Towards circular economy in production planning: Challenges and Opportunities

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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.

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Abstract

In the actual era of the international trade, global warming and depletion of Earth's natural resources, the willingness to generate sustainable and competitive benefits determines us to stop thinking *linearly* (produce, consume and dispose) and to shift towards a *circular* approach by closing material loops. The latter falls within the concept of *circular economy* that, in turn, derives from *reverse logistics*. This paper proposes a comprehensive state-of-the-art review around the topic of circular economy and reverse logistics with a particular emphasis on mid-term production planning under discrete time settings. 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 the 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. A cross-cutting analysis of the reviewed literature brought forward a number of research gaps and revealed multiple research opportunities to support the development of the circular economy. The key findings show an ever growing interest in making sustainable the traditional linear industrial processes within a circular economy context.

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 Directive[1] (2008); in USA, the Enactment of the Resource Conservation and Recovery Act[2] (1984) and the Pollution Prevention Act[3] (amended in 2002); in China, the Circular Economy Promotion Law[4] (2008); in Japan, the Law for establishing a Material Cycles Society[5]; in Vietnam, the Environmental Protection Law[6] (2005); in Korea, the Waste Control Act[7] (amended in 2007) and the Act on Promotion of Resources Saving and Recycling[8] (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** (CE) 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 Remanufacture[9] (United Kingdom) and the Institut de l'Économie Circulaire[10] (France), have been created to help industrial actors adopting this concept in their production and supply chains.

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 environmentally-friendly operations related to the reuse of products and raw materials. For example, the European Commission established, by Article 4 of the Waste Framework Directive[1], 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 Directive[1], *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 the 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 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 and its three pillars (economic, environmental and social):** By virtue of its definition, the circular economy encompasses the *sustainable development*, defined as the *"development that meets the needs of the present without compromising the ability of future generations to meet their own needs"* (Keeble, 1988).

  This paper addresses the sustainable development in discrete mid-term production planning via its triple-bottom-line dimension. The *economic* pillar is implicitly considered by means of economic-oriented objective functions of CE-related lot-sizing problems, which include economic metrics such as costs, profits, incomes. The *environmental* pillar is explicitly addressed in Section 7. Due to the lack of research studies, the *social* pillar of production system is discussed only in the concluding section.

To highlight how the circular economy redraws the classical linear production approach, Figure 1 maps the aforementioned five waste management options into production systems. Dashed backward arcs correspond to the production activities related to the circular economy, and bring out the relationships between them (see e.g. Govindan and Soleimani (2017); Kumar and Putnam (2008); Soleimani and Govindan (2014); Srivastava (2008); Thierry et al. (1995)). As shown in Figure 1, the interference between the reverse and forward flows affects the production planning process, which includes: **(i)** the planning of recovery and raw material procurement, and **(ii)** the planning of the production activities required to transform input materials into finished products to satisfy the customer demands, covering both remanufactured and new products (Dekker et al., 2013). The reverse flows impact the decision levels of production systems in different proportions:

- The *operational* production planning problems refer to short-term decisions, such as line balancing or scheduling.

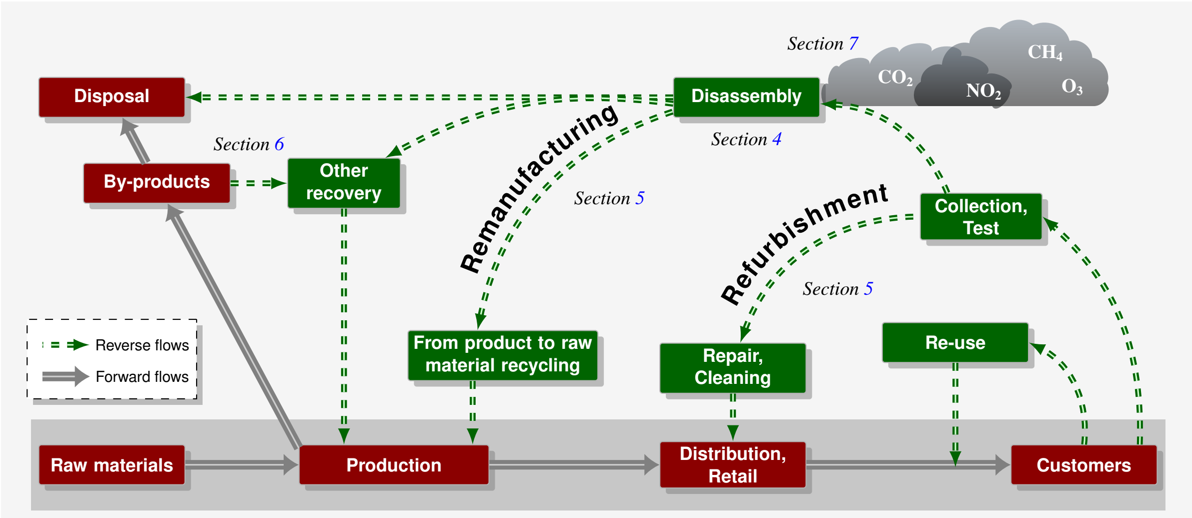


Figure 1: Circular economy: *An overview*

Once the mid-term needs are determined, these decision-making problems can, in most cases, assimilate the reverse production streams without additional constraints or costs in objective functions.

- The mid-term production planning problems seek to assist managers/firms at *tactical* level in deciding how much and when: to produce and order new goods, to (dis-)assemble, and 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 (see Figure 1). All of these CE-oriented flows change the structure of the traditional linear production path, by adding an additional layer of complexity to the mid-term production planning.
- More broadly, *strategic* planning problems operate at the supply chain level, by integrating procurement, distribution and recovery decisions. Although the strategic CE-decisions are of crucial importance and investment, their posing and making are less frequent and take place upstream the supply chain constitution. The reader is referred to the literature review of Moreno-Camacho et al. (2019) for an analysis of sustainability at the strategic level of the supply chain management.

Motivation and contributions. Under the pressure of the actual new environmental regulations worldwide and motivated by the sustainable opportunities that CE can procure, this review puts the spotlight on mid-term production planning viewed through the prism of the circular economy. As previously noted and illustrated in Figure 1, the CE-oriented flows break the structure of the well-studied tactical decision-making problems based on a linear production approach. Reverse streams cannot be assimilated as such, and require to be explicitly integrated and considered in the actual production environments. In this context, the contribution of the current paper is manifold: **(i)** to offer a representative overview of the research and industrial efforts made towards a circular economy in production planning, **(ii)** to provide an unequivocal taxonomy and definitions of inherent CE-oriented industrial processes, and **(iii)** to derive new avenues for both academics and practitioners as to how recovery options can be suitably integrated within traditional production environments to converge towards an environmentally-friendly economy.

