

ЭКОНОМИКА ФИРМЫ, ПРОИЗВОДСТВЕННЫЙ МЕНЕДЖМЕНТ И УПРАВЛЕНИЕ ЦЕПОЧКАМИ ПОСТАВОК

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A circular economy perspective on sustainable supply chain management: an updated survey

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Environmental and social impact of the world economy is increasingly attracting public attention around the globe. The society expects from the businesses a responsible action towards depletion of scarce natural resources, environmental pollution, and people — so as to achieve sustainable development goals. An essential element of today's economy, supply chains represent networks of companies that create and deliver products and services to the ultimate customers. The present paper classifies scholarly research in sustainable supply chain management in terms of its main paradigms, and further reviews research work centred around the circular economy paradigm — designated commonly as closed-loop supply chain management. We offer a literature review that updates the taxonomy of this research area originally proposed by Atasu et al. in 2008. To this end, we describe analytical modelling and decision-support approaches adopted in the literature, as well as main insights offered by these. In particular, we focus on the studies that have an integrated perspective at closed-loop supply chain management by addressing supply-chain design and coordination problems and taking into account operational-level aspects. We further classify the work within the design and coordination research stream, identify connections emerged between different streams of literature over time, and suggest directions for future work.

Keywords: supply chain management, closed-loop supply chains, remanufacturing, sustainability.

Introduction

Environmental and social impact of the world economy is increasingly attracting public attention around the globe. These concerns have led to an increased pressure on businesses from the society and governments and also entered the agenda of international political institutions. The society expects from the businesses a responsible action towards depletion of natural resources, environmental pollution, and people — i.e., employees, consumers, and communities. Governments respond to these expectations by tightening legislation. Examples are the take-back legislation in Europe and the US making the manufacturers responsible for collecting and processing used products [Atasu et al., 2009], environmental taxation and emissions trading regulation in Australia, Europe, and the US [Directive 2003/87/EC..., 2003; Krass et al., 2013; Robson, 2014], and European legislation on energy efficiency [Directive 2012/27/EU..., 2012]. International political institutions play a major role in coordinating these efforts on a global scale, which has resulted in a number of international treaties — such as the Montreal Protocol, directed towards protecting the ozone layer [Montreal Protocol..., 1989]; the Kyoto Protocol, directed towards prevention of global warming via reduction of greenhouse gas emissions [Kyoto Protocol..., 2005]; and, more recently, its successor — the Paris Agreement, intended to guide countries' efforts towards emissions mitigation and adaptation to consequences of global warming from 2020 onward [Report of the Conference..., 2016].

Outlining basic principles and guidelines for the world's sustainable development had been called for by the United Nations General Assembly yet as early as in 1983, and it is now three decades since the General Assembly has pointed out that sustainable development needs to be understood from three basic, interrelated perspectives: economic, environmental, and social, thus calling for a multi-lateral attitude towards world's development to be adopted by governments, organizations, businesses, and individuals [Report of the World Commission..., 1987]. The concept of sustainability has since then entered the public, political and academic discourse [Linton et al., 2007] and has become a widely adopted paradigm — being also expressed in terms of its three dimensions as “people, planet and profits” [Elkington, 2004, p. 2].

Yet in today's globalised economy, where the value is being increasingly created by networks of companies — i.e., the *supply chains* — it is essential to understand sustainable action of businesses and organizations from the integrative perspective of supply chain management. Over the past two decades, scholarly research has extensively addressed a broad range of topics pertaining to sustainable supply chain management. This research has been prominently centred around two main paradigms: the paradigm of a *circular economy*, and the *emissions reduction* paradigm. The former paradigm refers to re-use of used products — so as to prevent depletion of scarce natural resources and reduce the volume of solid waste, while the latter paradigm is concerned with environmental pollution, in particular via greenhouse gas emissions. A more recent research is increasingly adopting a combined perspective and involves the social dimension of sustainability.

