting the specifications of a target product are commonly called <i>byproducts</i> [...] difficult to differentiate the main product from the byproducts since the products are all equally important."		✓		✓		✓		G
Spengler et al. (1997)	"the problem structure of <i>by-product</i> management [...] [includes] collection of valuable residues, handling and recycling of production residues, car and electronic scrap recycling ..."	✓				✓		✓	iron and steel
Taşkın and Ünal (2009)	"This is how <i>co-production</i> is encountered in float glass production: non-controllable errors in process result in simultaneous production of several products."	✓				✓		✓	float glass
Lu and Qi (2011)	"... the production of some products will generate some other <i>by-products</i> that can also be sold, and the production quantity of each by-product is linearly proportional to the quantity of the main product."	✓		✓	✓		✓		G
Ağralı (2012)	"... products [co-products] that have to be produced simultaneously and producing one item of a product requires producing exactly one item of other products [co-products] [...] when a certain product is produced some known percentage of other products are also produced as <i>by-products</i> ..."	✓		✓			✓		G
Santos and Almada-Lobo (2012)	"During the cooking of wood chips in the digester, two <i>by-products</i> are produced ..."	✓				✓		✓	pulp and paper mill
Sridhar et al. (2014)	"... the production process creates a mixture of desirable products and undesirable <i>byproducts</i> ."	✓			✓		✓		G
Rowshannahad et al. (2018)	"The used raw material (considered as a kind of <i>by-product</i>) ..."	✓				✓		✓	semiconductor

specifies: "A *substance or object, resulting from a production process, the primary aim of which is not the production of that item, may be regarded as not being waste, [...] but as being a **by-product** only if the following conditions are met: (a) further use of the substance or object is certain; (b) the substance or object can be used directly without any further processing other than normal industrial practice; (c) the substance or object is produced as an integral part of a production process; and (d) further use is lawful...*".

In addition, the commission of the European communities elaborated an ad-hoc communication aiming to interpret and clarify the distinction between waste and by-products. Based on this document, let us propose the following definitions, which conciliate all aforementioned legislative references:

Definition 2. A *product* is all lawful material deliberately created in a production process. The term includes *co-products*.

Definition 3. A *production residue* is a material not deliberately produced in a production process, but may or may not be considered as waste.

Definition 4. A *by-product* is a production residue that is not a waste. By definition, *by-products* are lawful production outputs, whose further use is economically and environmentally sustainable.

In order to deal efficiently with different outputs produced simultaneously, a number of studies have been conducted in both co-production systems and those with by-products (see Table 5). Given the legislative context, the cohabitation of different interpretations of the same words, by-product and co-product, is not surprising. Whatever the used term, let us focus on environmental-friendly and economic recovery of production residues.

5.1. Mathematical formulations

Besides the production planning models conceived to address specific industrial applications, several research efforts have been dedicated to proposing generic lot-sizing formulations for production systems with by-products. Except the model given by Sridhar et al. (2014), these generic models trigger production runs for satisfying demands of so-called by-products (Bitran and Leong, 1992; Ağralı, 2012; Lu and Qi, 2011). Such a strong assumption is inconsistent with the widely accepted meaning of by-products, but can be encountered in production systems with co-products.

For clarifying the differences between co-products and by-products, let us discuss the basic version of the lot-sizing problem for production systems with co-products proposed and formulated by Ağralı (2012). In the framework of a such system, a main product, indexed by 0, is generated together with K co-products at a known proportion α^k , $\forall k \in \llbracket 1, K \rrbracket$.

By definition, α^0 is equal to 1. Each product k has its own demand d_t^k to be satisfied in every period t . The production launched at a given period t entails a joint fixed setup cost f_t and a unitary production cost p_t^k per product k . Moreover, a holding cost h_t^k is incurred on each product k held in inventory at the end of a time period t . In this setting, the problem raised consists in determining when and how much to produce, over a planning horizon of T periods, while meeting all demands and minimizing the sum of the related costs.

For modeling purposes, denote by: **(i)** X_t : production quantity in a given period $t \in \llbracket 1, T \rrbracket$, **(ii)** Y_t : binary indicator of production setup in period $t \in \llbracket 1, T \rrbracket$, and **(iii)** I_t^k : inventory level of product k at the end of period t .

$$\min \sum_{t=1}^T \left[f_t Y_t + \sum_{k=0}^K (p_t^k \alpha^k X_t + h_t^k I_t^k) \right] \quad (17)$$

s.t.

$$I_{t-1}^k + \alpha^k X_t = I_t^k + d_t^k \quad \forall t \in \llbracket 1, T \rrbracket, \forall k \in \llbracket 0, K \rrbracket \quad (18)$$

$$I_0^k = 0 \quad \forall k \in \llbracket 0, K \rrbracket \quad (19)$$

$$X_t \leq \max_{k \in \llbracket 0, K \rrbracket} \left\{ \frac{d_t^k}{\alpha^k} \right\} Y_t \quad \forall t \in \llbracket 1, T \rrbracket \quad (20)$$

$$X_t \geq 0, I_t^k \geq 0 \quad \forall t \in \llbracket 1, T \rrbracket, \forall k \in \llbracket 0, K \rrbracket \quad (21)$$

$$Y_t \in \{0, 1\} \quad \forall t \in \llbracket 1, T \rrbracket \quad (22)$$

The objective function (17) minimizes the sum of setup, production and inventory costs. Inventory balance constraints are ensured by equalities (18). The set of constraints (19) initializes the inventory levels of each product. Each production launch triggers a setup cost via constraints (20). Nonnegativity and binary requirements are expressed in constraints (21)-(22).

