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The boomerang returns? Accounting for the impact of uncertainties on the dynamics of remanufacturing systems

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Recent years have witnessed companies abandon traditional open-loop supply chain structures in favour of closed-loop variants, in a bid to mitigate environmental impacts and exploit economic opportunities. Central to the closed-loop paradigm is remanufacturing: the restoration of used products to useful life. While this operational model has huge potential to extend product life-cycles, the collection and recovery processes diminish the effectiveness of existing control mechanisms for open-loop systems. We systematically review the literature in the field of closed-loop supply chain dynamics, which explores the time-varying interactions of material and information flows in the different elements of remanufacturing supply chains. We supplement this with further reviews of what we call the three ‘pillars’ of such systems, i.e. forecasting, collection, and inventory and production control. This provides us with an interdisciplinary lens to investigate how a ‘boomerang’ effect (i.e. sale, consumption, and return processes) impacts on the behaviour of the closed-loop system and to understand how it can be controlled. To facilitate this, we contrast closed-loop supply chain dynamics research to the well-developed research in each pillar; explore how different disciplines have accommodated the supply, process, demand, and control uncertainties; and provide insights for future research on the dynamics of remanufacturing systems.

Keywords: Closed-loop supply chain; forecasting; inventory control; remanufacturing; supply chain dynamics; uncertainty

1. Introduction

Remanufacturing, which may be defined as ‘the transformation of used products (referred to as cores), consisting of components and parts, into products that satisfy exactly the same quality and other standards as new products’ (Guide and Jayaraman 2000, 3780), is not a new concept. Indeed, the origins of remanufacturing date back to the 1940s in both US and European automotive firms aiming at retaining the value of their products (Zhang and Chen 2015). However, increasing sustainability concerns over the last two decades have resulted in a shift from a linear to a circular production model (Lieder and Rashid 2016), which has enormously increased attention to remanufacturing practices (Guide 2000).

From this perspective, remanufacturing networks are gaining momentum as the backbone of ‘circular economy’ models, given their strong association with financial, environmental and social sustainability (Giutini and Gaudette 2003; United States International Trade Commission 2012; Agrawal, Singh, and Murtaza 2015; European Remanufacturing Network 2015; Abbey and Guide 2018). The value of remanufacturing has recently been estimated at \$43 billion in the United States (United States International Trade Commission 2012) and €30 billion in the European Union (European Remanufacturing Network 2015). Closely related to these developments is an evolution in the concept of supply chains (Govindan, Soleimani, and Kannan 2015). These are transforming from open-loop architectures, i.e. from resource extraction to landfill (Figure 1a), to closed-loop architectures, which also consider the processes of collecting and recovering the used products (Figure 1b). In Figure 1, the width of the connecting arrows represents the relative sizes of the material flow, indicating significant reductions in resource extraction and landfill in the closed-loop archetype.

The demand-returns cycles in closed-loop architectures have analogue with the throwing and catching of a ‘boomerang’ (see Posazhennikova, Davey, and Hirschfeld 2010) in that a product is ‘thrown’ (sold) into the marketplace and there is an expectation that it will return for some form of reuse. We will use this term throughout the paper as a metaphor for the sale, consumption, and return processes, and we will examine its impact on the supply chain, and reflect on how it can be

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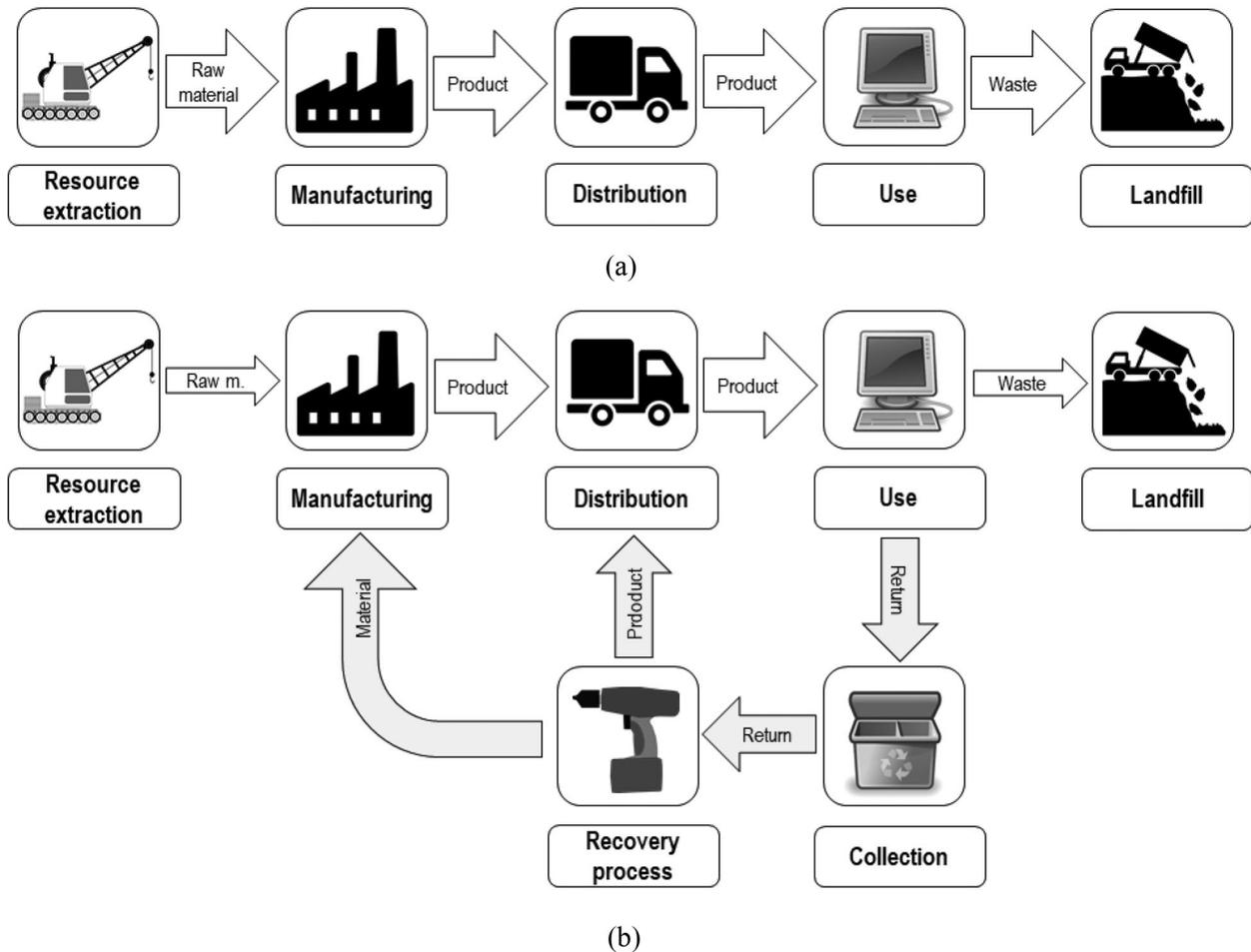


Figure 1. Evolving from a linear to a circular supply chain model. (a) Open-loop supply chain archetype (b) Closed-loop supply chain archetype.

adequately managed. If we think of sales as throwing boomerangs, remanufacturers need to know: ‘when’, or if, they will return (the timing); ‘how many’ will return (the quantity); as well as the ‘condition’ of the ones that will return (the quality). Understanding how this ‘boomerang’ behaves is essential to integrate the traditional forward and the reverse logistics operations into resilient closed-loop supply chains (see Purvis et al. 2016).

The work presented in this paper is the outcome of a project we currently run in the area of remanufacturing, funded by the Engineering and Physical Sciences Research Council (EPSRC, UK). It has been motivated by a series of conversations with our industrial partners, with differing degrees of experience in the remanufacturing industry, and further enriched by the participation of the European Remanufacturing Network (<http://www.remanufacturing.eu/>) and the Waste & Resources Action Programme (WRAP) of the Welsh Government (<http://www.wrapcymru.org.uk/>). We have extensively talked with them about the opportunities and challenges presented by circular economy models. Two concepts, not independent but rather strongly interrelated, came up repeatedly during our initial meetings: the importance of adopting a *whole systems perspective*, and the need for controlling the augmented *uncertainties* that closed-loop systems entail. Both points may be interpreted as drivers of this article. Subsequent focus groups identified three main decision-making processes to be considered in systemic approaches (specifically: estimation of demand and returns, core collection, and inventory and production control) that are jointly called upon to deal with the various sources of uncertainty.

Two interesting notes emerge from this inductive exercise. First, the two points raised describe the *raison d’être* of closed-loop supply chain dynamics, to be discussed in detail below. Second, the survey of the relevant literature (that follows in Section 2) reveals the same pertinent decision-making processes. This also closely coincides with prior efforts at classifying contributions in this area (see, for example, the categorisation of research in production planning and control for remanufacturing by Guide 2000).

1.1. Closed-loop supply chain dynamics

Supply chain management is well known to be a highly complex and dynamic problem. *Complexity* refers to the interaction among processes, decisions, and structures of the different supply chain actors, which strongly affect the performance of the system. These interactions underline the need to analyse and solve the problem holistically (Mason-Jones and Towill 1997), instead of approaching it as an aggregation of serial independent constituent parts. *Dynamism* emerges from the volatile conditions of the current, highly variable business environment. In this sense, static models become insufficient to capture the essence of the supply chain problem, which should be considered through a dynamic perspective (Sarimveis et al. 2008).

Both features, complexity and dynamism, converge in the discipline of *supply chain dynamics* (Towill 1991). This domain of operational research explores the time-varying interactions of the different elements of a supply chain, by looking at the evolution of the flows of materials and information that collectively define its behaviour (Naim, Disney, and Towill 2004). Although much of the pioneering work was undertaken by Jay W. Forrester in the late 1950s (Forrester 1958), it was not until the 1990s that this area attracted many contributions. At that time, increased competition and elongated supply chains emphasized the need for appropriate supply chain management. Firms began noticing counterintuitive and irregular phenomena. For example, Procter & Gamble observed that the relatively constant demand of the customers for one of their products surprisingly resulted into a highly variable production rate that greatly hindered operations. They labelled this distortion of the order pattern across the supply chain the Bullwhip Effect (Lee, Padmanabhan, and Whang 1997), which can be interpreted as a practical evidence of what Burbidge (1984) referred to as ‘the Law of Industrial Dynamics’.

Sound supply chain management has become a source of competitive advantage for organisations, and as such a growing body of literature is looking at the dynamics of these systems. We refer to Wang and Disney (2016) for a recent literature review of the area. Such papers employ a wide range of methodological approaches, and are mainly concerned with the variability of orders and inventories across the system (e.g. Chen et al. 2000; Dejonckheere et al. 2003; Croson and Donohue 2006; Warburton and Disney 2007; Dominguez, Framinan, and Cannella 2014). Practical evidence has shown that production, transportation, and inventory costs rely heavily on the variability of production orders, shipping orders, and net stocks. The case study of Lexmark can be presented as an example of a company significantly benefiting from the improvement of the dynamic behaviour of its supply chain (Disney et al. 2013). Despite the need for the appropriate control of supply chain dynamics, most supply chains still suffer from a poor dynamic behaviour, often associated with large Bullwhip problems (Isaksson and Seifert 2016).

Through the years, supply chain dynamics has matured as a discipline for traditional open-loop systems. Conversely, the body of knowledge looking at the problem in closed-loop supply chains is relatively limited (Wang and Disney 2016), lagging behind the growing importance of such systems. The complex dynamic behaviour of open-loop systems does not go away when we move to closed-loop ones; on the contrary it may increase, as we will discuss later. To the best of our knowledge, and as supported by our structured literature review, the first contribution in this area is the one by Tang and Naim (2004). It adapts the widely-used open loop APIOBPCS archetype¹ to a closed-loop supply chain in the form of a hybrid manufacturing/remanufacturing system.

We conceptualise Tang and Naim’s representation of the closed-loop system in order to highlight the processes of forecasting, collection, and inventory and production control. We reached these three processes through an sequential approach that started with our partner’s recommendations (through focus groups) and further sustained through the review of the literature. These constitute what one may refer to as the three ‘pillars’ of closed-loop supply chains. We introduce the three-pillar representation of the closed-loop supply chain in Figure 2; this represents our study’s framework.

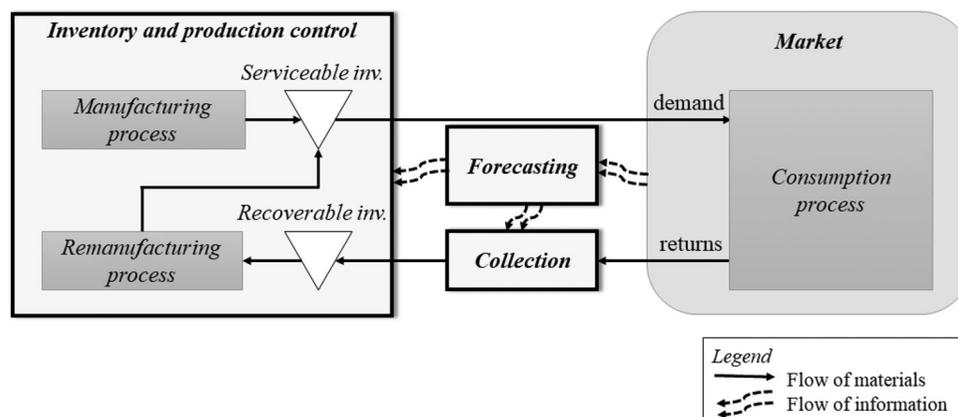


Figure 2. Conceptual representation of the closed-loop supply chain, highlighting the three pillars.