Content structure. Being written in the complementarity of the existing related surveys discussed in Section 2, this paper is structured as follows. The reviewed publications are categorized and discussed with respect to the recovery loops depicted in Figure 1, namely: **(i)** disassembly for recycling in Section 4, **(ii)** from product to material recovery in Section 5, and **(iii)** by-products and co-production in Section 6. To go further than these reverse logistics processes, Section 7 takes interest in the quantitative implications resulting from the consideration of greenhouse gas emissions and energy consumption in the production planning process. Section 8 consolidates the findings of this state-of-the-art review and derives a number of opportunities for future research based on the identified gaps. Finally, Section 9 concludes this review paper.

Content analysis. For the sake of rigor, this literature review follows a systematic scheme to present and to analyze the content of the collected papers:

- **Material collection:** see Section 3.
- **Material description:** This step aims: **(i)** to present the context of the topic under focus, **(ii)** to elucidate the related definitions, and **(iii)** to review the mathematical formulations jointly with a structured overview of the existing solution methods, and to discuss the industrial implications of addressed problems.
- **Material analysis:** Each of Sections 4-7 complies with a unique common thread. For each of the topics addressed in Sections 4-7, we identified the key classification parameters and features based on the characteristics of the problems under study. In accordance with the proposed topic-specific taxonomy, the papers are characterized in tables and graphics, and their content is cross-analyzed and discussed in the paper text.

2. Position in the literature

Since the 2000s, the keyword *circular economy* (CE) appears explicitly in the title of many reviews in various areas, such as environmental science, energy, engineering, or resource management. The definition and the contextualization of CE given in the current review are based on the findings discussed in previous general-purpose reviews on the topic (see e.g. Kirchherr et al. (2017); Homrich et al. (2018); Reike et al. (2018)). To provide an overarching picture of the CE emergence and its actual context, let us take a historical look and examine the literature reviews conducted on other notable CE-related concepts (see Figure 2 and Table 1).

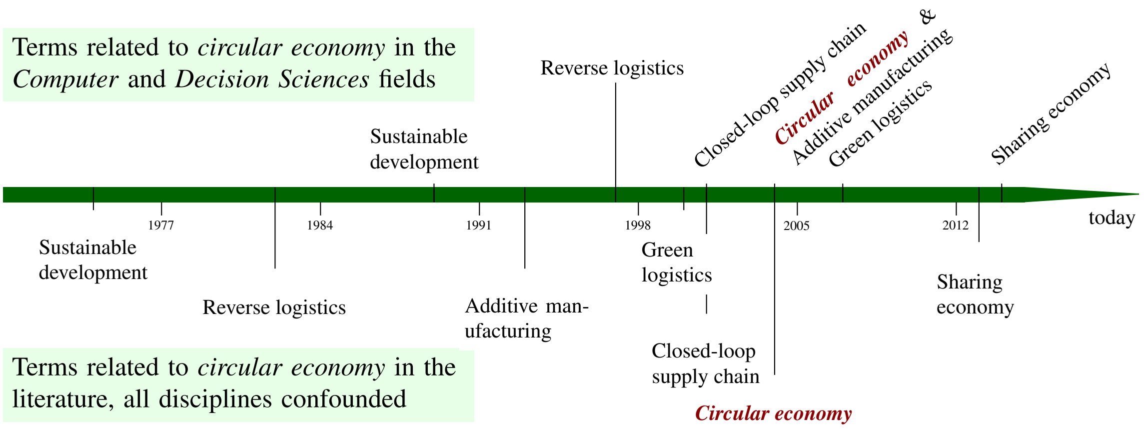


Figure 2: The emergence of *circular economy* and its precursors in the literature: *A brief chronology based on the database Scopus (in Title, Abstract and Keywords)*

Falling within the CE, the circular way of thinking derives from the concept of *reverse logistics* (or reverse supply chain) introduced in the late 1970's, 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). The network including both forward and reverse supply chains simultaneously is known in the literature under the umbrella term *closed-loop supply chain* (CLSC) (Dekker et al., 2013; Govindan et al., 2015), and starts to be evoked in earnest in the 2000s. Since then, a number of surveys have been conducted on reverse logistics and CLSCs. The interested reader can refer to the review of Govindan et al. (2015) to take note of review studies published until 2015. For years after 2015, Singh et al. (2016) evaluate the impact of reverse logistics on apparel industry in their industry-specific survey. More generally, Kazemi et al. (2019) review the articles on reverse logistics and CLSCs published only in the International Journal of Production Research.

To foster the generation of sustainable and competitive benefits, governments definitely want to stop thinking linearly for shifting towards a circular approach by: **(i)** eco-designing products, **(ii)** waste preventing, reusing and recovering, **(iii)** exploiting renewable energy resources. 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. Even if the sustainable development finds its roots much earlier, its formal introduction dates from 1987 by the World Commission on Environment and Development with the publication of the so-called *Our Common Future* or *Bruntland Report* (Keeble, 1988). Since this milestone, multiple events and research efforts continue to trace the evolution of the sustainable development (Eustachio et al., 2019). For example, let us mention the additive manufacturing (also known as 3D printing) developed in the 1980's, whose potential to support the sustainable product design is actively promoted in the last decade (Sauerwein