The mixed integer program (17)-(22) lends itself well to co-production systems, when all production outputs are deliberately produced and their own demands are sufficient to trigger the production process. Given the set of constraints (20), this program does not encompass the downstream canalization of production residues. Note that the by-product management does not fall within classical co-production settings.

5.2. Complexity and solution approaches

Ağralı (2012) showed that the linear model (17)-(22) can be reduced to the single-item lot-sizing problem, for which a dynamic programming algorithm running in $O(T \log(T))$ exists. However, extensions of this basic problem can make it intractable and encourage the researchers to develop competitive heuristic approaches, as done for example in the problem case with lost sales (Lu and Qi, 2011).

By virtue of their ease of use and affordability, optimization software products are usually used to solve problems encountered in the industry world (Spengler et al., 1997; Taşkın and Ünal, 2009; Rowshannahad et al., 2018). Often, existing solvers are not sufficient to face the complexity and the intractability of specific industrial features. A number of heuristic methods can be found in the literature for achieving industrial needs, whether to handle uncertainty (Bitran and Gilbert, 1994) or to deal with the curse of dimensionality of real-world instances (Santos and Almada-Lobo, 2012). Inspired by issues stemming from industry, several research studies addressed production planning problems under real-life non-linear or non-deterministic features, by passing through a linear approximation step (Bitran and Leong, 1992, 1995; Sridhar et al., 2014).

5.3. Industrial implications and discussions

In spite of the confusion in the literature, let us distinguish the phenomenon of conversion of production residues into by-products from that of co-production. One similitude is sure, these two phenomena are typical for process industries: semiconductor fabrication (Bitran and Gilbert, 1994; Rowshannahad et al., 2018), metal processing (Spengler et al., 1997), pulp and paper industry (Santos and Almada-Lobo, 2012), glass manufacturing (Taşkın and Ünal, 2009). Even if both of them, by-products and co-products, refers to the joint production of multiple outputs in one run, their management principles and goals in production planning are different.

Consistent with the scope of this review, focus on downstream management of lawful outputs, non-deliberately generated during a production process. The conversion of production residues into by-products forms part of the circular economy drivers. Commonly referred as *by-product synergy* (or *industrial symbiosis* in the industrial ecology literature), this practice lies on the use of a by-product stream produced by one process as input into another process as depicted in Figure 4 (Lee and Tongarlak, 2017; Lee, 2012). In spite of its opportunistic character, by-product synergy is applicable in many industry sectors, ranging from agriculture to manufacturing. However, its industrial implementation is not obvious. A number of challenges and gaps remains to be tackled:

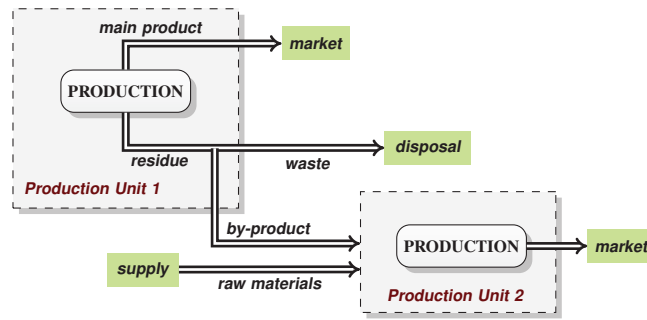


Figure 4: Process flow diagram of by-product synergy

- *Supporting the decision-making in real-life environments:* As we can infer from Table 4, there is still room for theoretical research on production planning with by-products: **(i)** to model generic problems and propose competitive solution methods, **(ii)** to take into account real-life features, such as irregular cost profiles (Rowshannahad et al., 2018), non-linear or non-deterministic production mixture of outputs (Sridhar et al., 2014; Bitran and Gilbert, 1994), uncertain by-product demands (Lee and Tongarlak, 2017); **(iii)** to explore the implications on production planning of all aspects related to the by-product synergy, namely economic, managerial and environmental (Lee and Tongarlak, 2017).
- *Identifying and understanding synergy mechanisms:* Given the opportunistic use of production residues, the joint production settings depend strongly on the factors that determine the by-product generation. For example, in manufacturing and service environments, production residues are generated as a result of physical characteristics of the production processes, hence: **(i)** the production capacities are usually known; **(ii)** and the generated quantities of main products and by-products can be estimated, since they are correlated. In retail context, by-product quantity depends on unsatisfied demands of the main products, which are generally unknown, but can be probabilistically expressed (Lee and Tongarlak, 2017).
To sum up, the formalization of industrial evidences and field knowledges plays a key role in supporting, optimizing and facilitating the by-product synergy.
- *Studying and analyzing different policies of joint production:* The coordination between different production processes raises many economic and operations management questions: How to ensure the synchronization between their production activities? How to share the benefits and costs of a such complementary relationship? How to make the by-product synergy robust for all implicated production processes and mitigate their interdependence?, How to setup self-sufficient industrial parks in a sustainable manner?, etc.