The forecasting pillar aims at estimating the future demand and returns. The collection process seeks to manipulate the return of used products back into the supply chain. The inventory and production planning mechanism focuses on effectively managing the flow of materials to meet the demand for the product. Note that both the forward and the reverse flows must be integrated into the same business model in order to cope with a wider range of uncertainties. This forces one to question the established ideas for the traditional system (Guide, Harrison, and Van Wassenhove 2003). Overall, these strongly interconnected pillars may be interpreted as decision-making fields from an operations management perspective, and as such they constitute avenues for improving the performance of closed-loop systems. In this sense, these pillars provide us with an interesting lens for the investigation of the dynamic behaviour of remanufacturing supply chains.

1.2. Sources of uncertainty in remanufacturing systems

Uncertainty refers to ‘any deviation from the unachievable ideal of completely deterministic knowledge of the relevant system’ (Walker et al. 2003, 5). It is widely known that managing uncertainty represents a core issue for traditional supply chains; see, for example, Datta and Christopher (2011). In open-loop systems, the sources of uncertainty are commonly classified into three categories: *supply*, *process*, and *demand uncertainty* (Davis 1993). Mason-Jones and Towill (1998) expanded this framework by considering a fourth source, namely *control uncertainty*. They defined an ‘uncertainty cycle’, where the three aforementioned inherent sources are iteratively augmented by the uncertainty introduced through the control mechanisms that try to manage them (this has been explored in several practical contexts, see e.g. Sanchez Rodrigues et al. 2008).

Supply uncertainty relates to the materials’ supply. In open-loop contexts, it mainly consists of two areas of uncertainty from an operational point of view: raw material availability (Alonso et al. 2007) and delivery schedule adherence (supply lead time, Kim and Chien 2011). When we move to closed-loop contexts, supply uncertainty also includes the probabilistic nature of both the rate (time and quantity) and quality of returns (Zeballos et al. 2012). The collection procedure and transportation lead times also contribute to generation of inefficiencies in closed-loop contexts (Wei et al. 2015).

Overall, this reverse flow uncertainty generally becomes the dominant force in terms of supply uncertainty, as the channels for collecting cores tend to be far more uncertain, especially in global supply chains, than those for transporting raw materials (Fleischmann et al. 2000). This suggests that remanufacturers often need to hold high levels of cores to buffer against variations in the supply (Guide 2000). This is something we have observed e.g. in the automotive remanufacturing industry (Briggs 2017).

Process uncertainty covers those areas inherent in performing the production process. It is linked to the stochastic nature of machine performance, mainly in terms of yield and quality (Gurnani and Gerchak 2007), processing times (Cao, Patterson, and Bai 2005), and availability (van Kampen, van Donk, and van der Zee 2010). These sources of uncertainty are similar in open- and closed-loop contexts. However, again, their intensity is generally more acute in the latter case. While manufacturing times can be generally regarded as fixed, remanufacturing times tend to be highly variable, mainly depending on the condition of the cores. For instance, Denizel, Ferguson, and Souza (2010) observed that a used laptop may require up to three times more production capacity if the condition is poor (in comparison with this being fair) before it matches the quality standards, implying a level of variability that hardly ever exists in traditional manufacturing environments.

In this regard, it should be noted that manufacturing companies typically forecast an (independent) customer demand, and explode that demand through a largely static *bill of materials* to order the (dependent) parts required. In terms of scheduling, they similarly explode the forecasted demand through a comparably static *bill of operations*, which will dictate a series of processes to be executed. However, in remanufacturing the bill of materials and the bill of operations are no longer a *dependent prescription* of materials and operations, but rather *independent stochastic ranges* subject to the condition of the cores – and, as such, need to be forecasted (Shaw 2017). This accentuates the difference in terms of process uncertainty between open- and closed-loop contexts.

Demand uncertainty refers to the uncertainty related to demand quantity, timing, and locations (Angkiriwang, Pujawan, and Santosa 2014), customers’ product specifications (van Hoek 1997) and life-cycle considerations (Blundell, Browning, and Meghir 1994). It also relates to other areas outside the operational scope of the system, such as price sensitivity (Erdem, Swait, and Louviere 2002) and the decision making of the competitors (Wong, Boon-itt, and Wong 2011). At first glance it may seem that the demand uncertainty is similar in open- and closed-loop contexts; however, some additional aspects must be considered in the latter. An example would be the governments’ decisions that may significantly motivate or discourage customers from purchasing remanufactured products (Zhang et al. 2011).

Of special importance is the potential cannibalisation of remanufactured to new products, which is a major concern for firms involved in both operations, e.g. Hewlett-Packard (Atasu, Guide, and Van Wassenhove 2010). In this sense, some reverse logistics contexts recover cores up to several standards (i.e. output qualities) to satisfy various target markets.

Overall, we need to highlight that understanding the customer attitudes to recovered products, and product substitution, becomes essential to support well-informed decision making in this area (Radhi and Zhang 2016), which includes deciding on the products to remanufacture and developing smart pricing strategies.

Finally, *control uncertainty* refers to uncertainty introduced from our own efforts to cope with the other sources of uncertainty in the first place. That is, it stems from the mechanisms employed to control the supply, process, and demand uncertainties (Mason-Jones and Towill 1998). These mechanisms include forecasting procedures, inventory and production policies, batching rules, information sharing policies, and so on. We may attribute control uncertainty to the lack of understanding of the interdependencies between the relevant parts of the system; in light of this, it can appear within, but also across, different echelons of supply chains.

An example of the former (within echelons) could be the well-reported *decoupling effect* between demand forecasting and inventory control (see e.g. Prak, Teunter, and Syntetos 2017). It emerges from the fact that, on one hand, inventory control theory has not been developed taking into account the fact that demand is forecasted. On the other hand, forecasting methods do not reflect inventory implications (such as inventory costs or service levels) – rather, optimisation is based on some forecast error metric (e.g. mean squared error). This breakdown results in target service levels seldom being met and safety stock investments being sub-optimal. Recoupling the forecasting and inventory control processes (i.e. conditioning inventory theory development to forecasting considerations, and vice versa) would undoubtedly result in control uncertainty being mitigated.

When referring to the latter (across echelons), we highlight the previously discussed Bullwhip Effect (Lee, Padmanabhan, and Whang 1997) as a clear manifestation of control uncertainty. This phenomenon springs from the interaction of the many control mechanisms in the supply chain. In this sense, control uncertainty strongly depends on the partners' approach to supply chain management, i.e. holistic versus reductionist thinking (Holweg and Bicheno 2002; Puche et al. 2016). As a consequence, collaborative mechanisms for process integration and partners' decision synchronisation may significantly decrease the control uncertainty, as discussed, for instance, by Simatupang and Sridharan (2005) and Asgari et al. (2016).

Table 1 provides an overview of examples of areas of uncertainties in closed-loop supply chains from an operational standpoint, by making a distinction between those in the forward and the reverse flows of materials. Note that the reverse flow uncertainties compound upon – rather than replace – the forward.

1.3. Scope, contribution, and structure of the paper

In this work we propose forecasting, collection, inventory and production control as the three main 'pillars' managers may refer to in order to manage uncertainty in closed-loop supply chains. These are, of course, research areas on their own

Table 1. Examples of areas of uncertainty in closed-loop supply chains from an operational perspective (adapted from Mason-Jones and Towill 1998).

	Forward flow	Reverse flow
Supply uncertainty	<ul style="list-style-type: none"> • Raw material availability • Supply lead time (schedule adherence) 	<ul style="list-style-type: none"> • Cores availability • Quality of cores • Collection procedure • Transportation lead time
Process uncertainty	<ul style="list-style-type: none"> • Yield and quality [Man.] • Processing times [Man.] • Machine availability [Man.] 	<ul style="list-style-type: none"> • Yield and quality [Reman.] • Processing times [Reman.] • Machine availability [Reman.]
Demand uncertainty	<ul style="list-style-type: none"> • Quantity • Timing • Locations • Product specification • Life-cycle stage 	<ul style="list-style-type: none"> • Product cannibalisation • Product substitution
Control uncertainty	<ul style="list-style-type: none"> • Serviceable stock control policy • Raw material stock control policy • Demand forecasting method • Batching rules • Capacity planning decisions • Policies and methods interactions 	<ul style="list-style-type: none"> • Recoverable stock control policy • Returns forecasting method

right. We investigate how each pillar has been represented in the closed-loop supply chain literature, and then visit literature that is specific to each one of them, to contrast and highlight different representations, modelling decisions and methods.

This is achieved by pursuing three main objectives, which in turn constitute our contribution to the existing literature of operations management in closed-loop supply chains, and significantly differentiate our work from reviews conducted by others in the field of reverse logistics (e.g. Govindan, Soleimani, and Kannan 2015; Barbosa-Póvoa, da Silva, and Carvalho 2017; Kirchherr, Reike, and Hekkert 2017; Govindan and Hasanagic 2018; Kazemi, Modak, and Govindan 2018):

- (1) *Reflect on the current state of knowledge in the field of closed-loop supply chain dynamics*, by systematically reviewing and synthesising the literature, towards a deep understanding of the dynamic behaviour of relevant systems and strategies for managing the closed-loop uncertainties.
- (2) *Consider how the literature in adjacent fields may provide guidance towards the management of the dynamics of closed-loop systems*, drawing inspiration from how the three identified pillars (i.e. forecasting, collection, and production and inventory control) complementarily deal with the different sources of uncertainty in closed-loop supply chains.
- (3) *Identify gaps in the literature and propose avenues for future research*, by understanding the way uncertainties could be addressed in closed-loop contexts, considering the actual challenges faced by supply chain managers, and reflecting on the current limitations of the existing works.

In accordance with these research objectives, the remainder of this paper has been structured as follows. Section 2 describes the systematic review methodology and synthesises the reviewed papers in the field of closed-loop supply chain dynamics. Section 3 visits problem-specific literature to see how the methods developed there can lend themselves to supply chain dynamics formulations and implications. Specifically, Section 3.1 is devoted to analysing how the forecasting community contributes to reducing the impact of uncertainty on closed-loop supply chains by increasing the understanding on the boomerang trajectory. Section 3.2 focuses on different strategies for cores collection in closed-loop contexts, as mechanisms for influencing the boomerang trajectory to mitigate the reverse flow uncertainty. Section 3.3 describes the relevant models for production and inventory planning in remanufacturing, which regulate the throwing and catching of the boomerang, in order to appropriately manage the uncertainty. Finally, Section 4 proposes key directions for future research in this field and concludes by looking at the relevant opportunities and challenges.

2. The dynamic behaviour of remanufacturing systems

We adopt the methodology of Tranfield, Denyer, and Smart (2003) to conduct a systematic review of the existing literature in the field of closed-loop supply chain dynamics (as it was previously defined), which specifically focuses on developing evidence-informed managerial knowledge. This methodology considers five main steps in the process of conducting the review: (1) identification of research; (2) selection of studies; (3) study quality assessment; (4) data extraction and monitoring progress; and (5) data synthesis. The planning and development of the review of the literature, which is described below, was carried out by the authors of this article with the advice of an expert panel formed by seven industrial partners.

2.1. Locating and selecting the relevant studies

In order to select the studies to be reviewed, we followed a two-stage process. First, we carried out a keyword search with the aim of identifying the core of the relevant literature, which represents our initial sample. Second, we conducted an initial review of the relevant articles in order to add new articles that, without having met the search criteria, are relevant for our research (or *type I errors*) and to remove those articles that, having met the search criteria, are not central to our purpose (or *type II errors*). After a recursive analysis, we obtained the final sample of relevant articles in the field of closed-loop supply chain dynamics. Our research protocol is described in detail in Table 2 to clearly delimit this process and for the sake of reproducibility.

To identify the first sample, we used the Scopus database. We selected this database as it covers a very wide range of academic publications (over 22,000 titles from more than 5,000 international publishers). We limited our search to peer-reviewed journal articles, as they are assumed to represent completed pieces of research. Moreover, we only searched for articles written in English, to ensure readability across the team of authors.

In accordance with the focus of this study, we looked for articles that simultaneously deal with the concepts of ‘*remanufacturing*’ and ‘*supply chain dynamics*’ in their title, abstract, or keywords. We used these terms in the search string, but also some synonym concepts, which were derived through a iterative process of refinement aimed at including relevant work that used alternate wording. For example, we initially employed ‘*remanufacturing*’ as the only word to refer to the first search

Table 2. Research protocol for the selection of the relevant studies and overview of the initial and final samples.

	Field of study	The dynamic behaviour of remanufacturing networks	Sample size
<i>Identification of research</i>	<i>Databases</i>	SCOPUS	
	<i>Publication type</i>	Peer-reviewed articles	
	<i>Language</i>	English	
	<i>Search fields</i>	Title, abstract, and keywords	
	<i>Search terms</i>	<i>Search term #1: Remanufacturing (or Closed-loop supply chain/s or reverse logistics)</i> [and] <i>Search term #2: Supply chain dynamics (or Dynamic behaviour or dynamic performance or Bullwhip or order variance or order variability or inventory variance or inventory variability or demand amplification or variance amplification or APIOBPCS or IOBPCS)</i>	
	<i>Date range</i>	up to Nov 2017 (date of search)	<i>Initial sample: 29 [Jan 1994 - Nov 2017]</i> <i>-11 deselected</i>
<i>Selection of research</i>	<i>Deselection criteria</i>	<i>Deselection criteria #1: Semantic confusion</i> <i>Deselection criteria #2: Lack of specific of insights to our research area</i>	<i>'Clean' sample: 18</i>
	<i>Addition techniques</i>	<i>Addition technique #1: Snowballing</i> <i>Addition technique #2: Reverse snowballing</i>	<i>+7 added</i>
			<i>Final sample: 25 [Jan 2004 - Aug 2018]</i>

term. Nevertheless, we found that this leads to relevant articles (that analyse the dynamic behaviour of remanufacturing systems through closed-loop supply chains) not being included. Similarly, we initially used 'system dynamics' as a synonym term of supply chain dynamics. However, we found that utilisation of this keyword results into a considerable number of articles included in the sample that are not central to our field of study (i.e. articles employing the system dynamics methodology for analysing a wide variety of problems in reverse logistic systems²).