Table 1: Previous review studies

Reference	Field		Focus	Scope	Covered period
	GP	OR			
Sbihi and Eglese (2007)		✓	GL	quantitative models dealing with GL issues	until 2007
Sarkis et al. (2011)		✓	GL	organizational theory of green supply chain management	until 2010
Dekker et al. (2013)		✓	CLSC	quantitative models for closed-loop supply chains	until 2003
Demir et al. (2014)		✓	GL	quantitative models for transportation	until 2013
Fahimnia et al. (2015)		✓	GL	bibliometric and network analysis of green supply chain management	until 2013
Govindan et al. (2015)		✓	RL, CLSC	content analysis of RL and CLSC	2007 - 2013
Marshall et al. (2015)		✓	SD	environmental and social pillars of SD in the supply chain management	until 2015
Singh et al. (2016)		✓	RL	RL in the apparel industry	until 2016
Kirchherr et al. (2017)	✓		CE	definitions and content analysis related to CE	until 2017
Barbosa-Póvoa et al. (2018)		✓	SD	OR methods to support SD in the supply chain management	until 2016
Kaur and Awasthi (2018)		✓	GL	challenges in green supply chain management	until 2015
Homrich et al. (2018)	✓		CE	definitions; semantic, bibliometric and content analysis related to CE	until 2017
Reike et al. (2018)	✓		CE	historical development of CE, resource value retention options	until 2017
Bektaş et al. (2019)		✓	GL	OR methods in green freight transportation	until 2018
Bibri (2019)	✓		SD	sustainability of smart cities in the era of big data	until 2018
Curtis and Lehner (2019)	✓		SD	sharing economy for sustainability	until 2019
Kazemi et al. (2019)	✓		RL, CLSC	bibliometric and content analysis of CLSC	until 2017
Mathiyazhagan et al. (2019)	✓		GL	environmental pillar in sustainable manufacturing	2002 - 2017
Moreno-Camacho et al. (2019)	✓		SD	sustainability metrics of the supply chain network design	2015 - 2018
Nascimento et al. (2019)		✓	CE	industry 4.0 technologies for CE in manufacturing	until 2018
Nenni et al. (2019)		✓	SD	OR methods for sustainable urban freight transportation	2009 - 2018
Pinheiro et al. (2019)		✓	CE	new product design and development with CE	until 2018
Sauerwein et al. (2019)	✓		CE	additive manufacturing for the product design in CE	until 2019
Thies et al. (2019)		✓	SD	OR methods for sustainability assessment of products	until 2018
Waltho et al. (2019)		✓	GL	carbon emissions and environmental policies in the supply chain design	2010 - 2017
This paper		✓	CE	CE in production planning	until 2019

GP: General-Purpose, OR: Operations Research, GL: Green Logistics, RL: Reverse Logistics, CLSC: Closed-Loop Supply Chain, SD: Sustainable Development, CE: Circular Economy

et al., 2019). Further on the subject of sustainability, sustainable consumption practices are, in recent years, propagandized in the framework of the sharing economy, a broad concept still in maturation (Curtis and Lehner, 2019).

Since 2003, more than a hundred of reviews are published, preponderantly in environment, social and energy fields. In the field of *Computer* and *Decision Sciences*, the literature on sustainability is mainly reviewed to highlight and quantify the effect of its consideration in the conventional organization of different activity sectors, such as urban systems (Bibri, 2019), transportation (Nenni et al., 2019), supply chain (Moreno-Camacho et al., 2019; Barbosa-Póvoa et al., 2018; Marshall et al., 2015), and production (Thies et al., 2019).

With regard to the environmental dimension of sustainability, the prefix *green* is reserved, and commonly used to underscore the explicit consideration of environmental aspects in a given industrial activity. In *Computer* and *Decision Sciences* literature, the greenness of different logistics activities has been reviewed (Sbihi and Eglese, 2007) e.g.: manufacturing (Mathiyazhagan et al., 2019), freight transportation (Demir et al., 2014; Bektaş et al., 2019), supply chain (Waltho et al., 2019; Kaur and Awasthi, 2018; Fahimnia et al., 2015; Sarkis et al., 2011). Note that green logistics activities are not necessarily reverse logistics (Rogers et al., 1999).

To the best of our knowledge and based on the Scopus database, only two review studies, including in their title the keyword *circular economy*, have been conducted in the field of *Computer* and *Decision Sciences* , namely: **(i)** Nascimento et al. (2019) surveyed the integration of industry 4.0 technologies with CE practices in a manufacturing context, from an operations management point of view, and **(ii)** Pinheiro et al. (2019) touched upon the new product development and life cycle within the CE. More widely, our review seeks to map the existing literature on production planning integrating CE practices, while taking into account earlier review studies from a range of disciplines (see Table 1).

3. Material collection

This literature review covers 160 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 purpose and scope of this review, we defined two sets of keywords, namely:

- *Production planning:* Besides the keyword *production planning*, this set includes also *lot-sizing*. Note that the production planning aiming at determining the size of production lots and the time of production, is known in the literature as the *lot-sizing* problem.
- *Circular economy:* This set includes the terms corresponding to all industrial CE-oriented processes illustrated in Figure 1: *recycling*, *disassembly*, *remanufacturing*, *refurbishment*, *repair*, *reuse*, (*by-product* or *byproduct*), (*co-production*, *co-product* or *coproduct*). In addition, 4 keyword strings have been considered to capture the sustainable property of CE: (*sustainability* or *sustainable*), *zero waste*, (*human* or *social* or *ergonomics*), (*carbon emissions* or *greenhouse gas emissions* or *energy*).

- All of 16 possible combinations of keywords from the first and second sets have been applied to query Scopus, one of the largest online databases of peer-reviewed literature. Interestingly, no documents were found in Scopus by using the string of keywords: [*zero waste* and (*production planning* or *lot sizing*)]. To keep the collection of papers to a manageable cardinality and avoid redundancies between conference papers and their extended article version, we only considered journal articles published or "in press" and book chapters, without time limit.
- In the next stage, we proceeded to a backward reference search, by checking the complete reference lists of all previously retrieved papers to identify other relevant articles that cited them.
- After having removed articles deemed out of scope and duplicates, we reached a total of 103 papers distributed per topic as follows: 29 papers on *disassembly for recycling*, 50 papers on *recovery options like remanufacturing and refurbishment*, 10 papers on *by-products* and/or *co-production*, 14 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 103 papers in the field of operations research, we added 56 transdisciplinary general-purpose and review papers.
- A particular attention has been paid to industrial applications found in the reviewed articles. To feed into the discussions on the CE development, the industrial dimension of this state-of-the-art review has been strengthened by surveying: **(i)** the library of industrial symbiosis case studies proposed by Evans et al. (2017), **(ii)** the research and innovation projects relevant to the circular economy strategy funded by the European Commission[11].

4. 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. Kalaycılar 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).

4.1. *Mathematical formulation*

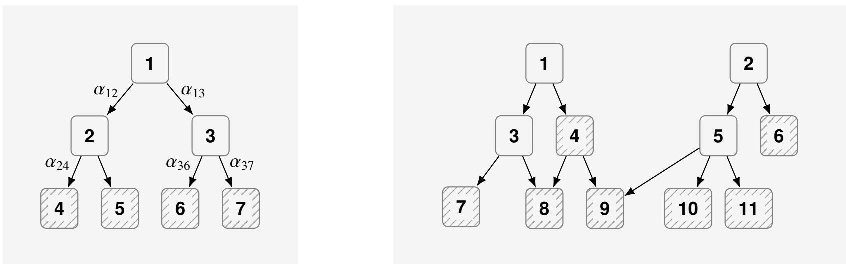
Two classes of problems revolve around production planning in disassembly systems, namely disassembly-to-order and disassembly lot-sizing. Table 2 analyzes the identified papers focusing particularly on the class of disassembly scheduling problems, which can allow:

Table 2: Disassembly lot-sizing

Reference		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)	Reviewed in Kim et al. (2007)	✓					✓		✓			✓		G
Taleb and Gupta (1997)		✓	✓	✓			✓			✓		✓		G
Taleb et al. (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. (2006b)		✓	✓	✓			✓			✓		✓		G
Kim et al. (2006c)		✓				✓	✓			✓		✓		G
Langella (2007)		✓	✓	✓			✓			✓		✓		G
Qu and Williams (2008)			✓			✓	✓				✓		✓	automotive
Barba-Gutiérrez and Adenso-Díaz (2009)		✓						✓		✓		✓		G
Kim et al. (2009)		✓					✓		✓			✓		G
Xanthopoulos and Iakovou (2009)			✓	✓		✓	✓				✓	✓		electric appliance
Kim and Xirouchakis (2010)			✓			✓		✓		✓		✓		G
Ahn et al. (2011)							✓			✓		✓		G
Prakash et al. (2012)		✓		✓			✓			✓		✓		G
Han et al. (2013b)						✓	✓				✓	✓		G
Wang and Huang (2013)		✓	✓	✓		✓		✓			✓	✓		G
Sung and Jeong (2014)		✓				✓	✓			✓		✓		G
Ji et al. (2016)			✓	✓		✓	✓			✓			✓	valve factory
Fang et al. (2017a)			✓	✓		✓		✓		✓			✓	iron and stell
Habibi et al. (2017)						✓	✓				✓	✓		G
Kim et al. (2018)		✓	✓	✓	✓		✓			✓		✓		G
Liu and Zhang (2018)						✓		✓		✓			✓	valve factory
Tian and Zhang (2019)			✓			✓	✓			✓		✓		G

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

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 3(a)), and **(ii)** *general type*, otherwise (see Figure 3(b)).



(a) Assembly structure (b) General structure

Product part   Product part with demand

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

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.

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 3(a). All items are numbered level by level: $1, 2, \ldots, \ell, \ell + 1, \ldots, N$, 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 $1, 2, \ldots, T$. 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}, $\forall t \in [\![1, T]\!], \forall i \in [\![1, \ell - 1]\!]$.

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, $\forall t \in [\![1, T]\!], \forall i \in [\![2, N]\!]$. The available quantity of the root-item is supposed unlimited. The parameters and decision variables are given in Table A.7. A generic version of the disassembly lot-sizing problem is given below:

$$\text{minimize} \sum_{t=1}^{T} \left[\sum_{i=1}^{\ell-1} f_i Y_{it} + \sum_{i=2}^{N} h_i I_{it} \right] \tag{1}$$

subject to:

$$I_{i,t-1} + \alpha_{(i),i} X_{(i),t} = I_{it} + d_{it} \qquad \forall t \in [\![1, T]\!], \forall i \in [\![\ell, N]\!] \tag{2}$$

$$I_{i,t-1} + \alpha_{(i),i} X_{(i),t} = I_{it} + X_{it} \qquad \forall t \in [\![1, T]\!], \forall i \in [\![2, \ell - 1]\!] \tag{3}$$

$$I_{i,0} = 0 \qquad \forall i \in [\![2, N]\!] \tag{4}$$

$$X_{it} \leq M Y_{it} \qquad \forall t \in [\![1, T]\!], \forall i \in [\![1, \ell - 1]\!] \tag{5}$$

$$I_{it} \geq 0 \qquad \forall t \in [\![1, T]\!], \forall i \in [\![2, N]\!] \tag{6}$$

$$X_{it} \geq 0 \text{ and integer} \qquad \forall t \in [\![1, T]\!], \forall i \in [\![1, \ell - 1]\!] \tag{7}$$

$$Y_{it} \in \{0, 1\} \qquad \forall t \in [\![1, T]\!], \forall i \in [\![1, \ell - 1]\!] \tag{8}$$

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)). Even if rare, of importance to mention is the explicit consideration in the mathematical models of CE issues, other than those related to the disassembly process per se. For example, the legislative and environmental requirements, imposed by the Directive 2002/96/EC, appear in the constraints of a mathematical model proposed by Xanthopoulos and Iakovou (2009) for a case study encountered in a manufacturing enterprise of electric heating appliances.

4.2. 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 this 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 heuristic approaches can be found: 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, 2019).

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).

4.3. Industrial implications and discussion

With respect to disassembly scheduling, Kim et al. (2007) provided a literature review 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, 2019; Qu and Williams, 2008), leveling and scheduling (Kang et al., 2012).
- *Integration with other activities in recovery systems:* Roughly speaking, a typical remanufacturing system covers three stages: disassembly, reprocessing, and reassembly. The process interconnections and information flows between these core stages make recovery systems complex to be managed as a whole, and pose multiple research problems, earlier identified by Guide Jr (2000). From the 2000s onward, several research studies have been undertaken, e.g.: Ahn et al. (2011) studied a three-stage lot-sizing model integrating disassembly, reprocessing and reassembly processes; Hashemi et al. (2014) addressed an integrated system of manufacturing and remanufacturing, including disassembly for the aerospace industry. As also underscored in Section 5, additional efforts remain to be carried out to harmonize the coordination between disassembly release with reassembly, while sustainably closing the products use cycle.

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; Fang et al., 2017a; Liu and Zhang, 2018).

5. 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.

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 4. 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)).

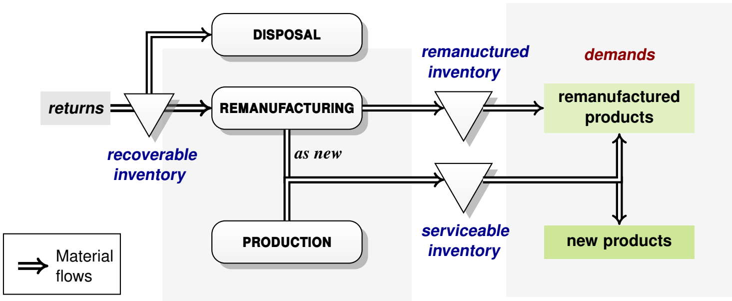


Figure 4: Production system including remanufacturing

5.1. Mathematical formulation

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 (see e.g. Sahling (2013)), 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 thereby 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 have 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 4, 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 quantity of returns, $\forall t \in [\![1, T]\!]$. 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 $\hat{h}_t$, $\forall t \in [\![1, T]\!]$.