Table 5: Greenhouse gas emissions

ETH: Emission threshold, ET: Emission tax, ETr: Emission trading, EO: Emission offset, PC: Periodic constraint, CC: Cumulative constraint, GC: Global constraint, RC: Rolling constraint, TC: Trading constraint, MPM: Multiple production modes, Cap: Capacitated, D: Deterministic, ND: Non-Deterministic, Ex: Exact, App: Approximate, Sol: Solver, R/B: Random or Benchmark, I: Industrial, G: Generic

Authors	Emission regulation				Emission constraint					MPM	Cap	Type		Resolution			Instance		Application area
	ETH	ET	ETr	EO	PC	CC	GC	RC	CTC			D	ND	Ex	App	Sol	R/B	I	
Benjaafar et al. (2013)	✓	✓	✓	✓			✓		✓			✓			✓		✓		G
Absi et al. (2013)					✓	✓	✓	✓	✓	✓		✓							G
Fahimnia et al. (2013)	✓				✓					✓	✓				✓			✓	textile
Zakeri et al. (2015)		✓	✓							✓	✓				✓			✓	metal furniture
Kantas et al. (2015)			✓		✓				✓	✓	✓				✓			✓	biofuel
Retel Helmrich et al. (2015)							✓			✓				✓			✓		G
Hong et al. (2016)	✓		✓		✓				✓	✓		✓			✓		✓		G
Purohit et al. (2016)			✓		✓				✓	✓				✓			✓		G
Absi et al. (2016)	✓				✓					✓		✓			✓				G
Zouadi et al. (2018)	✓						✓			✓		✓			✓			✓	G
Wu et al. (2018)	✓				✓					✓	✓	✓		✓	✓		✓		G

6. Greenhouse gas emissions and energy consumption

6.1. Greenhouse gas emissions

Global warming is currently a hot research topic and raises major political, economic, as well as, social concerns. Greenhouse gas (GHG) emissions in the atmosphere have been identified as one of the main contributors to global

warming. In order to tackle the issues caused by these gases, a number of climate-oriented action plans have been implemented by governments around the world, e.g.: (i) the *Kyoto Protocol*¹¹ is an international treaty adopted in 1997, which extends the *United Nations Framework Convention on Climate Change*¹² (UNFCCC), that commits states parties to reduce greenhouse gas emissions. As of May 2013, 191 countries and the European Economic Community have ratified the agreement (Canada withdrew in 2012); (ii) the *Paris Climate Agreement*, another initiative under the UNFCCC, was ratified in 2016 by 174 out of 197 countries. It aims to maintain the global temperature below 2° Celsius above pre-industrial levels and to limit its increase to 1.5° Celsius¹³.

The standard way of measuring carbon footprints is to consider *carbon dioxide equivalent* (CO₂e). The idea behind this measure is to express the impact of each greenhouse gas in terms of the amount of CO₂ that would create the same global warming potential. That way, the carbon footprint represents the impact of all greenhouse gases using the same metric. In the following, we use the terms *carbon emissions* and *GHG emissions* to consider emissions of all greenhouse gases.

For achieving the aforementioned reduction targets, governments established and deployed various regulation policies (Hong et al., 2016). As far as GHG emissions reduction is concerned, the most common policies are the following:

- *Emissions threshold*: A threshold-based regulatory policy imposes a maximum quantity of carbon emissions, that cannot be violated (Fahimnia et al., 2013; Benjaafar et al., 2013). The key disadvantage of this policy is the lack of incentives to reduce emissions beyond the required cap of free emissions. Companies can decide to reach the imposed threshold even if they could meet their needs by emitting less greenhouse gas.
- *Carbon pricing*: This regulatory tool taxes and penalizes GHG emissions according to their quantity (Benjaafar et al., 2013; Zakeri et al., 2015). Aiming at reducing pollution and encouraging more environmentally conscious production processes, this policy presents a number of drawbacks: induce expensive administration costs, stimulate shift production to countries without a such a tax, promote covert operations, etc.
- *Carbon/Emissions trading* is a market-based instrument to reduce GHG. This form of regulation represents a trade-off between the previous two discussed policies and refers to: (i) the limitation of the amount of GHG emissions over a specific time horizon, and (ii) the firms granting with so-called *permits* to emit a given amount of GHG. In thus emerged carbon markets, GHG emissions are traded under *cap-and-trade* schemes or with permits that pay for or offset GHG reductions (Purohit et al., 2016; Benjaafar et al., 2013; Zakeri et al., 2015; Kantas et al., 2015). Among the numerous regulatory benefits exhibited by these trading systems, they are subject to heavy criticism: difficulty in standardizing the maximum threshold, volatility in emissions allowance prices, speculation in carbon markets, etc.
- *Carbon offsets* policy is a more intricate extension of the emission trading system, allowing companies to invest in so-called *offsets*. A carbon offset is a credit for GHG reductions obtained by one party, that can be purchased and used to compensate the emissions of another party (Benjaafar et al., 2013).