As a result of this search, we identified 29 articles in the time interval 1994–2017 (November). These were the following (in chronological, and then alphabetical, order): Kumar, Vrat, and Sushil (1994), Tang and Naim (2004), Zanoni, Ferretti, and Tang (2006), Zhou and Disney (2006), Zhou et al. (2006), Pati, Vrat, and Kumar (2010), Ruebeck and Pfaffmann (2011), Adenso-Díaz et al. (2012), Das and Dutta (2013), Jing et al. (2013), Lehr, Thun, and Milling (2013), Li (2013), Turrise, Brucocoleri, and Cannella (2013), Corum, Vayvay, and Bayraktar (2014), Ling (2015), Liu (2015), Shi, Sheng, and Xu (2015), Yuan and Zhang (2015), Cannella, Brucocoleri, and Framinan (2016), He, Yuan, and Zhang (2016), Liu et al. (2016), Wei and Yuan (2016), Zhang and Yuan (2016), Dev, Shankar, and Choudhary (2017), Harris and Natarajarathinam (2017), Salviano and Andres (2017), Wang et al. (2017), Zhang, Li, and Zhang (2017), and Zhou, Naim, and Disney (2017).

Interestingly, the same search for '*supply chain**' as the only word in the first search term resulted in 774 articles returned. This translates in a ratio of approximately one article in closed-loop supply chains per 26 articles in traditional, or open loop, systems. This number may not be definitive, but is nonetheless indicative of the imbalance between the academic studies conducted in these two areas.

We used two deselection criteria in order to remove type II errors – i.e. articles that are included in the sample, but should not be there. To do so, we first reviewed the abstract of the 29 articles and, if further clarification was required, we checked the main text. First, we focused on articles that have been included due to some semantic confusion (i.e. words with different meanings based on the context), but clearly fall out of the research area that we aim to review. Four articles were deselected according to this criterion. Ling (2015), Liu (2015), and Liu et al. (2016) explore the problem of remanufacturing from a completely different perspective (specifically, physics and mechanical engineering). Second, we considered articles that do not provide any specific insight on closed-loop supply chain dynamics in the way we defined this concept in Section 1.1. This led in the deselection of a further seven articles to a reduced new 'clean' sample of 18: Kumar, Vrat, and Sushil (1994), Ruebeck and Pfaffmann (2011), Lehr, Thun, and Milling (2013), Li (2013), Shi, Sheng, and Xu (2015), Harris and Natarajarathinam (2017), Salviano and Andres (2017), and Wang et al. (2017). These articles explored the dynamic response of closed-loop supply chains from other perspectives (see footnote 2). All in all, the deselection process reduced the period of study to 2004–2017, given that the only article before this period in the initial list, i.e. Kumar, Vrat, and Sushil (1994), was removed from the sample.

In order to rectify type I errors – i.e. to include articles that should be in the sample, but are not –, we employed forward and reverse snowballing. The former refers to the process of checking the citations of the articles in the sample, while the latter entails looking at those papers citing the articles in the sample. Forward snowballing led to the inclusion of the following

five papers: Huang and Liu (2008), Da, Sun, and Zhou (2008), Ding and Gan (2009), Wang and Ding (2009), and Hosoda, Disney, and Gavrimeni (2015). None of these articles were ‘returned’ in the initial search; the first four because they are conference papers and the last one due to a search term misalignment, but all five of them are clearly relevant for our research.

When it comes to reverse snowballing, we scanned the title and keywords (and when needed the abstract and text) of 218 articles in the Scopus database that cited our ‘clean’ sample of 18 articles. This resulted in the incorporation of one more research article to our sample, that of Sy (2017).

Given that snowballing must be an iterative process, we repeated the process on the six new articles, which resulted in including Hosoda and Disney (2018) in the sample. The inclusion of seven articles from the forward and reverse snowballing to our ‘clean’ sample of 18 brought our final sample to 25 papers in total.

2.2. Quality assessment and data extraction

The articles in the final sample, shown in Table 3, were reviewed in full detail. Figure 3(a) illustrates the distribution of publications per year, while Figure 3(b) presents the citations to these articles. We represented a three-year moving average in both graphs in order to outline and ‘smooth’ the research evolution. Overall, these figures show that the field of closed-loop supply chain dynamics has been gaining attention exponentially over the last decade. It can be understood as a response to the relevance of this area in the industrial landscape and the need to understand the dynamics of closed-loop systems in the same way as that of traditional ones.

Following the methodology of Tranfield, Denyer, and Smart (2003), quality assessment was the next step in the review process. This refers to the appraisal of the validity of the design and analysis of the different research works in our sample. To this end, we evaluated each study against a checklist of three criteria: (C1) Is the article published in a journal indexed in the Thomsom Reuters’ 2016 Journal Citation Reports? (C2) Is the mathematical model of the supply chain described in enough detail to reproduce it (Boylan 2016)? (C3) Are the results appropriately discussed in terms of their contribution to the literature of closed-loop supply chain dynamics? Our evaluation of the final sample of 25 articles against these criteria can be seen in columns C1, C2, and C3 in Table 3.

C1 refers to the journal the work appears in. This is a commonly used indicator of quality of publications since the Journal Citation Reports is the world’s most influential resource for evaluating peer-reviewed journals. 19/25 articles (76%) verified this criterion. Huang and Liu (2008), Da, Sun, and Zhou (2008), Ding and Gan (2009), and Wang and Ding (2009) are conference papers; while Pati, Vrat, and Kumar (2010) and Wei and Yuan (2016) are published in journals non-indexed in this list; although we recognise the contribution of these articles to the field of study. C2 refers to the level of detail of the mathematical model in each work. The ability of the reader to understand the model, gain insights and trust the results depends on the clarity with which they are presented. 24 articles (96%) have met this criterion. Huang and Liu (2008), who provided only general information about the closed-loop model, is the article that does not satisfy it. Finally, C3 refers to the results and discussion of each piece of work. This is employed to take into account whether the work under concern has a contribution to the literature of closed-loop supply chain dynamics. After careful consideration, we have concluded that all 25 selected articles verify this criterion despite any differing strength of their contribution to the existing literature. This allows us to check the appropriateness of the previous selection process.

Overall, 19 out of the 25 selected articles (76%) have met all three criteria; five articles (20%) have met two criteria; and one article (4%) has met only one. We decided to categorise in Table 2 and analyse in Section 2.3 all 25 articles, with the exception of synthesising and discussing insights (Section 2.3.1.) where we only draw on the 19 articles that have met all three criteria.

The identification of the three pillars as they appear in Figure 2 and Table 3 (i.e.: forecasting, collection, inventory and production control) are the result of a sequential process commencing from our partner’s recommendations and further confirmed through the review of the papers in the sample. It is interesting to note that the review of the 25 research articles also inductively reveals the three pillars, with the majority of the articles making a series of assumptions and modelling decisions for each. As previously discussed, the interesting issue about this classification is that each pillar represents a decision-making field. Each of these decision making areas has the potential to enhance the dynamics of closed loop systems, by better dealing with the sources of uncertainty. These three pillars have been taken into consideration in the next step of our systematic review of the literature, which was the process of extracting the relevant information from the articles. This was carried out via a data-extraction form, through which we consider the forecasting approach employed in these studies (if any), the collection model, and the ordering policy for inventory and/or production control. In addition, we explicitly look at the methodological approach adopted by each paper, as well as its main contribution to the field of closed-loop supply chain dynamics. The above information is presented in Table 3. Please refer to the table footnotes for a clarification on the different nomenclature used in the various columns.

Table 3. Categorisation of studies in the field of the dynamics of closed-loop supply chains.

General information	Quality checklist				Data extraction form				
	Ref.	Authors (year)	C1	C2	C3	The three pillars			Main contribution to the literature on closed-loop supply chain dynamics ⁵
						Meth./Top. approach ¹	Forecasting approach ²	Collection model ³	
[1]	Tang and Naim (2004)	✓	✓	✓	CT-C HMRS	Dem:ES Ret:No	FPoDaFT	POUT ^O POUT ^C	<ul style="list-style-type: none"> • First paper exploring Bw and NSamp in CLSCs • Comparison of three different policies based on the level of information transparency • Evaluation of the impact of several parameters: β, Tr, Tc
[2]	Zanoni, Ferretti, and Tang (2006)	✓	✓	✓	SIM-DE HMRS	Dem:No Ret:No	IoD	PULL ^C DUAL ^C	<ul style="list-style-type: none"> • Proposal of new policies: shifted and separate PULL • First exploration of Bw in continuous-review inventory systems in CLSCs
[3]	Zhou and Disney (2006)	✓	✓	✓	CT-C HMRS	Dem:MMSE Ret:No	FPoDaLT	POUT ^O	<ul style="list-style-type: none"> • Analytical expressions of Bw and NSamp in CLSCs • Evaluation of the impact of several parameters: β, Tr, Ti, Tw
[4]	Zhou et al. (2006)	✓	✓	✓	CT-C HMRS	Dem-Ret:ES	FPoDaLT	POUT ^C	<ul style="list-style-type: none"> • Design of a Kanban policy for the remanufacturing system • Evaluation of the impact of several parameters: β, Tr, Ti, Tw, Ta, Tm, Td
[5]	Da, Sun, and Zhou (2008)		✓	✓	SIM-SD HMRS ^e	Dem:ES Ret:ES	FPoDaLT	OUT ^C	<ul style="list-style-type: none"> • Consideration of capacity planning strategies • Comparison of an open-loop reverse SC and a CLSC
[6]	Huang and Liu (2008)			✓	SIM-SD HMRS ^e	Dem:NS Ret:No	NS	NS	<ul style="list-style-type: none"> • Evaluation of the impact of several parameters: β, Tr
[7]	Ding and Gan (2009)		✓	✓	SIM-SD HMRS	Dem:ES Ret:No	FPoDaLT	POUT ^C	<ul style="list-style-type: none"> • Evaluation of the impact of several parameters: β, Ti, Tw
[8]	Wang and Ding (2009)		✓	✓	SIM-SD HMRS	Dem:ES Ret:No	FPoDaLT	POUT ^C	<ul style="list-style-type: none"> • Evaluation of the impact of β
[9]	Pati, Vrat, and Kumar (2010)		✓	✓	SA PRS	Dem:MMSE Ret:No	ULAoR	OUT ^C	<ul style="list-style-type: none"> • Analytical expression for Bw in a six-echelon production and recycling system.

(Continued)

Table 3. Continued.

General information	Quality checklist					Data extraction form				
	Ref.	Authors (year)	C1	C2	C3	Meth./Top. approach ¹	The three pillars			Main contribution to the literature on closed-loop supply chain dynamics ⁵
							Forecasting approach ²	Collection model ³	Ordering policy ⁴	
[10]	Adenso-Díaz et al. (2012)	✓	✓	✓	SIM-DE PRS	Dem:ES,MA Ret:No	FPoDaLT	POUT ^O	<ul style="list-style-type: none"> Evaluation of the impact of several parameters: β, T_i, T_w, T_m, T_c, σ, ϕ, γ Evaluation of the impact of the forecasting method, the level of information transparency, and the demand trend. 	
[11]	Das and Dutta (2013)	✓	✓	✓	SIM-SD HMRS	Dem:ES Ret:ES	FPoDaLT	POUT ^C	<ul style="list-style-type: none"> Consideration of three ways for recovering the material Exploration of the impact of the product exchange policy Evaluation of the impact of β 	
[12]	Jing et al. (2013)	✓	✓	✓	CT-D HMRS	Dem:ES Ret:No	FPoDaLT	PIDOUT ^C	<ul style="list-style-type: none"> Design of a PID controller to mitigate B_w in a CLSC Frequency analysis of B_w 	
[13]	Turrisi, Bruccoleri, and Cannella (2013)	✓	✓	✓	SIM-SD HMRS	Dem:ES Ret:No	FPoDaLT	POUT ^O POUT ^C	<ul style="list-style-type: none"> Comparison of two policies for managing CLSCs Evaluation of the impact of several parameters: β, Tr, T_m, and analysis of the interactions 	
[14]	Corum, Vayvay, and Bayraktar (2014)	✓	✓	✓	SIM-DE HMRS	Dem:No Ret:No	IoD	PULL ^C PUSH ^C	<ul style="list-style-type: none"> Evaluation of the impact of several parameters: β, Tr, T_m 	
[15]	Hosoda, Disney, and Gavrieni (2015)	✓	✓	✓	SA HMRS	Dem:MMSE Ret:MMSE	PCtD	OUT ^C	<ul style="list-style-type: none"> Investigation of the impact of advance notice of returns Consideration of random yield in the remanufacturing process and correlation between demand and returns Analytical expressions of order and inventory variance Evaluation of the impact of several parameters: β, Tr, T_m, θ, ξ 	
[16]	Yuan and Zhang (2015)	✓	✓	✓	SIM-SD PRS	Dem:MA Ret:No	FPoDaLT	POUT ^O	<ul style="list-style-type: none"> Consideration of two different retailers Consideration of the response of recyclers to governments policies Evaluation of the impact of several parameters: β, Tr, T_m 	

(Continued)

Table 3. Continued.