Let X_t ($\hat{X}_t$) be the quantity of manufactured (remanufactured) products and Y_t be ($\hat{Y}_t$) the binary indicator for manufacturing (remanufacturing) in period $t \in [\![1, T]\!]$. 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 summarized in Table A.8, the LSR problem with time-dependent parameters and separated setups can be formulated as follows:

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

subject to:

$$\hat{I}_{t-1} + r_t = \hat{I}_t + \hat{X}_t \qquad \forall t \in [\![1, T]\!] \tag{10}$$

$$I_{t-1} + \hat{X}_t + X_t = I_t + d_t \qquad \forall t \in [\![1, T]\!] \tag{11}$$

$$I_0 = \hat{I}_0 = 0 \tag{12}$$

$$\hat{X}_t \leq \sum_{i=t}^{T} d_i \hat{Y}_t \qquad \forall t \in [\![1, T]\!] \tag{13}$$

$$X_t \leq \sum_{i=t}^{T} d_i Y_t \qquad \forall t \in [\![1, T]\!] \tag{14}$$

$$\hat{X}_t, X_t, \hat{I}_t, I_t \geq 0 \qquad \forall t \in [\![1, T]\!] \tag{15}$$

$$\hat{Y}_t, Y_t \in \{0, 1\} \qquad \forall t \in [\![1, T]\!] \tag{16}$$

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).

5.2. 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 have 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: con-

Table 3: Lot-sizing with remanufacturing options

Reference	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
Jayaraman (2006)		✓			✓	✓		✓				✓	cellular telephones
Li et al. (2006)		✓		✓		✓		✓	✓		✓		G
Teunter et al. (2006)			✓	✓		✓		✓	✓		✓		G
Li et al. (2007)		✓		✓	✓	✓			✓		✓		G
Li et al. (2009)							✓	✓			✓		G
Pan et al. (2009)		✓			✓	✓		✓			✓		G
Piñeyro and Viera (2009)		✓		✓		✓			✓		✓		G
Xanthopoulos and Iakovou (2009)	✓			✓	✓	✓				✓	✓		G
Denizel et al. (2010)		✓			✓		✓		✓		✓		G
Piñeyro and Viera (2010)	✓	✓		✓		✓			✓		✓		G
Ahn et al. (2011)		✓		✓		✓			✓		✓		G
Schulz (2011)				✓		✓			✓		✓		G
Zhang et al. (2011)		✓		✓	✓	✓			✓			✓	steel
Tao et al. (2012)							✓		✓		✓		G
Zhang et al. (2012)	✓	✓		✓	✓	✓			✓		✓		G
Han et al. (2013b)	✓	✓			✓	✓				✓	✓		G
Naeem et al. (2013)				✓	✓	✓	✓	✓			✓		G
Sahling (2013)			✓	✓	✓	✓				✓	✓		G
Wang and Huang (2013)				✓	✓		✓			✓	✓		G
Baki et al. (2014)				✓		✓			✓		✓		G
Cai et al. (2014)							✓			✓	✓		G
Chen and Abrishami (2014)	✓	✓		✓		✓			✓		✓		G
Hashemi et al. (2014)				✓	✓	✓				✓	✓		aerospace
Li et al. (2014)				✓		✓			✓		✓		G
Mehdizadeh and Fatehi Kivi (2014)		✓		✓	✓	✓			✓		✓		G
Retel Helmrich 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
Ali et al. (2018)		✓		✓		✓				✓	✓		G
Kilic et al. (2018)				✓			✓		✓		✓		G
Koken et al. (2018a)	✓				✓	✓			✓		✓		G
Koken et al. (2018b)	✓				✓	✓			✓		✓		G
Piñeyro and Viera (2018)				✓		✓			✓		✓		G
Zouadi et al. (2018)				✓		✓			✓		✓		G
Cunha et al. (2019)		✓		✓	✓	✓			✓		✓		G
Kilic and Tunc (2019)				✓			✓		✓		✓		G
Kilic and van den Heuvel (2019)		✓		✓		✓			✓		✓		G

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

structive (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 (MDLSRP), and **(ii)** with product returns and recovery (ELSRP). These instances are available on `http://users.uom.gr/~sifalera/benchmarks.html` and described in (Sifaleras et al., 2015; Sifaleras and Konstantaras, 2017).

5.3. *Industrial implications and discussion*

The management of production planning with remanufacturing differs from management activities in traditional production systems in several aspects: **(i)** the integration of return flows, whose quantity, quality and timing 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) has 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 4), **(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.
- As highlighted in Section 4, the coordination between disassembly, remanufacturing and reassembly deserves more theoretical and practical attention. The evaluation of different management policies between these strongly correlated industrial processes could help to identify opportunities to improve the overall performance of such integrated systems.
- 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. Only a few real-life applications can be found in the literature, e.g. in the steel industry (Zhang et al., 2011; Fang et al., 2017a), aerospace manufacturing (Hashemi et al., 2014), or cellular telephone industry (Jayaraman, 2006). The coming into effect of the European Directive Waste Electrical and Electronic Equipment[12] (WEEE) and other similar legislative instruments all around the world, has given birth to many companies specialized in recovery operations and the resale of WEEE, like ARC[13] (USA), Recommerce[14] (France), Refurb Phone[15] (UK). The proliferation of such companies makes us expect new innovative applications in the electrical and electronic industry, playing one of the leading roles in the (re-)manufacturing sector.

6. 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).

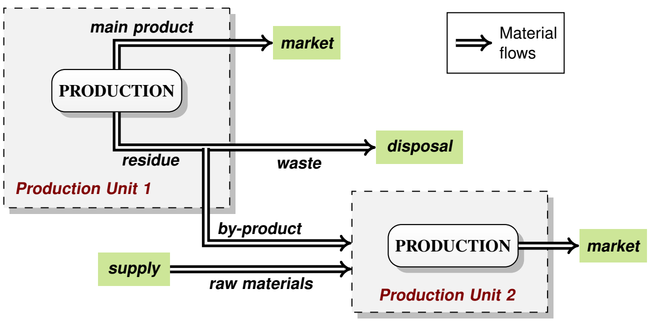


Figure 5: Process flow diagram of by-product synergy

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.

Table 4: By-products versus co-products

Reference	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 *by-product*."		✓		✓		✓		G
Bitran and Gilbert (1994)	"… a *co-production* 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 *byproducts* [...] 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 *by-product* 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 *co-production* 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 *by-products* 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 *by-products* … "	✓		✓			✓		G
Santos and Almada-Lobo (2012)	"During the cooking of wood chips in the digester, two *by-products* are produced … "	✓			✓			✓	pulp and paper mill
Sridhar et al. (2014)	"… the production process creates a mixture of desirable products and undesirable *byproducts*."	✓			✓		✓		G
Rowshannahad et al. (2018)	"The used raw material (considered as a kind of *by-product*) … "	✓				✓		✓	semiconductor

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

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 Law[4] (China) mentions the by-products without giving an explicit definition. Under the Resource Conservation and Recovery Act[2] (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 Directive[1] (Europe) pays special attention to the specification of the term *by-product*. Notably, Article 3 of this directive 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 4). 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.