Note that climate-warming emissions arisen from business and government operations are quantified and managed via global standardized frameworks, such as Greenhouse Gas Protocol¹⁴, EcoTransIT World¹⁵, etc.

Given the topicality and the importance of the GHG reduction, there is an extensive literature related to carbon emissions in many research fields. At operational management level, carbon emission concerns are increasingly considered within the framework of various applications, including: facilities location choices in supply chain network design problems (e.g. Mohammed et al. (2017); Das and Posinasetti (2015)), production scheduling and road freight/maritime transportation problems (e.g. Fang et al. (2011); Bektaş and Laporte (2011); Demir et al. (2014); Bouman et al. (2017)), inventory management problems (e.g. Toptal et al. (2014); Hovelaque and Bironneau (2015)), production planning (see Table 5).

In particular, reductions in GHG emissions stemming from industrial processes and systems are primordial for reaching worldwide agreed targets related to the climate change mitigation. In accordance with the scope of this survey, let us put the spotlight, in what follows, on production planning problems including GHG emission issues.

6.1.1. Mathematical formulations

As Table 5 witnesses, a number of studies have started to take into account GHG emissions issues in production planning problems and to assess their incidence on operational decisions. Depending on the nature of regulation policies previously evoked, carbon emissions considerations can appear in both the objective function or constraints. For instance, additional costs due to emissions are usually incorporated in the objective function when carbon pricing and cap-and-trade regulation schemes are under study. Meanwhile, carbon emission limitations due to the cap-and-trade or threshold regulation are modeled by constraints (Benjaafar et al., 2013; Hong et al., 2016; Purohit et al., 2016; Zakeri et al., 2015).

According to the manner in which carbon emissions are allocated over the planning horizon, four classes of carbon emissions constraints can be distinguished in production planning problems: **(i) global constraint**: the carbon emissions capacity is available on the whole horizon (Benjaafar et al., 2013; Absi et al., 2013; Retel Helmrich et al., 2015); **(ii) periodic constraint**: the amount of carbon emissions, which is not used in a given time period, is lost (Absi et al., 2013; Hong et al., 2016; Fahimnia et al., 2013; Kantas et al., 2015; Absi et al., 2016); **(iii) cumulative constraint**: the amount of carbon emissions, which is not used in a given time period, can be used in the next periods while respecting an upper cumulative capacity (Absi et al., 2013); **(iv) rolling constraint**: the carbon emissions can only be compensated on a rolling period (Absi et al., 2013).

Green production aims to be profitable via environmentally friendly industrial processes. In this sense, many efforts have been deployed in the quest of both environmentally and economically viable production and transportation (supply) modes. Kantas et al. (2015) investigated multiple sources to produce one final product, in order to identify the less pollutant processes used to transform different raw materials. Toward the same goal, Fahimnia et al. (2013) and Zakeri et al. (2015) showed how to analyze multiple production and/or transportation modes depending on the used technology and the equipment age. As far as the demand is concerned, it can be specific to each production mode (Absi et al., 2013), or common for all possible combinations of production sources and transportation modes (Hong et al., 2016; Absi et al., 2016). Note that all of these problems with multiple production and/or transportation modes operate with only a single product in most cases. Nevertheless, companies rarely produce only one product type. Among all the reviewed quantitative models considering GHG emissions, only two deal with multiple products, namely Fahimnia et al. (2013); Zakeri et al. (2015).

Finally, as limiting the production capacity makes any problem much more difficult to solve, most of the available models in the literature are uncapacitated (see Table 5). However, problems modeling industrial supply chain are still capacitated in order to get closer to the reality (Fahimnia et al., 2013; Kantas et al., 2015; Zakeri et al., 2015).

Consider for instance an uncapacitated single-item lot-sizing problem with carbon emissions, as done in the paper of Retel Helmrich et al. (2015). It aims to determine, over a planning horizon of T periods, when and how much to produce a product to satisfy a deterministic demand d_t for every period $t \in \llbracket 1, T \rrbracket$. At each time period a fixed setup cost f_t and fixed setup emissions \hat{f}_t occur when production occurs in this period. Furthermore, p_t and h_t are unitary production and holding costs, and \hat{p}_t and \hat{h}_t are unitary production and holding emissions, respectively. Carbon emissions are limited by a maximum emission capacity \hat{C} over the whole time horizon.