General information	Quality checklist				Data extraction form					
	Ref.	Authors (year)	C1	C2	C3	Meth./Top. approach ¹	The three pillars			Main contribution to the literature on closed-loop supply chain dynamics ⁵
							Forecasting approach ²	Collection model ³	Ordering policy ⁴	
[17]	Cannella, Bruccoleri, and Framinan (2016)	✓	✓	✓	SIM-SD HMRS ^e	Dem:ES Ret:No	FPoDaLT	POUT ^O POUT ^C	<ul style="list-style-type: none"> • Exploration of the relationship between Bw and NSamp and the number of tiers in the supply chain • Comparison of two policies for managing CLSCs • Evaluation of the impact of several parameters: β, Tr, and analysis of interactions 	
[18]	He, Yuan, and Zhang (2016)	✓	✓	✓	SIM-SD PRS	Dem:MA Ret:No	FPoDaLT	POUT ^O	<ul style="list-style-type: none"> • Consideration of a third-party recycler • Similar approach to Yuan and Zhang (2015) 	
[19]	Wei and Yuan (2016)		✓	✓	SIM-SD PRS	Dem:MA Ret:No	FPoDaLT	POUT ^O	<ul style="list-style-type: none"> • Exploration of different replacement policies • Similar approach to Yuan and Zhang (2015) 	
[20]	Zhang and Yuan (2016)	✓	✓	✓	SIM-SD PRS	Dem:MA Ret:No	FPoDaLT	POUT ^O	<ul style="list-style-type: none"> • Consideration of three ways for product recovery • Consideration of an old-for-new policy 	
[21]	Dev, Shankar, and Choudhary (2017)	✓	✓	✓	SIM-DE HMRS	Dem:No Ret:No	IoD	PULL ^C OUT ^C	<ul style="list-style-type: none"> • Comparison between continuous and periodic-review policies • Consideration of the trade-off between stochastic demand, stochastic lead times, and review periods • Evaluation of the impact of several parameters: β, Tr, Tm, λ 	
[22]	Sy (2017)	✓	✓	✓	SIM-SD HMRS ^e	Dem:No Ret:No	FPoDaLT	NS	<ul style="list-style-type: none"> • Consideration of three ways for product recovery • Modelling of returns of two different qualities: no-fault returns and quality returns 	
[23]	Zhang, Li, and Zhang (2017)	✓	✓	✓	CT-SS HMRS ^e	Dem:No Ret:No	FPoDaLT	Various	<ul style="list-style-type: none"> • Design of a fuzzy controller to mitigate Bw in a CLSC • Consideration of commercial returns and the quality issue in the third-party recovery provider 	
[24]	Zhou, Naim, and Disney (2017)	✓	✓	✓	CT-C HMRS ^e	Dem:ES Ret:No	FPoDaLT	POUT ^C	<ul style="list-style-type: none"> • Consideration of three ways for recovering the material in the same (three-echelon) closed-loop supply chain • Evaluation of the impact of several parameters: β, Tr, Tm, Tc 	

(Continued)

Table 3. Continued.

General information	Quality checklist					Data extraction form				
	Ref.	Authors (year)	C1	C2	C3	Meth./Top. approach ¹	The three pillars			Main contribution to the literature on closed-loop supply chain dynamics ⁵
							Forecasting approach ²	Collection model ³	Ordering policy ⁴	
[25]	Hosoda and Disney (2018)	✓	✓	✓	SA HMRS	Dem:MMSE Ret:MMSE	PCtD	OUT ^C	<ul style="list-style-type: none"> • Consideration of random yield in the remanufacturing process and correlation between demand and returns • Analytical expressions of order and inventory variance • Observation and in-depth analysis of the ‘lead-time paradox’ • Evaluation of the impact of several parameters: β, Tr, Tm, θ, ξ 	

¹*Methodological and topological approach.* Regarding the methodological approach, CT-C: control theory in the continuous (s) domain; CT-D: control theory in the discrete (z) domain; CT-SS: control theory through state-space analysis; SA: stochastic analysis, SIM-DE: discrete-event simulation; SIM-SD: system dynamics simulation. Regarding the topological approach, HMRS: hybrid manufacturing/remanufacturing system; PRS: production and recycling system; the superscript ‘e’ indicates that the traditional structure has been expanded by considering a larger number of echelons.

²*Forecasting approach.* ‘Dem’ stands for demand and ‘Ret’ stands for returns. ES: exponential smoothing; MA: moving average; MMSE: minimum mean squared error; No: no forecasting; NS: non-specified.

³*Collection model.* FPoDaLT: returns are a fixed percentage of demand after the lead time (i.e. returns are perfectly correlated to demand); IoD: returns are independent of demand; NS: non-specified; PCtD: returns are partially correlated to demand; ULAoR: unlimited availability of returns (i.e. they do not constitute a constraint in the operation of the system).

⁴*Ordering policy.* DUAL: (continuous-review) dual sourced policy; OUT: (periodic-review) order-up-to policy; POUT: (periodic-review) order-up-to policy regulated through a proportional controller; PIDOUT: (periodic-review) order-up-to policy regulated through a proportional-integral-differential controller; PULL: (continuous-review) pull-based policy; PUSH: (continuous-review) push-based policy; NS: non-specified. Superscript ‘C’ indicates that the policy has been adapted to closed-loop environments (i.e. the model considers the return pipeline in the ordering policy), while superscript ‘O’ refers to the authors having used the traditional policy for open-loop environments (i.e. the model does not consider the return pipeline in the ordering policy).

⁵*Main contribution to the literature on closed-loop supply chain dynamics.* Abbreviations employed. Bw: Bullwhip ratio, measuring order variability; CLSC: closed-loop supply chain; DoE: design of experiments; NSAmp: net stock amplification ratio, measuring inventory variability; Ta: exponential smoothing parameter; Tc: consumption time; Td: time to adjust inventory in a Kanban system; Ti: time constant of the inventory controller in a POUT policy; Tm: manufacturing lead time; Tr: remanufacturing (or recycling) lead time; Tw: time constant of the WIP controller in a POUT policy; β : return yield; γ : lot size; θ : correlation between demand and returns; ξ : remanufacturing random yield; λ : length of the review period; σ : demand variability; ϕ : capacity limit.

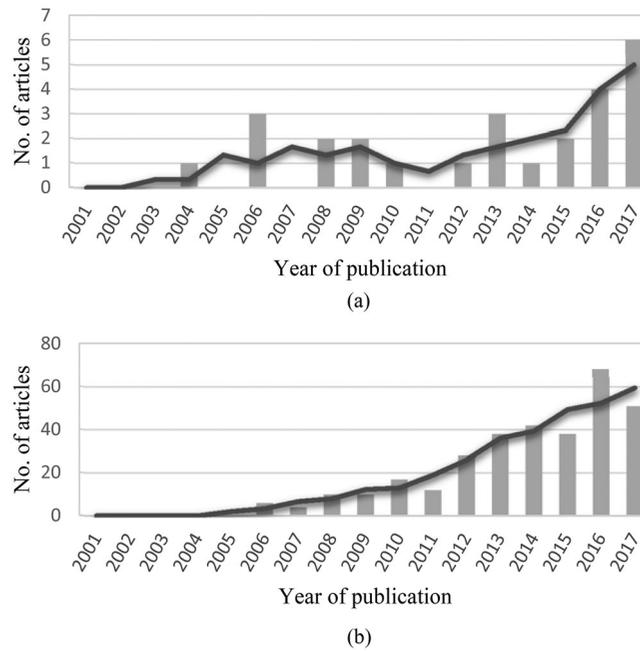


Figure 3. Evolution of research and interest on the field of closed-loop supply chain dynamics. (a) Number of articles per year and three-period moving average. (b) Citations to articles per year and three-period moving average.

2.3. Research synthesis and discussion of the literature

The objective of the data synthesis, the fifth step of the Tranfield, Denyer, and Smart's (2003) methodology, is to summarise, integrate, and cumulate the findings of the different research studies. To this end, we start by considering the results of the data extraction process and categorising the research studies. Figure 4 describes the body of research according to different criteria.

Figure 4(a) focuses on the methodological approach. Given the complexity of the mathematical analysis involved, most of the works employ a simulation-based approach (16 articles), with system dynamics being the most commonly used one (12 studies), followed by discrete event simulation (4 studies). Interestingly, agent-based techniques, an emerging modelling paradigm that has proven to be especially effective for exploring the dynamics of traditional supply chains (e.g. Ponte, Sierra et al. 2017), have not yet been employed in the closed-loop field. Finally, nine articles used analytical approaches: discrete (four), continuous (one), state-space control theory (one), and stochastic analysis (three).

Figure 4(b) considers the topological approach, touching on the inventory and production control pillar. Following the work of Tang and Naim (2004), most of the studies (specifically, 19 out of the 25 articles) explore the dynamics of closed-loop supply chains via hybrid systems with both manufacturing and remanufacturing processes. It should be noted that we have included within this category studies that, besides remanufacturing, also consider other forms of material recovery in more complex (multi-echelon) supply chain structures, such as the recent works by Cannella, Bruccoleri, and Framinan (2016), Sy (2017) and Zhou, Naim, and Disney (2017). This constitutes an emerging avenue of research in this field. The remaining six articles study production and recycling systems, in which the reverse flow of materials is governed by the process of recycling of used products. While these systems may have some things in common with pure remanufacturing systems, it is relevant to note that the dynamic behaviour of the latter, which are very common in practice (Wei, Tang, and Sundin 2015), seems to be under-investigated in the literature.

Figure 4(c) and (d) synthesise the forecasting pillar approach to control *supply and demand uncertainty* related aspects of these papers. Five articles do not consider the problem of forecasting, which is relatively common under continuous review inventory models (e.g. Zaroni, Ferretti, and Tang 2006). The majority of the remaining articles that do consider forecasting, 15 out of 20, do so as in open-loop supply chains. That is, they only deal with forecasting of market demand, and not the returns. This may be interpreted as a consequence of the assumptions of the relevant models, such as perfect correlation between demand and returns (returns equal demand times a return yield, after a constant lead time) and a push system for the remanufacturing process (Tang and Naim 2004).

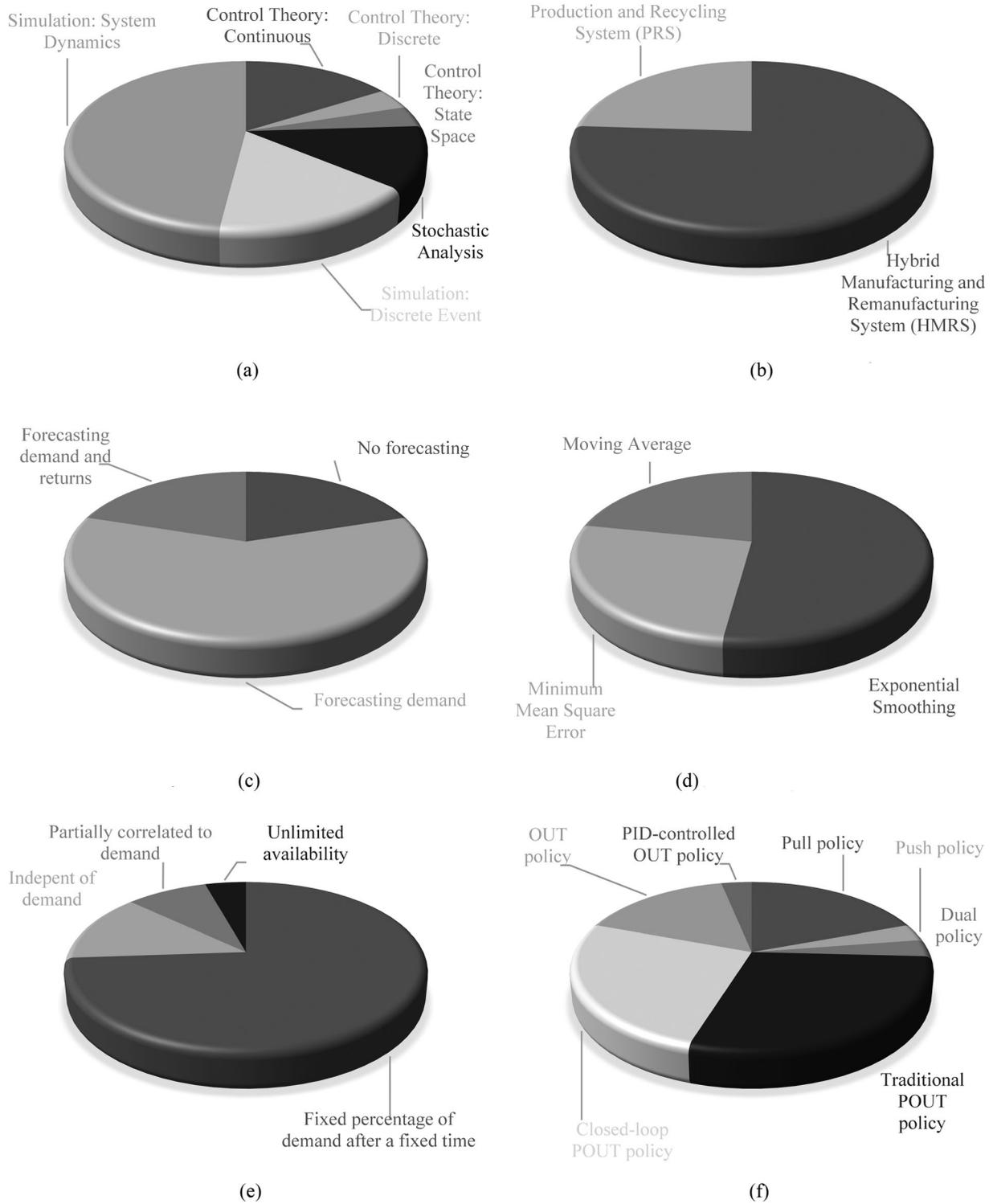


Figure 4. Categorisation of the existing research in the field of closed-loop supply chain dynamics. (a) Methodological approach (b) Topological approach (c) Forecasting approach (d) Forecasting methods (e) Collection model (f) Ordering model.