While research in sustainable supply chain management has seen a significant growth in the recent years [Ansari, Kant, 2017; Rajeev et al., 2017], closed-loop supply chain research appears to remain its major area [Lee, Tang, 2017], encompassing a broad variety of analytic and decision-support approaches. A decade ago, Atasu with co-authors proposed a taxonomy of this research area that naturally reflects the evolution of the field from stud-

ying individual activities to addressing complex problems involving coordination, competition, and behavioural issues [Atasu et al., 2008]. While several other classifications have been suggested more recently [Ilgin, Gupta, 2010; Govindan et al., 2015], the purpose of the present work is to update the original survey by Atasu with co-authors [Atasu et al., 2008] by reviewing recent research work through the lens of their taxonomy and identify directions in which the research has progressed over the past decade. This will help to better understand the evolution of the field and identify future research directions.

Given the considerable volume of published research in this area, we do not intend to review it in its entirety here and refer the reader to systematic literature reviews for this purpose [Govindan et al., 2015; Rajeev et al., 2017]. Instead, we intend to provide a sound comprehension of analytical and decision-support approaches adopted in the relevant literature as well as main insights offered by these. To this end, we follow Atasu with co-authors [Atasu et al., 2008] and Souza [Souza, 2013] by restricting the survey to selected studies only. Specifically, we focus on work published from 2008 onward and give priority to the studies that have an integrated perspective at closed-loop supply chain management, which is manifested in addressing supply-chain design and coordination problems and taking into account operational-level aspects. We further classify the studies within the design and coordination research stream and identify connections emerged between different streams of literature. The level of detail chosen for the exposition of material serves the purpose of providing the readership of this journal with a sound presentation of study approaches adopted by the current research in the field, integrating economic-theoretical, operational and mathematical considerations. We find this an important task in its own right given a limited attention to this field in Russian scholarly literature [Pakhomova et al., 2017]. This approach makes our final selection of literature inevitably subjective, which is a limitation of our study.

The rest of the paper is organised as follows. Section 1 outlines the paradigms of sustainable supply chain management. Section 2 defines closed-loop supply chain management in more detailed terms. In Section 3 we review selected closed-loop supply chain research work. Section 4 provides a conclusion and an outlook for future research.

1. Sustainable supply chain management research paradigms

In 1994, John Elkington introduced the term “triple bottom line” so as to express the sustainability concept in the language of an enterprise — which furnishes an accounting approach to the economic, environmental and social value that an enterprise creates [Elkington, 2004; Slaper, Hall, 2011]. As the businesses have increasingly come under pressure regarding their environmental and social impact [Elkington, 1994; Harrington, 2014; Krass et al., 2013; Sridhar, Jones, 2013], the triple bottom line approach to measuring sustainability has gained popularity in the corporate world as well as in the policy-making, and has become widely used for voluntary reporting purposes, despite a certain criticism [Slaper, Hall, 2011; Sridhar, Jones, 2013]. Recently, the United Nations General Assembly has adopted the 2030 Agenda for Sustainable Development, in which the three dimensions of sustainability have been further detailed and represented in terms of 17 Sustainable Development Goals, for which altogether 169 targets have been set, to be attained by 2030 [Transforming our world..., 2015].

A broad adoption of the sustainability concept has also come with the recognition that in today's globalised economy, value is being increasingly created within *supply chains* — that is, networks of companies or organizations “that are involved, through upstream and downstream linkages, in the different processes and activities that produce value in the form of products and services in the hands of the ultimate consumer” [Christopher, 2011, p. 13]. Therefore, the environmental and social value of products and services, as much as their economic value, needs to be tracked in the integrated fashion across the entire supply chain and throughout the entire product life cycle [Christopher, 2011, p. 243; Elkington, 1994; Harrington, 2014; Kim et al., 2014; Linton et al., 2007]. This has set the stage for the emergence of sustainable supply chain management practices [Wu, Pagell, 2011; Cetinkaya et al., 2011; Lee, Tang, 2018] — which has expanded the scope of supply chain management from its traditional focus on profit maximization and customer satisfaction [Stock, Boyer, 2009] to the environmental and social impact of value creation.