Making use of the notations introduced above, the uncapacitated single-item lot-sizing problem with a global carbon emission constraint can be formally defined as a mixed integer problem with the following decision variables: X_t represents the production quantity of the product in a given period $t \in \llbracket 1, T \rrbracket$, Y_t is a binary indicator of setup for production in period $t \in \llbracket 1, T \rrbracket$ and I_t denotes the inventory level of the product at the end of period t .

$$\min \sum_{t=1}^T (p_t X_t + f_t Y_t + h_t I_t) \quad (23)$$

s.t.

$$X_t + I_{t-1} = I_t + d_t \quad \forall t \in \llbracket 1, T \rrbracket \quad (24)$$

$$I_0 = 0 \quad (25)$$

$$X_t \leq \sum_{i=t}^T d_i Y_i \quad \forall t \in \llbracket 1, T \rrbracket \quad (26)$$

$$\sum_{t=1}^T (\hat{p}_t X_t + \hat{f}_t Y_t + \hat{h}_t I_t) \leq \hat{C} \quad (27)$$

$$X_t, I_t \geq 0 \quad \forall t \in \llbracket 1, T \rrbracket \quad (28)$$

$$Y_t \in \{0, 1\} \quad \forall t \in \llbracket 1, T \rrbracket \quad (29)$$

The objective function (23) minimizes costs. Constraints (24) are the inventory balance constraints. Constraint (25) fixes the initial inventory level to zero. Constraints (26) ensures that, in each period, there is production only if there is a setup. Constraint (27) limits globally emissions over the whole time horizon. Finally, nonnegativity and binary requirement constraints are given in expressions (28)-(29).

6.1.2. Complexity and solution methods

The manner in which carbon emissions constraints are modeled has a determinant impact on the problem complexity:

- *Global constraint*: Due to its similarity with capacity constraints, the lot-sizing problem with global carbon emissions constraints (23)-(29) is proved NP-hard even for linear cost functions (Retel Helmrich et al., 2015). The

problem with multiple production modes stays NP-hard (Absi et al., 2013). Note however that, the single-item single-mode lot-sizing problem with global emission constraints can be solved by a pseudo-polynomial algorithm under some assumptions on co-behaving costs.

- *Periodic constraints:* The uncapacitated multi-modes lot-sizing problem, subject to periodic emission constraints, is proved polynomial and can be solved by a dynamic programming algorithm (Absi et al., 2013; Hong et al., 2016).
- *Cumulative and rolling constraints:* The uncapacitated lot-sizing problems with cumulative or rolling emission constraints have only be used with multiple production modes. They are proved to be NP-hard (Absi et al., 2013). Note that rolling constraints with only one period become similar to periodic constraints, and the problems can be polynomially affordable by a dynamic programming algorithm.
- *Cap-and-trade constraints:* Lot-sizing problems with cap-and-trade constraints can be solved in a polynomial time by a dynamic programming algorithm (Hong et al., 2016).

6.1.3. Industrial implications and discussions

Either constrained by regulation policies or concerned about their green image, “a substantial number of companies publicly state carbon emission reduction targets...” (Velázquez-Martínez et al., 2014). In the production planning literature, one can find lot-sizing problems dealing with carbon emissions in several industry sectors: textile (Fahimnia et al., 2013), metal furniture (Zakeri et al., 2015), bio-fuel (Kantas et al., 2015).

Besides the academic and industrial interest of the reviewed models, the way in which carbon emissions are handled in the literature remains simplistic. Several aspects of the state-of-the-art modeling approach are open to further investigation:

- *Modeling accuracy:* Generally, carbon emissions are modeled using linear or affine functions, while the emissions reduction can exhibit irregular nonlinear trends (Zakeri et al., 2015; Purohit et al., 2016). It may be constructive to study more deeply the effects of emission parameters against regulatory mechanisms.
- *Toward multi-objective optimization:* The majority of existing studies deal with single-objective optimization problems. Basically, cost minimization and carbon emissions minimization are two conflicting objectives. One has to find the trade-off between the total cost and the total carbon emissions. Considering carbon emissions as a second objective and addressing bi-objective versions of lot-sizing problems with carbon emissions stand out as a worthwhile research avenue to be explored.
- *Emission reduction in both forward and reverse supply chain directions:* In the related literature, carbon emissions are mainly considered in the forward supply chain, but very rarely in the reverse one (Fahimnia et al., 2013). Note that greenhouse gas emissions also occur during collection, remanufacturing and recycling. For the sake of completeness, it would be useful to evaluate the emission parameters of each component of a supply chain in both forward and reverse directions.