Only the remaining five articles consider the need for forecasting returns. In Da, Sun, and Zhou (2008), Das and Dutta (2013), Hosoda, Disney, and Gavirneni (2015) and Hosoda and Disney (2018), the returns and the demand are forecasted independently, while Zhou et al. (2006) forecast what some papers call net demand, i.e. demand minus returns. On another note, Figure 4(d) shows that exponential smoothing is by far the most commonly used forecasting method in the

literature on closed-loop supply chain dynamics. Other articles, such as that by Hosoda and Disney (2018), have considered minimum mean squared error forecasting, while other studies employ a simple moving average (e.g. Adenso-Díaz et al. 2012; Zhang and Yuan 2016). Hence, the value of other forecasting methods for improving the dynamic behaviour of closed-loop supply chains still needs to be explored.

Figure 4(e) considers the used products' collection pillar. It underscores that 17 research articles assume that a fixed percentage of the products come back to the supply chain after the consumption of the product. This implies that demand and returns are perfectly correlated. On the contrary, three papers assume no correlation between them, that is, they consider that demand and returns follow independent stochastic processes, which is a common assumption in the reverse logistics literature (e.g. Fleischmann and Kuik 2003). Hosoda, Disney, and Gavirneni (2015) and Hosoda and Disney (2018) considered partial correlation between demand and returns, which raises an interesting question: how does the strength of the correlation impact on the supply chain response? Lastly, Pati, Vrat, and Kumar (2010) considered that a segregator, which separates the desired (recyclable) returns from what cannot be used, orders cores from a dealer without any restriction in core availability. In any case, it should be highlighted that the collection process tends to be largely simplified in these articles by ignoring the possibility of controlling *supply uncertainties* through this pillar. Nonetheless, some interesting exceptions are available; for example, Yuan and Zhang (2015) consider how governmental policies may increase the return rate and its impact on the supply chain.

Finally, Figure 4(f) shows that in the inventory and production control pillar the proportional order-up-to policy is the most commonly used policy. In this regard, some articles, such as that by Tang and Naim (2004) and Turrise, Bruccoleri, and Cannella (2013), have developed specific models for managing closed-loop supply chains by considering the work-in-progress in the reverse flow of materials, and have shown that these may generate a better dynamic performance in terms of order and inventory variability. The classic order-up-to policy, which can be interpreted as a degeneration of the previous one (for the unit value of the inventory and work-in-progress controllers), has also been used by several authors. It should be mentioned that Jing et al. (2013) design a proportional-integral-differential controller for managing the closed-loop supply chain via an order-up-to model. Only three research works, Zanoni, Ferretti, and Tang (2006), Corum, Vayvay, and Bayraktar (2014), and Dev, Shankar, and Choudhary (2017), have explored the dynamics of closed-loop systems via continuous-review inventory policies; this may be pointed out as an interesting area for further study.

2.3.1. Main insights derived from the articles in this field

Here we synthesise the main insights derived from the analysis of the literature of the 19 articles that have met all 3 criteria. The vast majority of papers we reviewed explore the impact of the returns rate (i.e. the average percentage of the used products that return to the supply chain) on the dynamics of the closed-loop system. This is particularly relevant since it allows researchers to compare the performance of closed-loop and traditional supply chains, the latter being associated with a zero return rate.

The impact of the return rate on order variability. The pioneering work by Tang and Naim (2004), explored a hybrid manufacturing/remanufacturing system. They showed that by appropriately making use of available information, the closed-loop supply chain might benefit from a significantly reduced order variability. Later pieces of research have confirmed that closed-loop systems may experience a lower Bullwhip Effect than open-loop ones in the context of perfect correlation; see Zhou et al. (2006), Zhou and Disney (2006), Turrise, Bruccoleri, and Cannella (2013), Zhang and Yuan (2016), Cannella, Bruccoleri, and Framinan (2016), Dev, Shankar, and Choudhary (2017), and Zhou, Naim, and Disney (2017). This implies that the reverse supply chain plays a beneficial role to reduce control uncertainty in the system.

However, other studies that have reached different conclusions. Adenso-Díaz et al. (2012) observed a nonlinear relationship in the impact of the return rate on a production and recycling system. For low values of the return rate, a smoothing effect was observed – that is, Bullwhip decreases –, while for high values, the return rate tended to increase the amplification of the variability of the orders. Zhou, Naim, and Disney (2017) extended the model by Tang and Naim (2004) to three-echelons, and showed that the dynamic performance of the supply chain generally, but not always, benefits from reverse logistics. Specifically, they found that for very high values of the remanufacturing lead time, the traditional supply chain outperformed the closed-loop system, which is consistent with the observations of Adenso-Díaz et al. (2012). Note the assumption of perfect correlation, in combination with the assumption of uniform quality of remanufacturable cores, oversimplifies the problem by leaving *supply uncertainty* outside the scope of the study in question. In fact, the above combination of assumptions removes all four uncertainties associated the reverse flow (right hand side of Table 2), in effect assuming that there is no extra uncertainty resulting from the dependence to the reverse supply chain.

Hosoda, Disney, and Gavirneni (2015, 831) relaxed the assumption of perfect correlation, concluding that 'a closed-loop supply chain is more likely to experience Bullwhip than a traditional supply chain' given the presence of two sources of

uncertainty. This paper is the first exploring the case of non-perfect (partial) correlation between demand and returns in the literature on closed-loop supply chain dynamics. Hosoda and Disney (2018) shed more light on this by showing that the order variance in their closed-loop system was the sum of the order rate in the open-loop supply chain plus the variance of the returns minus a function of the covariance between demand and returns. This indicates that the Bullwhip Effect can be accentuated or mitigated in closed-loop scenarios (in comparison with open-loop ones), depending on the strength of the relationship between demand and returns. As mentioned in Section 1.2, the Bullwhip Effect is a typical *control uncertainty*, as is the inventory variability discussed below.

The impact of the return rate on inventory variability. Some of the previous studies have also looked at the impact of the returns loop on the variability of the supply chain inventories. The majority of these studies have concluded that closed-loop supply chains benefit from a reduced inventory variability in comparison with traditional systems, (e.g. see Zhou et al. 2006; Zhou and Disney 2006; Cannella, Bruccoleri, and Framinan 2016). Conversely, some authors have observed that closed loop systems may suffer from higher inventory variability than open-loop ones (e.g. Turrise, Bruccoleri, and Cannella 2013). Tang and Naim (2004) explored three different types of closed-loop systems, differing in their level of information sharing, and concluded that this level of information transparency is a driver for decreasing the variance in the system. On the other hand, Hosoda, Disney, and Gavirneni (2015) showed that the variance of inventories also depends strongly on the correlation between demand and returns. These last two ideas help to explain how different assumptions can lead to contradictory results – that is, the closed-loop supply chain may be able to operate with a decreased inventory variability when the information transparency and the correlation between demand and returns are high, but may generate a higher inventory variability in other scenarios.

The impact of remanufacturing lead times. The impact of the remanufacturing lead time has also been explored in the literature. This refers to how uncontrolled supply uncertainty translates into process uncertainties and negatively impacting the remanufacturing process. Several authors have observed that, as expected, longer remanufacturing lead times decrease the dynamic performance of the supply chain through a higher order and/or inventory variability, e.g. Zhou and Disney (2006), Huang and Liu (2008), Cannella, Bruccoleri, and Framinan (2016), and Zhou, Naim, and Disney (2017). However, Tang and Naim (2004) and Hosoda, Disney, and Gavirneni (2015) commented on a ‘*lead-time paradox*’ that may emerge in closed-loop supply chains: shorter lead times may actually lead to a decreased performance. This generally occurs when the remanufacturing lead time is shorter than the manufacturing lead time, as the ordering policy is not able to make the best use of information regarding the remanufacturing work-in-progress, resulting in heightened control uncertainty. Note that when this relationship between both lead times holds, the manufacturing orders can make use of the remanufacturing completion rate (‘as-good-as-new’ products) for the period in which the new product will be available in the serviceable inventory. Hosoda and Disney (2018) explored this paradox in detail, and showed that it could emerge in several cases in closed-loop environments. In light of this, they demonstrated the advantages of shortening the manufacturing lead time until both lead times are equal. It should be noted that this counterintuitive result has also been observed in other reverse logistics studies. For example, van der Laan, Salomon, and Dekker (1999) showed that system-wide costs decrease monotonically in the remanufacturing lead time in a closed-loop system managed through a continuous review (s,Q) policy for the manufacturer and a push/pull policy for the remanufacturer.

Other relevant insights in the literature. Finally, we summarise additional noteworthy observations from these works. Adenso-Díaz et al. (2012) explored 12 factors in closed-loop systems and found the inventory controller as the one with the strongest impact on the Bullwhip performance. Das and Dutta (2013) suggested that the inclusion of several ways of product recovery in the same closed-loop supply chain helps improve the dynamics of the reverse logistics system. Cannella, Bruccoleri, and Framinan (2016) observed that the ‘*echelon-elimination principle*’, i.e. designing the supply chain with the minimum required number of echelons to improve supply chain performance (see e.g. Geary, Disney, and Towill 2006) also applies to closed-loop environments. Zhang and Yuan (2016) demonstrated the benefits, from a supply chain dynamics perspective, of old-for-new policies aimed at motivating customers to promptly return the used products. Dev, Shankar, and Choudhary (2017) concluded that periodic-review systems outperform continuous-review ones in terms of Bullwhip mitigation, especially when the return rate is high. Finally, Sy (2017) showed that vendor managed inventory schemes, aimed at integrating processes in the supply chains, also improve significantly the performance of closed-loop systems.

Having conducted the structured literature review of the area of closed-loop supply chain dynamics, we have now seen which modelling options and assumptions researchers apply, and which methods they adopt to manage the four sources of uncertainty. In the following section, we conduct semi-structured reviews of the research areas of forecasting, collection, and inventory and production control, which were previously introduced as the three main decision-making areas of remanufacturing systems.

3. The three pillars of remanufacturing systems

This section looks at the problem-specific literature related to the forecasting, collection, and inventory and production planning pillars that collectively constitute the conceptual framework of our investigation (Figure 2). It does so under the previously discussed uncertainty lens referring to four sources of uncertainty: supply, process, demand, and control. We explore how the research conducted in these closely related areas has attempted to address the sources of uncertainty described in Section 1 and observed in Section 2. Concepts appearing here may be used to educate supply chain dynamics modelling, and ultimately better the performance of closed-loop supply chains.

To return to the boomerang analogy, forecasting and collection help to understand and influence the boomerang's trajectory, respectively, while inventory and production control aims to receive and prepare it for the next throw. In real terms, companies can employ forecasting to estimate the flow of returns, collection strategies to manipulate it, and inventory control to effectively integrate into a resilient closed-loop system.

3.1. Forecasting in closed-loop supply chains

Forecasting is integral to the effective operational management of any supply chain. In closed-loop systems, this mainly entails forecasting demand, dealing with *demand uncertainty*, and returns, dealing with *supply uncertainty*; both having a major impact on the operational performance of the system.

Here, we are mainly concerned with the reverse loop and the forecasting of returns, as this is the additional aspect of supply uncertainty remanufacturers face; we refer the interest to Syntetos et al. (2016) for a literature review on demand forecasting methods. Depending on the setting, these returns forecasts can be used on their own, or subtracted from the demand forecasts to obtain net demand forecasts. A pure remanufacturer operating a push-based 'remanufacture-all-returns' system, such as a warranty service provider, would directly use the returns forecasts for capacity planning and inventory control. Conversely, a hybrid manufacturing/remanufacturing system, that satisfies part of their demand through remanufacturing returned products, may be interested in the net demand forecasts to appropriately plan manufacturing orders, or orders to a core broker (for the part of their demand that cannot be serviced through remanufacturing of returned products).

In the remanufacturing context, we are facing two main areas of *supply uncertainty* that need to be forecasted: the *rate* of the returns (time, or when a return will occur; and quantity, or how many items will be returned), and the *quality* of the returns (or condition, which relates to the viability, time and cost implications of reinstating the item to an 'as-good-as-new' state). The first issue has attracted some attention, albeit under some particularly 'convenient' assumptions. However as it will be shown, the latter remains largely unexplored, despite it being known that the quality of the returned items represents a crucial issue for reverse logistics systems (e.g. Van Wassenhove and Zikopoulos 2010). We revisit the quality issue in Sections 3.2 and 3.3.

The work of Goh and Varaprasad (1986) is often cited as the first paper to explore the correlation of returns (dependent variable) to past issues (independent variable), and used that relationship to forecast various product returns parameters. They were specifically interested in estimating a returns distribution through the probabilities associated with varying trip lengths (return lags), alongside the overall probability of returns. It is this returns distribution, and the way to calculate or derive it from the data available, that is central to the forecasting of product returns – either for remanufacturing or recycling or disposal. The researchers employed a Box–Jenkins transfer function model to characterise the returns distribution, based on monthly time-series of issues and returns – described as period-level data, in Toktay (2004) – for soft drink containers (specifically, Coca-Cola and Fanta).

Kelle and Silver (1989a) introduced four methods – A, B, C, and D, as reported in de Brito and van der Laan (2009) – to model and forecast multinomial returns of reusable containers based on past issues, distinct to each other, by augmenting data requirements (and accuracy of the forecasts). They were the first to include in their calculations within lead-time issued product returns, and to test the forecasting accuracy and inventory implications of their methods. It is important to note that by considering that returns in the lead time can also happen from within lead-time (forecasted) issues, the accuracy of the returns forecasts is also subject to the accuracy of the forward forecasts.

We refer interested readers to the original manuscript but also to the appendix of de Brito and van der Laan (2009) for a detailed explanation of these methods. Method A simplistically assumes a perfect correlation of sales to returns. Method B derives returns by multiplying past sales with a pre-derived returns distribution. Method C is of particular interest, employing a normal approximation to their multinomially distributed returns. It uses periodic aggregate issues and returns – or period-level data, as defined in Toktay (2004) –, to derive the returns distribution. On the contrary, Method D requires serialised issues and returns – or item-level data, as defined in Toktay 2004 –, which enable a complete characterisation of the returns distribution, as well as an update of which items have returned from which issue, and is employed as a benchmark.