6.1. Mathematical formulation

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, $\forall k \in [\![1, K]\!]$. 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 raised problem 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 $t \in [\![1, T]\!]$, **(ii)** Y_t: binary indicator of production setup in period $t \in [\![1, T]\!]$, and **(iii)** I_t^k: inventory level of product k at the end of period t. The notations are summarized in Table A.9.

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

subject to:

$$I_{t-1}^k + \alpha^k X_t = I_t^k + d_t^k \qquad \forall t \in [\![1, T]\!], \forall k \in [\![0, K]\!] \tag{18}$$

$$I_0^k = 0 \qquad \forall k \in [\![0, K]\!] \tag{19}$$

$$X_t \leq \max_{k \in [\![0,K]\!]} \left\{ \frac{d_t^k}{\alpha^k} \right\} Y_t \qquad \forall t \in [\![1, T]\!] \tag{20}$$

$$X_t \geq 0, I_t^k \geq 0 \qquad \forall t \in [\![1, T]\!], \forall k \in [\![0, K]\!] \tag{21}$$

$$Y_t \in \{0, 1\} \qquad \forall t \in [\![1, T]\!] \tag{22}$$

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.

6.2. 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).

6.3. Industrial implications and discussion

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, refer 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 CE 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 5 (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. For examples of real-life applications, the reader is referred to the database of industrial symbiosis case studies constructed by Evans et al. (2017) within the framework of the European project MAESTRI (under grant agreement No 680570), focused on the energy and resource management systems for improved efficiency in the process industries.

A number of challenges and gaps remain to be tackled:

- *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 strongly depend 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 knowledge plays a key role in supporting, optimizing and facilitating the by-product synergy.
- *Studying and analyzing different policies of joint production:* To give an order of idea, let us consider the eloquent case of the Danish Kalundborg symbiosis[16], which includes more than twelve different entities, linked by tens of heterogeneous flows: energy (e.g. steam, warm condensate), water (e.g. deionized water, used cooling water), and material (e.g. gypsum, biomass). Some of these flows have to be processed immediately being transported by pipeline (e.g. steam, waste water), others can be stored (e.g. gypsum, fly ash) within the limits of the inventory capacity. 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.

7. Greenhouse gas emissions and energy consumption

7.1. 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*[17] is an international treaty adopted in 1997, which extends the *United Nations Framework Convention on Climate Change*[18] (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° Celsius[19].

Until not long ago, researchers start to take a serious interest in reducing greenhouse gases, by integrating the carbon emissions generated during the production, transportation and remanufacturing operations in their models. The standard way of measuring carbon footprints is to consider *carbon dioxide equivalent* (CO_2e). The idea behind this measure is to express the impact of each greenhouse gas in terms of the quantity of CO_2 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 quantity of GHG emissions over a specific time horizon, and **(ii)** the firms granting with so-called *permits* to emit a given quantity 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, enabling 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 Protocol[20], EcoTransIT World[21], 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).

Table 5: Greenhouse gas emissions

Reference	Emission regulation				Emission constraint					MPM	Cap	Type		Resolution			Instance		Application area
	ETh	ET	ETr	EO	PC	CC	GC	RC	TC			D	ND	Ex	App	Sol	R/B	I	
Absi et al. (2013)					✓	✓	✓	✓		✓		✓							G
Benjaafar et al. (2013)	✓	✓	✓	✓			✓		✓			✓				✓	✓		G
Fahimnia et al. (2013)	✓				✓					✓	✓	✓				✓		✓	textile
Kantas et al. (2015)			✓		✓				✓	✓	✓	✓				✓		✓	biofuel
Retel Helmrich et al. (2015)							✓					✓			✓		✓		G
Zakeri et al. (2015)		✓	✓							✓	✓	✓				✓		✓	metal furniture
Absi et al. (2016)	✓				✓					✓		✓		✓					G
Hong et al. (2016)	✓		✓		✓				✓	✓		✓		✓			✓		G
Purohit et al. (2016)			✓						✓				✓			✓	✓		G
Wu et al. (2018)	✓				✓					✓	✓	✓			✓	✓	✓		G
Zouadi et al. (2018)	✓						✓					✓			✓		✓		G
Lamba and Singh (2019)			✓						✓			✓				✓	✓		G
Phouratsamay and Cheng (2019)	✓		✓		✓				✓	✓		✓		✓			✓		G
Shamayleh et al. (2019)		✓										✓			✓		✓		G

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

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.

7.1.1. Mathematical formulation

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 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 quantity 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 quantity 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. Towards 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 $t \in [\![1, T]\!]$. 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 described above and summarized in Table A.10, 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, Y_t is a binary indicator of setup for production in period t, and I_t denotes the inventory level of the product at the end of period t, $t \in [\![1, T]\!]$.

$$\text{minimize} \sum_{t=1}^{T} \left(p_t X_t + f_t Y_t + h_t I_t \right) \tag{23}$$

subject to:

$$X_t + I_{t-1} = I_t + d_t \qquad \forall t \in [\![1, T]\!] \tag{24}$$

$$I_0 = 0 \tag{25}$$

$$X_t \leq \sum_{i=t}^{T} d_i Y_t \qquad \forall t \in [\![1, T]\!] \tag{26}$$

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

$$X_t, I_t \geq 0 \qquad \forall t \in [\![1, T]\!] \tag{28}$$

$$Y_t \in \{0, 1\} \qquad \forall t \in [\![1, T]\!] \tag{29}$$

The objective function (23) minimizes costs. Constraints (24) are the inventory balance constraints. Constraint (25) fixes the initial inventory level to zero. Constraints (26) ensure that, in each period, there is production only if there is a setup. Constraint (27) limits global emissions over the whole time horizon. The unitary carbon emission is commonly considered proportional to the quantity of produced and transported units (Absi et al., 2013). Finally, nonnegativity and binary requirement constraints are given in expressions (28)-(29).

7.1.2. 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 (Absi et al., 2013).
- *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; Phouratsamay and Cheng, 2019).
- *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:* More flexible than emission cap policy, the emission cap-and-trade scheme is a market-based instrument, that allows production entities to relax their emission constraints via the trading of emissions permits. Lot-sizing problems with cap-and-trade constraints can be solved in a polynomial time by a dynamic programming algorithm (Hong et al., 2016).

7.1.3. Industrial implications and discussion

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.
- *Towards 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.

7.2. Energy consumption

An environmentally-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 planing, Table 6 lists and describes all identified references.