In this way, sustainable supply chain management (SSCM) has developed into a new mindset and attracted a significant attention from the academic research over the past two decades. In the present work, we intend to outline the main paradigms around which this research has been centred and review existing models and methods for supply chain analysis and decision support that represent one of its major paradigms — the *circular economy* one. In so doing, we will refer to the conceptual model of the PPP ecosystem by Tang and Zhou [Tang, Zhou, 2012] — as depicted, in a modified form, in Figure 1. According to Tang and Zhou, the society and the planet can be viewed as an ecosystem with the following key elements: the *consumers* — people who demand products and services; the *supply chains* — consisting of suppliers, manufacturers, distributors, and retailers that deliver those goods and, in turn, employ for that people — designated in Figure 1 as *producers*. In this way, supply chains incur costs and generate revenues, with an aim of maximizing their profits. The respective flow is depicted in Figure 1 by solid arrows and represents the economic dimension of sustainability. When producing, delivering and consuming the goods, the supply chains and the people use natural resources: like water, air, oil, land, woods, metals, while generating wastes and emissions — which is detrimental to the planet. The respective flow, depicted by the dashed lines in Figure 1, represents the environmental dimension of sustainability. Finally, the social dimension of sustainability is represented by the dotted arrow, indicating the fact that the producers should also be considered as potential consumers — so that companies and governments “need to develop the emerging market by helping the poor producers break the poverty cycle now so that they can become consumers later” [Tang, Zhou, 2012, p. 586].

Using Figure 1, we can represent the main paradigms of SSCM as follows. The *circular economy* paradigm refers to collection, recovery and re-use of used products [Geissdoerfer et al., 2017], which reduces the volume of solid waste and prevents depletion of scarce natural resources (like woods and metals) — that otherwise had to be consumed as virgin materials in order to produce new items and satisfy customer demand. The environmental dimension is represented in this paradigm by the inner dashed line in Figure 1, while the social dimension is not taken into account explicitly. The circular economy paradigm has enjoyed an extensive academic research in the area of supply chain management since the mid-1990s, which has offered a broad range of formal-analytical approaches for supply chain analysis and decision making, and has become commonly known as *closed-loop supply chain* research. Guide and Van Wassenhove consider this research evolving over five