The four methods were revisited by de Brito and van der Laan (2009) who extensively tested their inventory performance in the presence of imperfect information. This is a very important issue and the researchers highlighted that the most informed Method D more often than not performs worse than the more robust ones (e.g. Method C) in such scenarios. This can be interpreted in the following manner: when the approximation of the returns distributions (distribution assumption and/or parameter estimation) is poor, simpler methods generally outperform the more informed ones.

A few pieces of work resorted to Bayesian estimation methods and heuristic procedures to derive the distribution of returns in a distributed lag model formulation. The general form of a distributed lag model (DLM) when regression is employed to forecast returns is as follows: $\hat{r}_t = (\sum_{i=0}^n p_i \cdot d_{t-i}) + \varepsilon_t$; where d_t and \hat{r}_t are the demand and forecasted returns at period t , respectively; p_i is the (statistically significant – mostly above 0.01) probability of an item returning exactly i periods after its issue; and $\varepsilon_t \sim N(0, \sigma^2)$ is usually assumed to be additive white noise (an independent and identically distributed, i.i.d., variable normally distributed with mean 0 and variance σ^2). Toktay, Wein, and Zenios (2000) employed an Expectation-Maximization heuristic and a Bayesian updating procedure to produce estimates of the returns distribution. They applied their method on period-level data of Kodak single-use cameras (Method C). They constructed a queueing network and assumed Poisson demand with negative binomial and geometrically distributed returns, testing forecast utility performance through inventory cost savings. Clottey, Benton, and Srivastava (2012) employed a Metropolis-Hastings (M-H) Markov Chain Monte Carlo (MCMC) heuristic and a Bayesian updating procedure to model the return lags for exponentially distributed returns for an electronics OEM. They propagated the use of continuous time as it lends itself to using the latest data at the point of decision (between periods, as they are defined in the dataset – e.g. monthly). Clottey and Benton (2014) used a similar approach to model Gamma distributed returns in an adaptation of the procedure accommodating longer lags. Krapp, Nebel, and Sahamie (2013) used a DLM for a Poisson (returns) delay function. Again, these can be seen as different approaches to Method C, when some manipulation of item-level data is used to derive the returns distribution.

Carrasco-Gallego and Ponce-Cueto (2009) forecasted returns in the Liquid Petroleum Gas (LPG) through a dynamic regression model. They reported that their method outperforms unimodal forecast procedures that disregard the correlation between returns and past sales. In this, they agree with Kiesmüller and van der Laan (2001), who modelled Poisson demand and returns (lagged by a constant time since sold) by incorporating the former in the forecast of the latter by means of Markov chains. Clottey (2016) provide further support to the claim for when returns follow an autoregressive pattern, but not when they are random noise. In summary, research agrees that the dependence of returns to past sales should not be disregarded.

We present, in Table 4, an overview of the different approaches to forecasting returns by looking at the most influential works in this literature. Overall, DLM formulations appear to be the most promising way to model returns as a function of past sales, as they have been shown to offer a good trade-off between performance and ease-of-implementation (which e.g. refers to the data required to perform the forecasts). As seen in Section 2, the supply chain dynamics literature generally employs naïve methods both to model the relationship between returns and demand and to estimate the former as a function of the latter. Therefore, an interesting double opportunity would emerge from: (1) implementing more realistic return-demand models, which would allow a more nuanced representation of the ‘boomerang’ trajectory in practical scenarios; and (2) employing more appropriate forecasting techniques, which would help to improve the dynamics of closed-loop supply chains through a better understanding of that ‘boomerang’ trajectory.

The literature surveyed above deals with forecasting net demand, by subtracting the returns forecast from the demand forecast. Although the returns forecasting process is emphasised, is interesting to note that the (forward) demand forecasting

Table 4. An overview of different approaches to forecasting returns.

Authors (year)	Forecasting returns	Returns distribution assumption (context)
Goh and Varaprasad (1986)	Transfer Function	Empirical (Soda container bottles)
Kelle and Silver (1989a)	Normal approximation	Multinomial (Soda container bottles)
Toktay, Wein, and Zenios (2000)	DLM – Bayesian estimation/heuristic	Geometric and Negative Binomial (Kodak single use cameras)
Kiesmüller and van der Laan (2001)	Markov chains	Poisson (Theoretical)
Hanafi, Kara, and Kaebnick (2008)	Fuzzy Coloured Petri Net based approached	Empirical (Mobile phone collection)
Carrasco-Gallego and Ponce-Cueto (2009)	Transfer Function	Empirical (LPG containers)
Clottey, Benton, and Srivastava (2012)	DLM – Bayesian estimation/heuristic	Exponential (Electronics OEM)
Clottey and Benton (2014)	DLM – Bayesian estimation/heuristic	Gamma (Electronics OEM)

process is sidestepped through some convenient assumptions for the demand forecasts. This is an important omission, as forward demand forecasts do also considerably affect operations. It is also interesting to note that most of the returns forecasting literature employ some inventory policy (mostly order-up-to policies, driven by net demand). This is dissimilar to the general (supply chain) forecasting literature that is concerned with reporting forecasting accuracy but does not explore forecasting utility measures (such as inventory costs and achieved service levels, e.g. see Syntetos and Boylan 2008).

We need to emphasise that the returns forecasting literature focus on the time and quantity (rate) of returns; however, they have not contributed towards the estimation of the condition, or quality, of the returned items, which is equally important. This is an area open for contributions. A key question here is how the varying condition of returned cores affects the remanufacturing process, and what ways there are to alleviate its effects as a source of uncertainty on the performance of the closed-loop system.

So when will the boomerang return and what will it look like? The forecasting pillar should help understanding the trajectory of the boomerang – the rate and quality of returns. It provides advance information to facilitate decision making in the subsequent two pillars, either by informing appropriate acquisition strategies in collection, or initiating orders (in time and quality) in inventory and production control.

3.2. Collection of used products

For the purposes of this work, collection is interpreted as the process of: (1) incentivising the return of cores, which includes both pricing decisions and product acquisition strategies to motivate the green consumer behaviour (see e.g. Lao (2014)); (2) the design of the structure of the collecting channel (see e.g. Srivastava and Srivastava (2006) and Souza (2013)); and (3) pre-sorting mechanisms as a last control of supply uncertainty before the remanufacturing process (see e.g. Ferguson et al. (2009)). In this sense, decision making around collection should be aimed at optimising the return trajectory or ‘fly path’ of the ‘boomerang’ between the product leaves and returns to the firms’ facilities, so that it makes the best dynamic impact on the overall closed-loop supply chain. In this sense, determining an appropriate collection strategy is admittedly a rather involved process, whose efficiency and effectiveness nevertheless is critical to the overall performance of the supply chain (Goggin, Reay, and Browne 2000). Relevant decisions are explored by a number of practices and research areas such as supply chain integration, marketing, and pricing, and combinations thereof. The three previously defined facets of the collection process are reviewed below.

3.2.1. Incentivising returns

With regards to the pricing decision, Li, Li, and Saghaian (2013) studied the problem of the market-driven product acquisition, where the acquisition quantity of the cores is random and relates to the acquisition price. Additionally, they considered stochastic yield in the remanufacturing process due to the uncertainty in the quality of acquired cores. They found that the acquisition price should be used as a lever by manufacturers to alleviate uncertainties in cores acquisition (rate and quality) and remanufacturing yield. Wei and Zhao (2015) investigated the pricing policy and remanufacturing decisions in the duopoly market scenario, where two supply chains are competing at both the manufacturer and retailer levels. Using the Stackelberg game, they derived the optimal pricing policy of members in the supply chain under different industry structures and competing forms. Savaskan and Van Wassenhove (2006) studied the interaction between a manufacturer’s collecting channel and the strategic product pricing decisions in the forward channel in a competitive retailing environment. They considered two different collecting channels, via the manufacturer itself or via the retailers. If the manufacturer collects used products by itself, the scale of returns has a significant impact on the channel profits. On the contrary, if the manufacturer uses the retailers as the collecting channel, the supply chain profits are mainly driven by the competitiveness in the retailers.

Galbreth and Blackburn (2006) studied the optimal acquisition (in terms of quantity) and sorting policies under variable quality of returns, under both deterministic and stochastic demand. They showed that when the acquisition costs are linear, the optimal acquisition and sorting policy can be defined independently of the production lot size, as a simple proportion of demand. Zikopoulos and Tagaras (2015) considered the possibility of return sorting and multiple collection sites. They derived the analytical solution for the selection of the optimal sorting location in a special case of identical collection sites and examined the cost and accuracy of the sorting procedure on the profitability of the alternative supply chain configurations. Alegoz and Kaya (2017) studied the collection activities of end-of-life products, taking the quality of components in the returned cores into account. In their setting, the collection centre needs to decide the timing of dispatching to the remanufacturer and the optimal acquisition fee from the customer. By means of dynamic programming, they found the optimal dispatching and acquisition fee decisions. More importantly, their analysis showed that quantity-based policies outperform time-based dispatching ones.

3.2.2. *Designing the collection channel*

In terms of who collects the used products, there are three typical channels: (i) the manufacturer itself; (ii) the retailer; and (iii) a third party, such as professional collection companies and non-profit organisations, often described as ‘core brokers’ in the literature (e.g. Guide 2000). In addition, collection may take place via: (a) a single collecting channel, i.e. only one of three aforementioned channels; or (b) a multiple collecting channel, i.e. combining two or three of the channels discussed above. One of the pioneering contributions to the optimal single collecting channel problem was that by Savaskan, Bhattacharya, and Van Wassenhove (2004). They assumed the manufacturer to be the Stackelberg leader in a decentralised decision-making system, and found that the most effective undertaker of product collection is the retailer who is closer to the customer. Atasu, Toktay, and Van Wassenhove (2013) revisited the same problem to show that the effect of the collection cost structure plays a crucial role in a (re)manufacturer’s reverse channel choice. In their volume dependent reverse logistics cost model, they found that retailer-managed collection is optimal when economies of scale are present.

Choi, Li, and Xu (2013) examined the performance of different closed-loop supply chains under different channel leaderships, and found that the retailer-led model provides the highest effectiveness from an environmental and societal welfare perspective. As for the dual-channel collection, Hong et al. (2013) studied the optimal profit of all members in the supply chain under the manufacturer Stackelberg model and the strategic alliance model. They concluded that the manufacturer and the retailer hybrid collection channel is the most effective channel structure by examining several numerical examples. Huang et al. (2013) studied optimal strategies for dual-channel collection in a situation where the retailer and the third party competitively collect used products. Based on competing intensity, they suggested the decision criteria of choosing dual-channel or single-channel collection. The dual-channel only outperforms the single-channel when competition in collection is not very strong. Zhao, Wei, and Li (2017) investigated the optimisation problem of dual-channel collection in another situation where a manufacturer is the channel leader in a remanufacturing supply chain. Under various scenarios, they obtained the optimal choice of collection channel, the optimal pricing, and collecting effort decisions when the dual channel is comprised by i) the manufacturer and the retailer, and ii) the manufacturer and the third party.

3.2.3. *Pre-sorting of cores*

Presorting of cores refers to grading cores based on their quality, i.e. how easy (e.g. cost, time) they are to remanufacture. Ferguson et al. (2009) dealt with the remanufacturing operations of Pitney Bowes (P-B), provider of mailing automating solutions, and proposed a policy that grades returns upon arrival, in the absence of perfect substitution. They suggested an optimal remanufacturing policy under deterministic demand and returns rates, stationary costs and distribution of returns quality, and capacity constraints. They reported cost savings of 4%+ for the various pre-sorting settings they explored (when compared to the absence of pre-sorting). This agrees with earlier findings by Aras, Boyaci, and Verter (2004) for the complementary case where remanufactured and new items are perfect substitutes (which indicates that the quality aspect is equally important regardless of the substitution assumption, see Section 3.3.2). They explored the conditions under which quality-based categorisation leads to cost benefits for hybrid remanufacturers. In their study, the authors considered varying remanufacturing lead times based on the quality of the cores. They found that two prominent drivers for the categorisation to be impactful are: high return to demand rate ratios, and ‘the demand rate being low’ (i.e. slow-moving products). Zikopoulos and Tagaras (2008), who made assumptions along the above lines, also propagated the benefits of taking quality into account, even via simple sorting mechanisms, to provide advance information on the quality of the cores prior to the actual remanufacturing operations.

In summary, the literature in the area of core collection also underlines the importance of dealing with the uncertainty in both rate and quality of returns. It should be highlighted that the collection process can strongly influence both the rate and the quality of the items returned by the customer. Therefore, the collection pillar can be used to control this *supply uncertainty* for the remanufacturing system (e.g. by selecting an appropriate collection channel or incentivise timely returns), controlling in effect the (expected or not) the return rate and quality of returns – the boom-erang’s trajectory.

Despite the breadth of this concept and its recognised importance, the literature on the dynamics of closed-loop supply chains often relies upon simplified assumptions on the collection process that sidestep several sources of uncertainty (please refer also to Section 2). For example, fixed and independent return rates are often assumed, which despite their occasional realism reduce the collection process to a ‘passive’ receive of cores and hence ignores the important relationship between customers’ reaction and supply chain performance. Further, the same quality is often assumed for all the returns, an assumption that reduces analytical complexity but bears little resemblance to practical situations.

3.3. Inventory and production planning for remanufacturing

We here discuss how the different sources of uncertainty (viz.: supply, process, demand, and control) manifest and may be controlled, when it comes to inventory and production planning within closed-loop supply chains.

3.3.1. Production and inventory modelling decisions and policies

There are various issues to discuss with reference to modelling decisions and policy selection. Here, we review and discuss the distinction of hybrid and pure set-ups, push and pull strategies, and a number of replenishment rules. Interestingly, all four sources of uncertainty play an important role here.