Table 6: Energy consumption

Reference	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
Golpîra et al. (2018)	✓				✓			✓	✓		G
Rapine et al. (2018b)	✓		✓	✓		✓			-	-	G
Rapine et al. (2018a)	✓		✓	✓		✓			-	-	G
Wichmann et al. (2019)	✓			✓				✓		✓	warm and hot forming

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

7.2.1. *Mathematical formulation*

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 quantity of energy:* The limitations in the available quantity 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, $\forall t \in [\![1, T]\!]$. 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 quantity of energy is limited to E_t. Let e_t be the quantity of energy necessary to produce one unit of the considered product. The start-up of one machine in period t consumes a quantity of energy w_t. 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 are summarized in Table A.11

The energy-aware lot-sizing problem can be modeled as follows:

$$\text{minimize} \sum_{t=1}^{T} \left[f(M_t^+) + p_t X_t + h_t I_t \right] \tag{30}$$

subject to:

$$I_{t-1} + X_t = I_t + d_t \qquad \forall t \in [\![1, T]\!] \tag{31}$$

$$X_t \leq C M_t \qquad \forall t \in [\![1, T]\!] \tag{32}$$

$$I_0 = 0 \tag{33}$$

$$e_t X_t + w_t M_t^+ \leq E_t \qquad \forall t \in [\![1, T]\!] \tag{34}$$

$$M_t^+ \geq M_t - M_{t-1} \qquad \forall t \in [\![1, T]\!] \tag{35}$$

$$I_t, X_t \geq 0 \qquad \forall t \in [\![1, T]\!] \tag{36}$$

$$M_t^+, M_t \in \mathbb{N} \qquad \forall t \in [\![1, T]\!] \tag{37}$$

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 (33). 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).

7.2.2. Complexity and solution approaches

Rapine et al. (2018a) showed 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). Other studies found in the literature use either standard solvers to solve the resulting mixed integer programs (Wichmann et al., 2019; 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).

7.2.3. Industrial implications and discussion

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 a 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 (H_20) into hydrogen (H_2), 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 production runs 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.

  Note that the energy transition appears to be a global environmental priority and a future reality. For instance, GRTgaz, a French natural gas transmission system operator, is currently interested in developing the power-to-gas industry in France within the project Jupiter 1000[22], funded jointly by the European Union, the French Government and the Provence-Alpes-Côte d'Azur Region of France. Power-to-gas aims at transforming the surplus of renewable electricity into a storable energy. For example, the surplus of electricity can be transformed into hydrogen (H_2) that can be used to feed hydrogen installations or vehicles. The produced hydrogen can be also coupled with carbon dioxide (CO_2) to produce methane (CH_4) that can be injected within industrial gas networks. Obtained gases can be also used within power plants to generate electricity when needed. These processes face a major tactical decision problem. It consists in deciding when and how much electricity to transform/store and when and how much to retrieve in order to satisfy different sources of demands. Demands in energy can be expressed in different forms: electricity, gas or liquid. The objective is to optimize the system by minimizing the total cost while meeting environmental objectives.

8. Discussion and future research directions

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

Disseminate data. Even if the management science is less data-intensive than data sciences, data availability is a critical specification for a transparent and progressive scientific research. Having access to industry-relevant data or to conceptual generic data models reflecting the industrial complexity is of major importance for the scientific community in developing novel credible models and industrially-viable solution methods. To the best of our knowledge, benchmark instances are only available for remanufacturing problems. More efforts are welcome to support the well-posedness of new emerging problems and the analytic reproducibility of existing solution methods.

Characterize and handle different data formats. Decision-making under uncertainty 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 modes of operating.

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. On this topic, the European Commission has, through the Horizon 2020 program, funded the FUDIPO[23] project (under grant agreement No 723523), focusing on diagnostics and data reconciliation for improving data-intensive decision making in production planning and process optimization.

Sustainability in production planning. As underlined throughout different sections, numerous extensions are worth to be pursued. 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 sustainability are more or less studied. In the production planning literature, the only found social-aware studies operate in the framework of traditional (continuous-time) economic order quantity models (see e.g. Battini et al. (2014); Andriolo et al. (2016)), which are out of the scope of this review.

Besides the economic and environmental impacts, lot-sizing decisions also affect the workers health and security in terms of such human implications as the number of working hours, human fatigue and recovery, learning/forgetting effects, metabolic energy consumption and rest allowance (Andriolo et al., 2016). The integration of human factors and ergonomics into production planning is a particularly topical subject stressed by the increasing concern for a humanly-friendly production planning. The human well-being and ergonomics in production systems remain to be explored.

To suitably respond to the growing request of the sustainability in the actual society, lot-sizing decisions are expected to adhere simultaneously to all three economic, environmental and social goals. Significant work is still needed to balance economic, environmental and social performances in production planning.

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. A particular emphasis has been placed on emerging transversal problems having a strong production planning connotation. 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 7, 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 towards environmentally-friendly processes.

- *Towards eco-industrial parks: Self-sufficient industrial parks* (also called *eco-industrial parks*) emerge as an effective approach towards 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 6.3 and Section 7.2.3, 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 towards 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 towards a circular economy.

9. Concluding remarks

This paper presents a literature review 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 classified the identified papers 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 a clear picture of the existing literature are provided.

All in all, let us summarize the major achievements made in production planning for the circular economy:

- Since the 1990s, new classes of lot-sizing problems have been proposed and studied in the literature to suitably integrate recycling (see Sections 4-5) and other recovering operations (see Section 6). Pushed by legislation and regulations, the two most important drivers of the CE development, the scientific community begins from the 2010's to show serious interest in proposing more environmentally-friendly and energy-efficient production planning solutions (see Section 7).
- Generally speaking, the consideration of sustainability issues in operations management problems is attracting an increasing attention in the research field after the mid-1995s (see Section 2). No purely sustainable lot-sizing problems can be found in the literature. Acquired by inheritance from linear production schemes, the economic dimension continues to enjoy all the attention in the production planning literature. The newly introduced CE-related lot-sizing problems are strongly economic-oriented (see Sections 4-5). In addition to economic concerns, environmental considerations have been progressively introduced in the lot-sizing problems only in the last decade (see Section 7).

  To the best of our knowledge, the social criterion has been neglected in production planning problems. As concluded by other closely-related studies, this is also the case for other operations management problems (Moreno-Camacho et al., 2019). Given the actual shift towards a sustainable society, human-aware lot-sizing problems are pending.
- Together with the complexity analysis, both exact and approximate solution methods have been developed to cope with the combinatorial nature of the majority of reviewed problems. Theoretical results and efficient approaches

proposed to solve generic problems lay the foundations for the development of tractable and industrial viable decision-supporting tools. Even if the most of the studied problems are deterministic in spite of some real-life settings, the conducted industrial case-studies show the applicability of the current solution methods.