Table 6: Energy consumption

D: Deterministic, ND: Non-Deterministic, Ex: Exact, App: Approximate, Sol: Solver, R/B: Random or Benchmark, I: Industrial, G: Generic

Authors	Energy in the objective function depends on ...		Energy capacity	Type		Resolution			Instance		Application area
	Nb of machines	Produced quantity		D	ND	Ex	App	Sol	R/B	I	
Tang et al. (2012)		✓			✓		✓		✓		G
Giglio et al. (2017)	✓	✓		✓			✓		✓		G
Masmoudi et al. (2017)	✓	✓		✓			✓		✓		G
Wichmann et al. (2018)	✓			✓				✓		✓	warm and hot forming
Rapine et al. (2018b)	✓		✓	✓		✓			-	-	
Rapine et al. (2018a)	✓		✓	✓		✓			-	-	G
Golpíra et al. (2018)	✓				✓			✓	✓		G

6.2. Energy consumption

An environmental-friendly industrial activity must reflect an energy-efficient production management, in terms of both costs and GHG emissions involved by the energy consumption. Against the vast amount of literature aiming at making production technologies less energy consuming, it is only recently that energy-aware production planning has received the scientific attention. Among papers operating with managerial actions, the literature review of Biel and Glock (2016) revealed the predominant interest expressed for job allocation and sequencing problems and the deficit of attention manifested for mid-term lot-sizing problems. To provide a more accurate picture of existing studies on energy-aware production planning, Table 6 lists and describes all identified references.

6.2.1. Mathematical formulations

At the limit between tactical and operational levels, the energy efficiency considerations are separately or jointly integrated in lot-sizing problems, as follows:

- *Energy consumption modeling*: For the sake of simplicity, the energy consumption is usually measured via the production activity, i.e. either the size and usage duration of the resources park (Rapine et al., 2018b,a; Masmoudi et al., 2017) or the production quantity (Tang et al., 2012).
- *Energy related costs*: Energy pricing is a complex related matter. Apart from the reasons lied on seasonal cycles and highly market volatility, energy providers intensify the diversification of their pricing schemes with the development of renewable sources of energy. Accordingly, the academics tend to align their models with this economic conjuncture, by considering time-varying energy costs (Masmoudi et al., 2017; Rapine et al., 2018b).
- *Limitations in the available amount of energy*: The limitations in the available amount of energy per period or over the entire time horizon can be justified by different application reasons. In particular, that is the case of renewable energy sources, which require to carefully manage the electricity demand and balance electric grids. Hence, the electric energy can no longer be considered unlimited (Rapine et al., 2018b,a). To go further in this direction, Masmoudi et al. (2017) envisaged the case of more realistic energy supply contracts, defined in terms of the maximal power and electricity prices over time.

For modeling purposes, consider the energy single-item lot-sizing problem examined by Rapine et al. (2018b). This problem consists in determining the quantity X_t to be produced over a planning horizon of T periods, in order to satisfy each periodic deterministic demand d_t , $\forall t \in \llbracket 1, T \rrbracket$. The industrial process is performed on parallel and identical machines. The production capacity depends on the number of running machines M_t , which is bounded by a constant C per machine. The number of machines started-up at the beginning of period t is denoted by M_t^+ . I_t represents the inventory level at the end of period t . The available amount of energy is limited to E_t . Let e_t be the amount of energy necessary to produce one unit of the considered product. The start-up of one machine in period t consumes w_t amount of energy. The production process involves the following costs: (i) h_t , the unit holding cost, (ii) p_t , the unit production cost, (iii) $f(M_t^+)$, the cost to start-up M_t^+ machines.

The notations introduced above allow us to model the energy-aware lot-sizing problem as:

$$\min \sum_{t=1}^T [f(M_t^+) + p_t X_t + h_t I_t] \quad (30)$$

s.t.

$$I_{t-1} + X_t = I_t + d_t, \quad \forall t \in \llbracket 1, T \rrbracket \quad (31)$$

$$X_t \leq C M_t, \quad \forall t \in \llbracket 1, T \rrbracket \quad (32)$$

$$I_0 = 0 \quad (33)$$

$$e_t X_t + w_t M_t^+ \leq E_t \quad \forall t \in \llbracket 1, T \rrbracket \quad (34)$$

$$M_t^+ \geq M_t - M_{t-1} \quad \forall t \in \llbracket 1, T \rrbracket \quad (35)$$

$$I_t, X_t \geq 0, \quad \forall t \in \llbracket 1, T \rrbracket \quad (36)$$

$$M_t^+, M_t \in \mathbb{N}, \quad \forall t \in \llbracket 1, T \rrbracket \quad (37)$$

The traditional lot-sizing constraints are modeled by the first three constraints in the following order: flow conservation constraints (31), production capacity restriction (32), initial inventory setting (32). The energy consumption is limited via inequalities (34). Constraints (35) link the number of machines started-up at the beginning of t with the number of running machines in t and $t - 1$. The definition domains of problem variables are given by constraints (36)-(37). The cost-based objective function is provided by the expression (30).