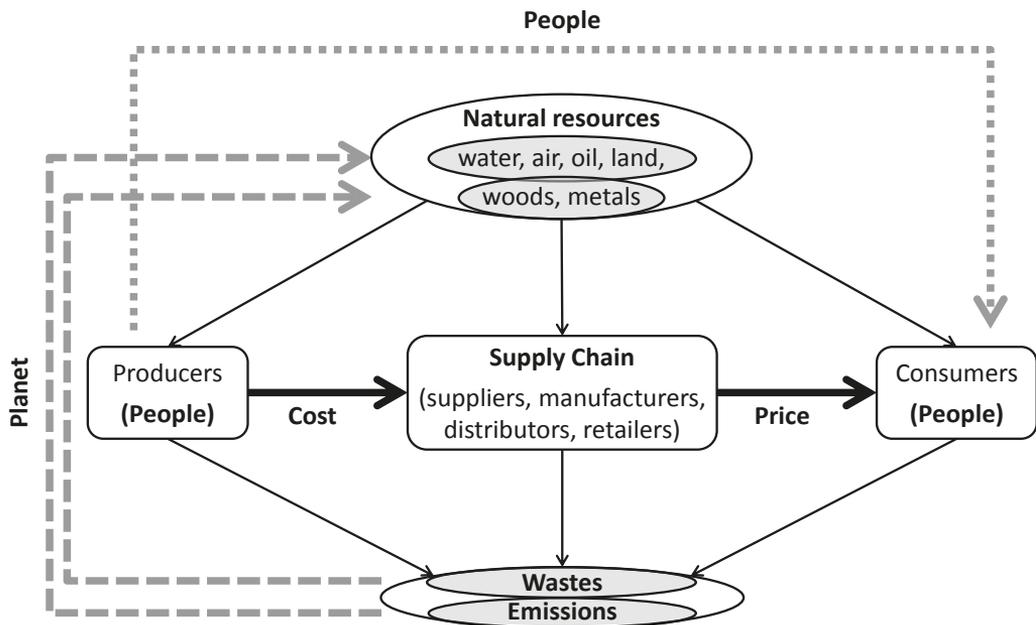


Figure 1. The PPP ecosystem: profit, planet, people

Note: adapted from: Tang C. S., Zhou S. Research advances in environmentally and socially sustainable operations // European Journal of Operational Research, 2012. Vol. 223, no. 3. P. 585–594.

phases, in which the focus is being set respectively on (i) optimisation of individual *activities*, such as shop floor control; (ii) *processes*, such as inventory control and used product acquisition; (iii) *coordination* between supply-chain members and products; (iv) closed-loop *design* over the product life-cycle; and (v) *marketing* issues [Guide, Van Wassenhove, 2009]. We refer the reader to Fleischmann with co-authors for an overview of the early work through 1997 [Fleischmann et al., 1997], to Ilgin and Gupta — for a review covering the period from 1998 to 2009 [Ilgin, Gupta, 2010], and to Govindan with co-authors — for a review over the period from 2007 to 2013 [Govindan et al., 2015].

The *emissions reduction* paradigm of SSCM addresses the environmental pollution, in particular via greenhouse gas emissions, through manufacturing and logistics operations in a supply chain. The environmental dimension is represented in this paradigm by the outer dashed line in Figure 1, while the social dimension is not taken explicitly into account. While the closed-loop supply chain research agenda has put emphasis on economic benefits of product re-use [Eskandarpour et al., 2015; Geissdoerfer et al., 2017], the work centring around the emissions reduction paradigm is more explicit in emphasizing both economic and environmental dimensions of sustainability. The central questions addressed in this research area concern design, coordination and operation of supply chains in the presence of various kinds of emission pricing policies and emission constraints — which are either adopted by companies on a voluntary basis or imposed by regulation. Examples include the *carbon tax* per ton of carbon dioxide equivalent emissions [Robson, 2014], the *carbon cap* that specifies an emission limit [Benjaafar et al., 2013], and the *emissions trading systems* that allow the companies to exceed a certain emission limit by

purchasing *emission permits*, as well as sell the permits in case of undershooting the limit. E.g., the EU Emissions Trading System (EU ETS) implements the so-called *cap-and-trade* mechanism — that puts a cap on the total emissions, allocates the respective number of emission permits among the participants, and lets them trade the permits between each other afterwards [Directorate-General for Climate Action..., 2015]. Seuring and Müller [Seuring, Müller, 2008] provide an overview of the early research in environmentally and socially responsible (forward) supply chain management, covering the time span from 1994 to 2007. Their findings indicate that the majority of research has been conceptual or empirical, while formal-analytical modelling for supply chain analysis and decision support has been pursued by that time in a few studies only. This finding has been confirmed by Seuring [Seuring, 2013] who has identified as few as 36 such formal-analytical studies published from 1997 to 2010, which was in contrast to the progress made by that time by the closed-loop supply chain research. Nevertheless, this body of work has begun to grow quickly just over the next few years [Brandenburg et al., 2014; Beske-Janssen et al., 2015].