- The findings discussed in Section 8 reveal a number of gaps and new insights as to how recovery options can be suitably integrated within traditional production environments for converging towards an environmentally-friendly economy.

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 production planning problems integrating the CE issues 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: http://data.europa.eu/eli/dir/2008/98/oj Access: 5 March 2020
2. The Resource Conservation and Recovery Act of the USA. https://www.gpo.gov/fdsys/pkg/STATUTE-90/pdf/STATUTE-90-Pg2795.pdf Access: 5 March 2020
3. The Pollution Prevention Act of the USA. https://www.law.cornell.edu/topn/pollution_prevention_act_of_1990 Access: 5 March 2020
4. The Circular Economy Promotion Law of the People's Republic of China. http://www.fdi.gov.cn/1800000121_39_597_0_7.html Access: 5 March 2020
5. The Law for establishing a Material Cycles society of Japan. https://www.env.go.jp/en/laws/recycle/12.pdf Access: 5 March 2020
6. The Environmental Protection Law of Vietnam. http://www.ilo.org/dyn/legosh/en/f?p=LEGPOL:503:7117708965374:::503:P503_REFERENCE_ID:172932 Access: 5 March 2020
7. The Wastes Control Act of Korea. https://elaw.klri.re.kr/eng_mobile/viewer.do?hseq=43284&type=part&key=39 Access: 5 March 2020
8. The Act on Promotion of Resources Saving and Recycling. http://elaw.klri.re.kr/eng_mobile/viewer.do?hseq=16020&type=part&key=39 Access: 5 March 2020
9. The Scottish Institute for Remanufacturing. http://www.scot-reman.ac.uk/ Access: 5 March 2020
10. The Institut de l'Économie Circulaire. https://www.institut-economie-circulaire.fr Access: 5 March 2020
11. Implementation of the Circular Economy Action Plan. https://ec.europa.eu/environment/circular-economy/ Access: 5 March 2020 .
12. The directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE). https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2012:197:0038:0071:EN:PDF Access: 5 March 2020
13. The ARC company. https://www.arcaugusta.com/ Access: 5 March 2020
14. The Recommerce-Group company. https://www.recommerce-group.com/en/ Access: 5 March 2020
15. The Refurb-Phone company. https://www.refurb-phone.com/ Access: 5 March 2020
16. The Kalundborg symbiosis. http://www.symbiosis.dk/en/ Access: 5 March 2020
17. The Kyoto Protocol. https://unfccc.int/resource/docs/convkp/kpeng.html Access: 5 March 2020
18. United Nations Framework Convention on Climate Change. https://unfccc.int/ Access: 5 March 2020
19. The Paris Agreement. http://unfccc.int/paris_agreement/items/9485.php Access: 5 March 2020
20. Greenhouse Gas Protocol. http://www.ghgprotocol.org Access: 5 March 2020
21. EcoTransIT World. https://www.ecotransit.org Access: 5 March 2020
22. The Jupiter 1000 project. https://www.jupiter1000.eu/english Access: 5 March 2020
23. The FUDIPO project. https://fudipo.eu/ Access: 5 March 2020

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Appendix A. Notations used in mathematical programs

Table A.7: Disassembly for recycling: *Notations*

Indexes and parameters:	
T	index of the last time period
N	index of the last item
ℓ	index of the first leaf item
(i)	parent of item $i > 1$
α_{ij}	proportion of item j obtained after disassembly of one unit of parent i
f_i	fixed setup cost for the disassembly of the parent item $i < \ell$ in each period
h_i	unit holding cost of the item $i > 1$ in each period
d_{it}	demand of the leaf item $i \geq \ell$ in period t
M	arbitrary large number
Decision variables:	
X_{it}	disassembly quantity of the parent item $i < \ell$ in period t
Y_{it}	binary setup indicator for disassembly of the parent item $i < \ell$ in period t
I_{it}	inventory level of the item $i > 1$ at the end of period t

Table A.8: From product to raw material recycling: *Notations*

Indexes and parameters:	
T	number of time periods
p_t	unit production cost for manufacturing in period t
$\hat{p}_t$	unit production cost for remanufacturing in period t
f_t	fixed setup cost for manufacturing in period t
$\hat{f}_t$	fixed setup cost for remanufacturing in period t
h_t	unit holding cost for serviceable products in period t
$\hat{h}_t$	unit holding cost for returns in period t
d_t	demand for serviceable products in period t
r_t	quantity of returns in period t
Decision variables:	
X_t	production quantity for manufacturing in period t
$\hat{X}_t$	production quantity for remanufacturing in period t
Y_t	binary setup indicator of manufacturing in period t
$\hat{Y}_t$	binary setup indicator of remanufacturing in period t
I_t	inventory level of serviceable products in period t
$\hat{I}_t$	inventory level of returns in period t

Table A.9: By-products versus co-products: *Notations*

Indexes and parameters:	
T	number of time periods
$K+1$	number of co-products
α^k	production coefficient of the co-product k
p_t^k	unit production cost of the co-product k in period t
f_t	fixed setup cost in period t
h_t^k	unit holding cost of the co-product k in period t
d_t^k	demand of the co-product k in period t
Decision variables:	
X_t	production quantity in period t
Y_t	binary setup indicator for production in period t
I_t^k	inventory level of co-product k in period t

Table A.10: Greenhouse gas emissions: *Notations*

Indexes and parameters:	
T	number of time periods
p_t	unit production cost in period t
f_t	fixed setup cost in period t
h_t	unit holding cost in period t
$\hat{p}_t$	unit production emission in period t
$\hat{f}_t$	fixed setup emission in period t
$\hat{h}_t$	unit holding emission in period t
d_t	demand for products in period t
$\hat{C}$	global emission capacity
Decision variables:	
X_t	production quantity in period t
Y_t	binary setup indicator of production in period t
I_t	inventory level in period t

Table A.11: Energy consumption: *Notations*

Indexes and parameters:	
T	number of time periods
p_t	unit production cost in period t
$f(M_t^+)$	fixed start-up cost of M_t^+ machines in period t
h_t	unit holding cost in period t
d_t	demand for products in period t
e_t	quantity of energy necessary to produce one unit of product in period t
w_t	quantity of energy necessary to start up a machine in period t
E_t	available quantity of energy in period t
C	capacity of a machine
Decision variables:	
X_t	production quantity in period t
I_t	inventory level in period t
M_t	number of running machines in period t
M_t^+	number of machines started up at the beginning of period t