6.2.2. Complexity and solution approaches

Rapine et al. (2018a) shown that the basic energy-aware lot-sizing problem (30)-(37) is NP-hard. However, under some strong assumptions (sometimes unrealistic), the program (30)-(37) can be solved by polynomial-time solution methods (Rapine et al., 2018b,a).

The rest of studies found in the related literature use either standard solvers to solve the resulting mixed integer programs (Wichmann et al., 2018; Golpîra et al., 2018), or developed heuristics (Relax-and-Fix, LP-based, Lagrangian Relaxation) to come up with feasible solutions (Masmoudi et al., 2017; Giglio et al., 2017; Tang et al., 2012).

6.2.3. Industrial implications and discussions

As Table 6 shows, very few research efforts have been dedicated to integrating energy efficiency issues in production planning problems. This topic deserves to be extended in several directions:

- *Theoretical development:* Rapine et al. (2018a) left open the question about the NP-hardness of the mixed-integer program (30)-(37). Is it NP-hard in the strong sense or in the weak sense? Generally speaking, the energy-aware lot-sizing problem remains open for extensively investigations from the theoretical point of view.
- *Energy consumption versus GHG emissions:* Future studies must take into account the contradictory character of the energy efficiency goals, notably the energy consumption (or its related cost) against greenhouse gas emissions. For example, coal-fired power plants are known to be the largest contributors to the atmospheric carbon dioxide concentrations, which usually generate cheap energy during off-peak consumption periods (Biel and Glock, 2016).
- *Renewable energy resources and energy storage:* One of the main issues of renewable energy resources (such as wind or solar energy sources) relates to their intermittent production and difficulty to store energy. For example, electricity can be stored in batteries or transformed into a storable energy. Excess of electricity production can be used to transform water (H₂O) into hydrogen (H₂), i.e. an energy easier to store. This hydrogen can be used to produce electricity when needed or to power hydrogen-based systems (vehicles, facilities, etc.). This way of considering energy poses a number of questions related to lot-sizing for energy management: When to buy energy? When to store it? How much to store, and when and how much to retrieve? In production planning models involving energy-related constraints, loss of energy should be taken into account.
- *Energy production and smart grids:* Since electricity is not easy to store, one may want to align electricity productions with electricity demands, or to create intermediate energy storage facilities for preserving unused energy. The alignment of demands with productions can be done by setting up some incentives (discounts, premiums, etc.) to move energy demands to periods where renewable energy is available. This mechanism of energy production and consumption leads to new lot-sizing models with special energy cost functions and intermediate energy storage facilities.

7. Summary of findings

The extensive breadth of studies, carried out to support the transition of industrial processes from a linear toward a circular economy, stands out across the different sections of this paper. Despite the significant research efforts dedicated to making *circular* production streams, a number of gaps remain to be filled and reflections to be conducted.

Characterize and handle different data formats. Decision-making under unknown data is one of the main issues of the most recovery operations. In upstream operations, the product returns and undesirable production outputs are both qualitatively and quantitatively subject to a high variability. This variability is often conditioned by factors difficult to be explained, controlled or anticipated. Further down the recovery chain, outgoing streams inherit the market volatility and sensitivity to economic and financial fluctuations, so specific for classical linear production schemes.

Some of aforementioned factors are measurable and can be quantified from available historical data, industrial evidence, or traceability information provided by new communicating technologies. The extraction of knowledge from available data may give valuable suggestions and contribute to soundly support the decision-making, whether the exhibited knowledge results in deterministic-based, probabilistic or fuzzy formats. In this respect, the scarcity of research studies dealing with non-deterministic or heterogeneous data formats is a major lack. Given the ubiquity of communicating technologies and the recent advances in high-performance computing technologies, it is imperative to fill this gap.

Extend existing models and consider real-life features. As underlined throughout different sections, numerous extensions are worth to be pursued. Let us now enumerate some of them, which are applicable for all topics covered by this review:

- In the context of international trade and climate policy, far more attention should be paid to the consideration of environmental implications into production planning including recovery operations.
- If the economic and environmental dimensions of the sustainable development are more or less studied, the social aspect remains to be explored. This is a particularly topical subject, given the actual multiple drivers of business relocation such as: globalisation, greenhouse gas emissions tax, slow return on investment, market proximity.

Integrate interrelated problems. Despite the proven benefits of handling various interrelated problems in an integrated way, there is a scarcity of studies that takes simultaneously decisions belonging to different class of problems. Given the plenty of interdependencies created by the circularity character of reverse logistics, a great deal of research should be done in this sense:

- *From returns collection to serviceable products distribution:* A typical remanufacturing facility includes three different subsequent industrial steps: disassembly, manufacturing/remanufacturing processing, and reassembly. This poses original lot-sizing problems under uncertainty on the quantities of returned products, qualities of products and sub-products, announced quality of returned products.

An original lot-sizing problem would be to integrate both disassembly and remanufacturing in the demand fulfillment of intermediate products. This is typically the case in the automotive industry, in which used vehicle components are remanufactured or refurbished in order to be sold.