The above two paradigms of SSCM have thus had their focus on the economic and environmental dimensions of sustainability and represented a research area also referred to as *green supply chain management* [Ahi, Searcy, 2013]. However, as the above overview shows, the academic research centred around either paradigm has mostly been evolving separately from one another. Also, while the social dimension of sustainability has been taken into account in a number of studies, this still represented a significantly smaller body of research in comparison to the above two main paradigms [Seuring, Müller, 2008; Seuring, 2013]; furthermore, the social dimension has been typically treated separately from the environmental one [Carter, Easton, 2011]. More recently, two substantial developments have taken place in the SSCM research. First, the paradigms of circular economy and emissions reductions have become combined in the formal-analytical modelling, which has led to new managerial insights. Second, the social dimension of sustainability has become explicitly addressed in modelling and decision support approaches, which gives an opportunity of looking at all three dimensions of sustainability in an integrated fashion [Brandenburg et al., 2014].

As explained in the Introduction, we shall below review the circular economy paradigm and related approaches to supply chain modelling, analysis and decision support more closely.

2. The circular economy paradigm: closed-loop supply chain management

As indicated in the Introduction, the circular economy paradigm refers to the economic and environmental dimensions of sustainability, by focusing on supply chain management approaches that allow for collection, recovery and re-use of used products — which helps to reduce the environmental burden by cutting the depletion of scarce natural resources and reducing the amount of solid waste. Thus, this paradigm assumes that the *forward flow* of goods in a conventional supply chain — from the raw materials supply to the market — is augmented with a *reverse flow* from the market back to various stages in the supply chain, which hence “closes the loop” in the flow of goods.

Figure 2 provides a schematic illustration of such a closed-loop supply chain that involves three stages in the forward flow: raw materials preparation, manufacturing, and distribution of the final products to the market. The reverse flow begins with the *acqui-*

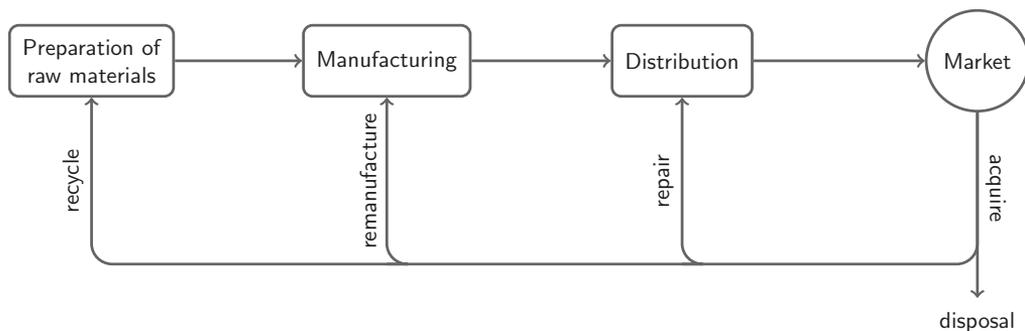


Figure 2. Schematic illustration of a closed-loop supply chain

Note: adapted from: Srivastava S. K. Network design for reverse logistics // Omega, 2008. Vol. 36, no. 4. P. 535–548.

tion of used products from the market; these may significantly vary in their quality, which is determined by the duration and intensity of use. For these reasons, the used products typically need to be inspected, sorted and graded. Depending on the quality grade, the products may require only a light repair — as in the case of packages (e.g. bottles) or commercial returns that typically occur quickly after purchase of the product by the consumer, e.g. via an online channel. In such cases, the products are often fully functional and require only some basic cleaning and re-packaging in order to be re-introduced to the market again [Guide, Van Wassenhove, 2009; Fleischmann et al., 1997]. Such form of product recovery does not require a substantial re-work of the product and can be conducted yet at the distribution stage of the supply chain (see Figure 2).

If a product underwent some period of use, and has been returned yet in a functional condition — for example, due to a product upgrade on the market (e. g., an introduction of a newer smartphone generation), then it represents an *end-of-use* return [Guide, Van Wassenhove, 2009]. These products can significantly vary in quality due to wear and tear. As they still carry a residual value, this value can be re-used by *remanufacturing* the product — what may require disassembly, parts replacement, and overhaul (see Figure 2). Thus this form of recovery still intends to conserve the product identity [Fleischmann et al., 1997]. A product may, however, be returned first when it became obsolete or has no value for the customer anymore — a so called *end-of-life* return [Guide, Van Wassenhove, 2009] — e. g., a typewriter. The only economic options for this kind of returns may often be either *parts recovery* or *recycling* of raw materials [Fleischmann et al., 1997] — which destroys the product identity and thus represents the most radical form of re-use. In certain cases, even the latter option may appear to be uneconomical, thus leading to product *disposal* (see Figure 2).