Hybrid versus pure systems. An important modelling decision involves how to model the remanufacturing production line: as a hybrid manufacturing/remanufacturing system, where both lines are integrated within the same production line, or as a pure remanufacturing system, that operates separately from the manufacturing line. Regarding this mix-or-match approach, several authors have advocated the importance of independent, pure remanufacturers, in the reverse logistics industry (e.g. from Lund 1984 to Wei, Tang, and Sundin 2015). Teunter, Kaparis, and Tang (2008) report that companies facing growing remanufacturing operations tend to move towards operating separate lines. However, most inventory literature on remanufacturing focuses on hybrid systems (Souza 2013; Wei, Tang, and Sundin 2015), in this being consistent with the discipline of closed-loop supply chains dynamics. We lend our support to this claim. We can independently reach this conclusion as most of the literature reviewed in this work also refers to hybrid systems. Understandably so, the hybrid assumption is not suitable for pure remanufacturers, or even for OEMs who keep remanufacturing separate from manufacturing. It also not suitable on situations where the assumption of perfect substitution (i.e. new and remanufactured items being undisguisable, serving the same demand) does not hold.

Tang and Teunter (2006) provided exact Mixed-Integer Linear Programming (MIP) and heuristic solutions for optimising separate lot sizes for manufacturing and remanufacturing in a hybrid production line (water pumps for the automotive industry), reporting 16% cost reductions when compared to the company practice. Teunter, Kaparis, and Tang (2008) used a similar methodology, on the same dataset, for the complementary case of separate lines for manufacturing and remanufacturing (pure). They reported the MIP formulations to be more complex, but yielding better results (average cost reduction of 6.5%). These reductions were attributed to lower production rates and increased scheduling flexibility for the split production lines, and increase sharply (>15% reduction) in increasing return rates (40% and higher). The above makes a good case for considering the question of hybrid versus pure setups when modelling remanufacturing operations, and explore the different dynamic behaviour of both systems.

'Push' and 'pull' policies in a tug of war. An important decision to be made by remanufacturers is whether to 'push' cores through a remanufacturing process (repairing all 'remanufacturable' returns as soon as they become available), or to 'pull' them by building up cores and controlling this inventory. One of the early attempts to explore these strategies for hybrid remanufacturers was that of van der Laan, Salomon, and Dekker (1999). They suggested the general effectiveness of the pull system (while noting that the effectiveness is subject to the valuation of the core and serviceable inventories), and urged remanufacturers to consider which items to remanufacture and when. They further suggested to control the uncertainty of the returns process and also track the correlation between demand and returns. Poles (2013) used a system dynamics simulation approach to explore the effects of capacity planning and lead time effects in push and pull systems, and reported that the pull system is associated with better performance in a range of scenarios (except when backorders are present). Van der Laan and Teunter (2006) provided a number of effective (near optimal), simple closed form expressions (heuristics) to compute the optimal policy parameters (re-order points and lot sizes) for both settings.

As we have seen in Section 2, the preferred modelling decision in the field of closed-loop supply chain dynamics is to 'push' the cores into the remanufacturing process. While this strategy has proven to perform well under some scenarios, it can be expected that the benefits of such systems (developed for open-loop systems) do not translate well in the presence of an elevated supply uncertainty in conjunction with an unknown quality of returns. In this pillar, in the absence of an inventory of cores the push system implies, no meaningful control of the supply uncertainty of either the rate or the quality of the returns can be employed. We will revisit this matter in Section 4.

Time is relevant: periodic versus continuous review. In an attempt to provide a brief overview of the policies employed in the inventory control literature in remanufacturing, we focus on the cases where demand and/or returns are stochastic processes (as opposed to being assumed deterministic³, which only applies in a very limited range of scenarios). These policies can be conceptually divided into periodic-review (where decisions are made in fixed intervals of time, e.g. weekly) and continuous-review (where decisions – whenever made- are based on live updates of the inventory position) policies. Overall, work that deals with periodic review policies emphasizes order-up-to level S , at a regular review interval T , (T, S) policies

(e.g. Simpson 1978; Kiesmüller 2003; Mahadevan, Pyke, and Fleischmann 2003) and less often reorder point s and order-up-to level S (T, s, S) ones (e.g. Fleischmann and Kuik 2003).

The use of discrete review order-up-to policies is very common in the supply chain dynamics literature. It occurs because replenishing inventories frequently is a common practice in some industries (Disney and Lambrecht 2008), but also due to the fact that a discrete time periodic basis reduces the complexity of the dynamic analysis. We refer interested readers to Lalwani, Disney, and Towill (2006) for a review of a wide variety of order-up-to models in this literature, depending on how the order-up-to level is computed. Applications considering continuous review either emphasize re-order point, s , order quantity, Q , (s, Q) policies (Muckstadt and Isaac 1981; van der Laan and Teunter 2006), or the determination of s and S to allow (s, S) implementations (e.g. Fleischmann and Kuik 2003; Zanoni, Ferretti, and Tang 2006). Please note that s , S , and Q need to be set for both manufacturing and remanufacturing operations, taking into account relevant complexities of pure and hybrid setups, and are dependent to each other in the presence of the perfect substitution assumption. Section 2 reveals that very little literature in the field of closed-loop supply chain dynamics considers the implications of continuous-review models. This could be pointed out as a relevant area for further research, especially in a context of technological changes (e.g. RFID technologies) that enable continuous review of the inventory.

3.3.2. *The assumption of perfect substitution*

The vast majority of publications reviewed so far in this section assume perfect substitution, where customer demand can be interchangeably serviced by new or remanufactured items – an assumption so common that is taken almost for granted when referring to remanufacturing operations (Souza 2013). There are of course examples where the assumption holds, such as the case of Kodak single-use cameras, where the final products might include a retrieved core, in the name of electronic circuit or lens (Toktay, Wein, and Zenios 2000). In such cases there are no demand uncertainty considerations (at least no new ones, from the reverse loop). However, as we observed in our industrial partners (Briggs 2017; Fitzsimons 2017; Shaw 2017), and also reported in the literature (e.g. see Wei et al. 2015), this premise is not very realistic, and admittedly ‘can reduce modelling efforts to elegant solutions addressing non-existent problems’ (Guide and Van Wassenhove 2009, 17).

Jaber and El Saadany (2009) were among the first to relax this assumption, using different inventory pools to service separate markets, reporting that doing so lead to stock outs (and lost sales, i.e. demand for newly manufactured items is lost during a remanufacturing cycle and vice versa). Singh and Saxena (2013) also relaxed the assumption of perfect substitution, but for perishable items, while cannibalising beyond economical repair cores (salvaging any residual value in terms of operational parts, as opposed to scrapping). Moshtagh and Taleizadeh (2017) considered a realistic system with different markets for manufactured (primary market) and remanufactured items (secondary market), stochastic core quality (assumed uniform, ascending and descending triangular distributions), defective product production and rework, as well as return rates dependent on a quality acceptance level. They showed that reduced remanufacturing costs make selling to the secondary market more profitable than the primary.

3.3.3. *Pre-sorting and the quality of returns*

We now turn our attention to related *supply uncertainty* considerations and specifically how the quality of the returns interacts with the production (remanufacturing) process. Relevant papers mainly propagate the value of quality information by (mostly) assuming that the quality classification of cores is predetermined and without inspection error (e.g. a set probability of a returned core to be remanufacturable versus being beyond economical repair), with limited consideration on how to incorporate it in the returns forecasts.

Ferguson et al. (2009), Aras, Boyaci, and Verter (2004) and Zikopoulos and Tagaras (2008), (reviewed in Section 3.3.2) all agree there are cost implications if quality is unknown when a core enters the remanufacturing process. Li, Li, and Cai (2016) found that for a newsvendor setting, pre-sorting is only useful in remanufacture to order systems (RMTO), but not in remanufacture to stock (RMST). Zikopoulos (2017) investigated the optimisation of recovery planning decisions, by means of considering stochastic remanufacturing lead-times, according to quality levels of returned products, classified into two groups (good and bad, with different processing times and costs). They built a stochastic inventory control model with normally distributed demand, assuming availability of cores, but by modelling the returns’ quality according to the Beta distribution. They concluded that accurately estimating the quality of the returns may offset any need for pre-sorting, while ignoring it can result in extensive additional costs, even when the variability in the quality of cores is low. This is a very interesting finding, and provides strong motivation for incorporating estimations of quality in the efforts to forecast returns (mentioned in Section 3.3.1) – in a sense moving from forecasting generic returns, to *forecasting returns for remanufacturing*.

The above-discussed approaches are not explicitly concerned with forecasting the quality of the returns, but do provide strong arguments for the importance of quality-related information, and guidelines about how such information may be used.

At the same time, as is the case in inventory control in general, some convenient assumptions have been made for the returns rate (outside Section 3.2.1). There is a consensus that pre-sorting and more generally the manipulation of the quality issue can lead to substantial benefits.

3.3.4. *The integration of forecasting in inventory models*

Some researchers attempted to tackle the inventory-forecasting problem jointly, by means of using some of the forecasting methods described in Section 3.1. Kelle and Silver (1989b) modelled a purchasing policy using the forecasting procedures they developed in Kelle and Silver (1989a). Under stationary demand, they reduced a stochastic lot-sizing problem to a deterministic, lot-sizing one and provided exact and approximate solution methods. Based on the above formulation, Clotey (2016) developed a rolling horizon purchasing policy for cores, that adapts previous methods found in Clotey and Benton (2014) to make multi-period ahead forecasts and evaluate their utility (inventory performance) on theoretically generated data (Gamma return delay, uniform demand, random noise and AR(1) sales). They reported that Bayesian estimation yields cost related benefits at high service levels (>95%) when compared with maximum likelihood estimations of the net demand distribution. As discussed in Section 3.1, we believe such (DLM) formulations lend themselves easily to supply chain dynamics representations, and are worthy if further consideration.

3.4. *Discussion*

We have seen the issue of quality arising throughout our investigation of the three main pillars. Although it constitutes a supply uncertainty, if not adequately controlled, it can also manifest itself in the form of process and control uncertainties. From this standpoint, the three pillars provide sequential opportunities to address the *supply uncertainty*: estimate (and plan for) it through adequate forecasting, manipulate it through correct collection strategies, or deal with it through elevated inventory control. In summary, this lens makes evident that the quality of the returns emerges as the main source of uncertainty in the reverse supply chain – we will further reflect on this in Section 4.1.1. Of course, this does not imply that the rate of returns is any less important. Indeed, the uncertainty concerning the availability of cores needs to be appropriately controlled at a different level than any uncertainties regarding raw materials availability. The forecasting pillar's interaction with the rate of returns will be considered in Section 4.1.2.

It has been shown that the collection pillar (and the related decisions) can also mitigate some of the uncertainty stemming from the supply. The collection channel selection, incentives such as pricing, and in general efforts to control the quality of the inbound cores (either from end customers or brokers) can directly and decisively influence the quality and quantity of the cores; hence offering opportunities for future research that will be evaluated in Section 4.1.3. Finally, the inventory and production control pillar needs to deal with all uncertainties that have not been controlled up to that point, including any control uncertainty. The decision to disengage manufacturing and remanufacturing operations, or optimise/set distinctly can alleviate process and control uncertainties. Opting to 'pull' rather than 'push' remanufacturing provides leeway in terms of managing the quality of the cores in the inventory of remanufacturables. A short, indicative survey in inventory for remanufacturing, with regard to the modelling options, revealed viable ways to effectively control the relevant processes. Section 4.1.4 will look at this relevant point.

We also need to highlight that a specific assumption, that of 'perfect substitution' between manufactured and remanufactured items, has received what may be interpreted as a disproportionate attention in all streams of literature surveyed. While it may hold true in some specific cases, customers commonly value new and remanufactured products in a different manner, which usually leads to the creation of separate markets. However, a major concern may emerge from this situation: market cannibalisation, which may decrease the attractiveness of remanufacturing practices for firms (Atasu, Guide, and Van Wassenhove 2010). In Section 4.1.5, we will consider the need for appropriately studying the interactions between different markets in closed-loop supply chains.

The insights from the structured literature review, and specifically common assumptions therein (most shared with the open-loop literature), have been informed with insights gained from the survey of the three pillars. This enables a discussion of the trade-off between simplicity and realism in the modelling of closed-loop supply chains, which will be explored in Section 4.1.6.

4. *Implications and the way ahead*

We established the current state of knowledge in the field of closed-loop supply chain dynamics (in Section 2), and discussed adjacent research in closely related areas (in Section 3), we are now concerned with identifying insights and gaps to be

explored, in the form of directions for future research. Building on the three pillars of closed-loop systems and the uncertainty-based lens put forward, we suggest six main directions for future research in this area.

4.1. Directions for future research

These may be interpreted as strategic avenues for unmasking the true potential of remanufacturing from an economic, social, and environmental perspective.

4.1.1. Car or goat? The quality of the returned items

Like in the popular Monty Hall problem (Selvin 1975), where participants must select between three doors behind which there are one car and two goats, supply chain actors do not know what is behind the ‘door’ when they receive a batch of used products. The condition of the received products has a significant impact on the operation of the supply chain, and hence on its dynamic behaviour. Unquestionably, this quality uncertainty is a crucial characteristic that differentiates closed-loop supply chain contexts from – and make them more complex than – traditional open-loop ones (Denizel, Ferguson, and Souza 2010). Indeed, we have observed that remanufacturers generally employ a single average cost per product family, which makes the profit margin obtained per unit of product strongly dependent on the quality of the returned items.