Another original problem consists in integrating disassembly with remanufacturing and reassembly. This is mainly the case for remanufactured products. Sometimes these products should be disassembled, sub-products are remanufactured or replaced and finally these sub-products are reassembled to be sold as new products. This generates lot-sizing problems in which all these processes need to be considered.

- *Carbon emission constraints in circular economy:* As shown in Section 6, the majority of studies dealing with carbon emissions addressed classical lot-sizing problems. Note that all circular economy concepts (disassembly, remanufacturing, by-products and co-production, etc.) should be environmentally viable. Accordingly, carbon emissions should become classical constraints and/or objectives in all these problems. This will naturally introduce an overlay of complexity, but will help converging toward environmentally-friendly processes.
- *Toward eco-industrial parks: Self-sufficient industrial parks* (also called *eco-industrial parks*) emerge as an effective approach toward a sustainable growth. Eco-industrial parks offer the same business advantages as classical industrial parks, while using resources more efficiently. As pointed out in Section 5.3 and Section 6.2.3, eco-industrial systems offer opportunities for all three dimensions of the sustainable development: **(i) economic:** to avoid disposal costs and increase resource efficiency by means of the industrial synergy between different industrial activities **(ii) environmental:** to reduce the raw material consumption and the environmental impact via the exchange of by-products and other collateral resources (energy, water, services, etc.), **(iii) social:** to support the regional economic development. Combining the constraints related to all of these flow exchanges and the multiple objectives posed by the sustainable development leads to new original and complex production planning problems. Multiple aspects should be integrated in these problems: resource flow synchronization, decision-making at different time granularity imposed by the production processes, simultaneous coordination of several industrial activities, etc.

Deal with real-life applications and support industries in their transition toward a circular economy. As can be drawn from this review, a number of academic models together with their solution methods are relatively well-posed and investigated. On the flip side, a few industrial case studies have been conducted in the literature, despite the highly industrial character of all recovery operations. Of particular interest are innovative applications which can be attractive for both: **(i) academics**, to better apprehend industrial realities and needs, as well as to address complex and ill-structured real-life problems, **(ii) practitioners**, to be assisted in solving their industrial problems. Moreover, we believe that the collaboration of these complementary communities is equally important to go even further into the reflection on how to facilitate and flourish the transition toward a circular economy.

8. Conclusion

This paper presents a state-of-the-art focused on discrete-time optimization models for tactical production planning under the prism of circular economy. The main recovery operations and notions with respect to this concept are clearly defined and discussed. In the light of global environmental pressures, an emphasis is also put on greenhouse gas emissions and energy consumption. Within this framework, we divided the state-of-the-art on the production planning problems dealing with circular economy concepts into four parts: **(i)** disassembly for recycling, **(ii)** product and raw material recycling, **(iii)** by-products and co-production, and **(iv)** greenhouse gas emissions and energy consumption. For each part, definitions for terms related to the topic under study and an overview of the existing literature are provided.

The findings of this review reveal a number of gaps and new insights as to how recovery options can be suitable integrated within traditional production environments for converging toward an environmentally-friendly economy. A particular emphasis has been placed on emerging transversal problems having a strong production planning connotation.

Based on the collection of gathered papers, the literature review presented in this paper may be termed subjective. Despite this, we believe that the selected publications give an informative and comprehensive view of the state-of-the-art for both researchers and practitioners.

Notes

1. The directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives. ELI: <https://eur-lex.europa.eu/eli/dir/2008/98/oj>
2. The Resource Conservation and Recovery Act of the USA. <https://www.gpo.gov/fdsys/pkg/STATUTE-90/pdf/STATUTE-90-Pg2795.pdf>
3. The Pollution Prevention Act of the USA. <http://www.moleg.go.kr/english/korLawEng?pstSeq=54749>
4. The Circular Economy Promotion Law of the People's Republic of China. http://www.fdi.gov.cn/1800000121_39_597_0_7.html
5. The Law for establishing a Material Cycles society of Japan. <https://www.env.go.jp/en/laws/recycle/12.pdf>
6. The Environmental Protection Law of Vietnam. http://moj.gov.vn/vbpq/en/lists/vn%20bn%20php%20lut/view_detail.aspx?itemid=5961
7. The Wastes Control Act of Korea. <http://www.moleg.go.kr/english/korLawEng?pstSeq=47552>
8. The Act on Promotion of Resources Saving and Recycling. <http://www.moleg.go.kr/english/korLawEng?pstSeq=54749>
9. <http://www.scot-reman.ac.uk/>
10. <https://www.institut-economie-circulaire.fr>
11. <https://unfccc.int/resource/docs/convkp/kpeng.html>
12. United Nations Framework Convention on Climate Change. <https://unfccc.int/>
13. The Paris Agreement. http://unfccc.int/paris_agreement/items/9485.php
14. Greenhouse Gas Protocol. <http://www.ghgprotocol.org>
15. EcoTransIT World. <https://www.ecotransit.org>

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