There are three options to control this *supply uncertainty*. In the forecasting pillar, even though quality forecasting papers are very scarce, developing methods to estimate the condition of returns may offset the need for the solutions in the collection pillar. In the collection pillar, one can influence the quality by either directly influencing the quality of the returns (e.g. by buyback schemes or leasing) or controlling it (by employing pre-sorting of the cores upon core arrival or by a third actor, namely, a core broker – in essence placing orders against some specific quality classes). In the inventory and production planning pillar, and specifically in the absence of robust controls of this form of uncertainty in the other pillars, a quality grading mechanism has proven to be very popular (Ferguson et al. 2009). It should be noted that in absence of any control of cores’ quality, and in general any supply uncertainty uncontrolled at the moment remanufacturing starts, translates into a high *process uncertainty* in the reverse flow of materials. One obvious effect is variability in the remanufacturing processing times (Behret and Korugan 2009). One way or the other, differences in the quality of the returns means that balancing demand with supply becomes a much more complicated problem.

Despite its proven relevance, most of the literature in production planning and control for remanufacturing assumes a single quality grade for all returns, as underscored by Jin, Ni, and Koren (2011). The same conclusion can be derived specifically for the field of closed-loop supply chain dynamics, which has barely taken this relevant characteristic of closed-loop systems into consideration. It should be noted that some papers consider different ways for recovering the used material; nonetheless, they assume that a fixed percentage of the returns undergo each different process, entailing that uncertainty is not directly dealt with by managers. For example, Zhou, Naim, and Disney (2017) modelled the refining, remanufacturing, and refilling processes in a three-node cartridge supply chain, assuming three different, and fixed, return yields.

All in all, there is a need to understand the dynamic implications of uncertain conditions in the collected returns. The quality aspect of supply uncertainty is critical and the three pillars can effectively lend mechanisms to cope with it. As discussed, this encompasses considering the value of forecasting the quality of the returned items, designing fit-for-purpose collection strategies, and implementing quality grading methods on arrival of cores.

4.1.2. When will the ‘boomerang’ return? Linking demand and returns forecasting

Knowing the condition of an item upon return may not be useful if it is not known when it will re-enter the production facilities. This puts emphasis on the value of developing accurate methods for forecasting returns. In this sense, it should be noted that academic literature in the area of forecasting returns is united in that the returns process is closely correlated to the demand process, although it is a common practice in the closed-loop literature to assume that they are independent. From this perspective, precisely capturing the relationship between the demand and returns flows becomes essential to improve the operational performance of remanufacturing systems.

Table 3 reveals that the literature on supply chain dynamics has been barely reflecting this important relationship between returns and the past sales. Indeed, most of the papers do not forecast the returns in the closed-loop system, some of them assuming that the return rate is fixed and known. Note that this may omit the consequences of the interaction between *demand* and *supply uncertainty*, which reduces the intrinsic complexity of the closed-loop scenario. Relevant exceptions are the papers by Das and Dutta (2013), Hosoda, Disney, and Gavirneni (2015) and Hosoda and Disney (2018), which however do not analyse the implications of appropriately forecasting the returns.

This uncovers a clear line of research that may look at the effect of the interaction between *demand* and *returns uncertainty* on the supply chain dynamics, and in that regard the validity and usefulness of the forecasting models described in Section 3.1. Interestingly, this perspective brings into the analysis the role of the correlation between demand and returns, where the works by Hosoda, Disney, and Gavirneni (2015) and Hosoda and Disney (2018) provide insights on the dynamics of closed-loop supply chains. The ease of implementation of DLMs combined with their efficacy makes them a robust suggestion for a) better modelling the relationship between demand and returns, and b) as a fit-for-purpose means to forecast the reverse flow of materials and control the temporal aspect of supply uncertainty.

4.1.3. *Who plays the catcher? Strategies for product collection and their implications*

As shown in Table 3, papers in the field of supply chain dynamics generally simplify the collection process – and do not really consider *supply* uncertainties –, often reducing the collection to a ‘passive’ receipt of cores of uniform quality. However, companies adopting a circular model have to deal with restoring cores of unknown quality to ‘as-good-as-new’ items. Unless the quality distribution can be forecasted accurately, remanufacturers need to appropriately incentivise customers and carefully design a channel to control when and in what conditions the cores are to return to the supply chain. Collection provides the last opportunity to control the supply uncertainties before having to resort to locking up cash in bigger inventories. In this sense, some relevant dilemmas emerge, such as: (1) own versus third-party collection of returns (i.e. channel selection); (2) early versus late evaluation of returns; and (3) manipulation of the return process through incentives (e.g. leasing, buy-back schemes).

These decisions will have knock-on effects on the remanufacturing process as they will affect sequencing (given potentially different delivery windows) and cycle times (due to the varying condition of the product at point of use). The effect of different collection decisions, and varying acquisition effort intensities, has not been adequately researched. Exploring these problems from a supply chain dynamics perspective is worth pursuing.

4.1.4. *What's in the pipeline? Models for controlling the remanufacturing loop*

Forrester coined the concept ‘pipeline management’ to describe the continuing controlled flow of materials on demand (Mason-Jones and Towill 1998). Increasing the visibility of this pipeline stock is well known to be a powerful mechanism to reduce the amplification of the variability of orders and inventories in the supply chain – and hence to mitigate *control uncertainties*; see e.g. Holweg et al. (2005). This rationale applies in open- and closed-loop production and distribution systems, although the pipeline covers different flows of material in both supply chain contexts. Literature in closed-loop supply chain dynamics is commonly concerned with exploring the behaviour of policies with different levels of information availability in the system. Order-up-to and proportional-order-up-to systems are widely adopted, but the question of their optimality needs to be addressed. Thus, a relevant direction of future research would be how to make the best use of information in closed-loop supply chains (selecting the best policy) from a perspective of smoothing their dynamic behaviour. Considering a more pluralistic stance by getting inspiration from the wide inventory control literature would enrich the analysis and define avenues for improving the dynamics of these systems.

In addition, most of the papers exploring hybrid manufacturing/remanufacturing systems assume a push policy at the remanufacturer, e.g. Tang and Naim (2004), Cannella, Bruccoleri, and Framinan (2016) and Hosoda and Disney (2018). This implies that once the returns are available, the remanufacturing process starts, and the remanufactured products are shipped to the available inventory without delay. Hosoda and Disney (2018, 315) argued that the use of push-based policies in the remanufacturing process ‘fits well with the ethics of sustainability’. Be that as it may, we have practically observed that companies tend to build up a recoverable inventory (see also, e.g. Difrancesco and Huchzermeier 2016) as a buffer against the intrinsic variability of returns (*supply uncertainty*). A pre-sorted inventory of cores allows a company scheduling flexibility, by e.g. remanufacturing good quality cores in periods of peak demand and scheduling remanufacturing of bad quality cores during lulls in demand. Arguably, the absence of any inventory of cores that the push system implies prevents any effective pre-shortening at the company. This in turn means that any uncontrolled up to that point supply uncertainty will be transformed in process uncertainty in the remanufacturing process.

As such, the development of policies for managing the returns inventory as well as their potential to improve the dynamics of closed-loop supply chains turn into a promising avenue for future research. Zhou et al. (2006) deserve a note as they employ a pull policy in the reverse loop through a Kanban rule for managing the recoverable inventory. The importance of controlling a core inventory to manage the quality aspect of the supply uncertainty, enabling the inventory and production pillar to mitigate uncertainty manifestations in the quality of the returns.

Lastly, the very question of whether to employ a hybrid versus a pure remanufacturing system should not be side-lined. The literature on closed-loop supply chains mainly focuses on the former, but the pure remanufacturing context is very

relevant in practice, as we have previously highlighted, and may lead to interesting explanations of the dynamic behaviour of real-world closed-loop supply chains.

4.1.5. *As good as what? Remanufacturing for different markets*

Analysis of the literature reveals that the majority of papers consider the case of perfect substitution. The same assumption is generally made in the inventory literature in remanufacturing systems, as noted by Akçalı and Çetinkaya (2011). This refers to the willingness of customers to pay the same price for a new item and a remanufactured item, enabling demand satisfaction from an aggregated serviceable inventory of manufactured and remanufactured items. This implies the perception of remanufactured products as 'as-good-as-new' products. For instance, in the case of Kodak single-use cameras, the customers are not even aware if the camera contains a new or re-used circuit board (Toktay, Wein, and Zenios 2000).

However, the assumption of same quality of output of manufacturing and remanufacturing processes would be deemed unrealistic in many practical settings. Indeed, product substitution represents a relevant component of the *demand uncertainty* in closed-loop scenarios. In this sense, elaborating remanufactured products with different standards of quality also represents a relevant opportunity for businesses to increase their overall market size, even if disaggregating the two demands can lead to higher number of lost sales (van der Laan and Teunter 2006). Debo, Toktay, and Van Wassenhove (2005, 1193) comprehensively summarise the problem as: 'used products can be remanufactured at a lower cost than the initial production cost, but consumers value remanufactured products less than new products'. Therefore, a relevant problem of market segmentation emerges, which requires some insights on the dynamic implications of closed-loop supply chains when the standard assumption does not apply. Consequently, there are considerable opportunities for future research by means of investigating the dynamic implications of non-perfect substitution between manufactured and remanufactured products and/or remanufacturing products with different quality specifications.

4.1.6. *Who sets the rules? Rethinking the assumptions*

Given the challenges discussed so far in production planning and control of remanufacturing systems, an additional requirement to consider is a methodological one. A significant part of the literature looking at the dynamic response of the supply chain from an analytical point of view employs linear models, as this significantly reduces the mathematical complexity. Linear supply chain models are based on a set of key assumptions. This implies that the results are generally derived from specific scenarios built on unconstrained production capacities, commercial returns allowance, and no lost sales in case of stock-outs, to name a few. Under these circumstances, a growing body of the literature in traditional, or open-loop, supply chains is analysing the implications of relaxing such assumptions. See, for example, Ponte, Wang, et al. (2017) for the assumption of unconstrained capacities, and Chatfield and Pritchard (2013) for the assumption of negative orders allowance.

The same relevant questions stand out for closed-loop scenarios. Indeed, the set of assumptions becomes larger as a consequence of the backward flow of materials. For example, linear closed-loop supply chain models (e.g. Tang and Naim 2004), need to assume that returns can be positive or negative. Common assumptions of constant remanufacturing times (i.e. known and constant quality) and perfect correlation of returns reduce the remanufacturing process to standard manufacturing with a longer lead time.

Exploring how relaxing these assumptions challenge the well-known results of linear mathematical models emerges as an interesting line of enquiry, which has not been exploited yet for reverse logistics systems. Indeed, it can be understood as an essential way to interpret the dynamic response of real-world supply chains, which operate in a wide variety of practical scenarios that would lead to significantly different assumptions in modelling.

4.2. *Concluding remarks*

The European Commission has recently launched the final work programmes (2018–2020) for Horizon 2020, with '*connecting economic and environmental gains*' through resilient circular economy systems being one of the four political priorities (European Commission 2017, 26). This was endowed with a budget of almost €1 billion in order to allow for research of 'sufficient scale, depth and breadth' (European Commission 2017, 15). This clearly illustrates a growing understanding of the urgency to accelerate the transition from a linear to a circular economy model, as well of the key role of research in the deployment of closed-loop supply chain models.

In these systems, a 'boomerang' effect emerges between the product going to the market and returning, which needs to be appropriately accommodated in closed-loop supply chains. Together with the *demand uncertainty*, the boomerang is accompanied by temporal, quantitative, and qualitative *supply uncertainty*, which if not controlled would result in a high

process uncertainty. The three pillars of remanufacturing, viz.: forecasting, collection, inventory and production control, provide methods to reduce the uncertainties. By first estimating and then adjusting the trajectory of the boomerang, a remanufacturer can reduce the effort it takes to receive, restore and throw it back. It is worth noting that the cost of dealing with uncertainty increase as we cascade through the pillars, to become prohibitive if left unchecked throughout. Care needs to be taken, through suitable integration mechanisms, to avoid *control uncertainties* resulting from the interactions of the pillars within remanufacturers and across supply chains.

A crucial perplexing factor is the unknown rate and quality of the returns. This returns' generating process is conditioned to past sales and the usage patterns or consumption rate of the products by the end customers. Forecasting methods can be employed to estimate the rate and quality of the returned items. At the same time, proper collection channels need to be designed to gain advance information on the reverse flow of materials. Inventory and production policies should be set up to handle any remaining uncertainties and optimise the dynamic behaviour of the system.

The extant supply chain dynamics literature offers much to enhance our understanding of open-loop systems, which in turn has been used to improve the dynamics of such systems in practice. However, the literature on supply chains dynamics has had less to say about closed-loop systems. Indeed, notwithstanding the contribution of the research to date, closed-loop supply chain dynamics in general, and remanufacturing systems in particular, are areas where further attention is required. In this article, we have conducted a structured review of the current state of knowledge in this field. In so doing, we have synthesised the main insights offered to date and have proposed an agenda for future research, comprised of six main avenues. We hope that this six-pronged research agenda will serve as a useful resource to help focus future academic scholarship in this area, as well as provide a useful reference for colleagues in industry to inform their practice.

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Notes

1. The Automatic Pipeline Inventory and Order Based Production Control System – APIOBPCS (John, Naim, and Towill 1994); see also Lin et al. (2016) for a review of its applications.
2. In this sense, we need to note that there is a growing body of literature using system dynamics techniques for supporting decision making in closed-loop supply chains from perspectives outside the scope of this work, such as: product acquisition strategies (e.g. Spengler and Schröter 2003), capacity planning (e.g. Vlachos, Georgiadis, and Iakovou 2007), and government subsidy policies (e.g. Wang et al. 2014). While we fully acknowledge the importance of such research, relevant articles have not been included in this section, as they fall outside the discipline of closed-loop supply chain dynamics, as it was defined in Section 1.1.
3. Due to the emphasis of this paper on uncertainty, deterministic models are not, in principle, covered in this work. However, it is clear that parts of the system are often simplified (e.g. assumptions of known and/or constant demand) in order to enable experimentation with the entire system.

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