The reverse flow may require establishing additional dedicated facilities — such as collection and inspection centres, and further gives rise to *reverse logistics* activities — such as transportation and storage of used products. Furthermore, product recovery may need to co-exist with traditional manufacturing operations, while remanufactured products need to be (re-)marketed together with the new ones. Overall, closed-loop supply chains involve a broader range of activities and usually a bigger number of actors than the conventional supply chains with only the forward flow [Guide, Van Wassenhove, 2009]. Coordination of these activities across the forward and reverse flows, for the ultimate purpose of maximizing the economic value created by a closed-loop supply chain, thus

becomes more challenging as well. From this, essentially business perspective, one can define *closed-loop supply chain management* (CLSCM) as “the design, control, and operation of a system to maximize value creation over the entire life cycle of a product with dynamic recovery of value from different types and volumes of returns over time” [Guide, Van Wassenhove, 2009].

The new challenges posed by CLSCM have been extensively addressed by the academic research since the mid-1990’s (when it was yet commonly referred to as Reverse Logistics, see e.g. [Dekker et al., 2004]). We will below focus on research work that employs analytical modelling for facilitating insight into the economics of closed-loop supply chains and providing decision aid to the business practice. While a number of excellent surveys of this research are available [Atasu et al., 2008; Guide, Van Wassenhove, 2009; Govindan et al., 2015], we intend to augment these by reviewing recent work and discussing principal features of the respective modelling approaches and key insights obtained by means of these.

3. Closed-loop supply chain research streams

As indicated in the Introduction, we will below follow the classification of closed-loop supply chain research proposed by Atasu with co-authors, who divide it into four major streams: (1) *industrial engineering / operations research* approaches; (2) *design*; (3) *strategy*; and (4) *behavioural studies* [Atasu et al., 2008]. We will review representative work in each of the streams and will generally proceed in the order of strategic, tactical and operational issues addressed therein, in line with the CLSCM definition.

3.1. Industrial engineering / operations research stream

Stream 1 comprises research work that focuses on specific activities [Atasu et al., 2008] — such as network design, inventory control, and vehicle routing [Souza, 2013].

Designing a logistics network for a closed-loop supply chain involves a range of *strategic-level* decisions — such as the number of facilities to be established, their geographic location and size, assignment of tasks to the facilities, and arrangement of product flows between them [Akçalı et al., 2009; Souza, 2013]. Akçalı with co-authors divide the respective research work into two major sub-streams: *reverse supply-chain network design* — that deals with the reverse flow only, and *closed-loop supply-chain network design* — that encompasses the forward and the reverse flows in an integrated fashion [Akçalı et al., 2009]. They further categorize this research according to the principal assumptions adopted in the respective study approaches: *deterministic* vs. *stochastic* modelling of demand and supply, *static* vs. *dynamic* planning, *number of stages* in the supply chain, and *single-* vs. *multi-source* structure of product flows. We refer the reader to Akçalı with co-authors for an overview of the earlier work, and discuss here selected follow-up research using the above categorization [Akçalı et al., 2009].

Reverse supply-chain network design. The study by Alumur with co-authors addresses a problem of designing a 3-stage reverse supply-chain network with multi-source product flows, deterministic demand and supply, and dynamic planning over a finite horizon [Alumur et al., 2012]. The authors develop a *mixed-integer linear programming (MILP) model* for determining the most profitable number, locations and capacities of inspec-

tion and remanufacturing facilities by considering the revenues obtained from remanufacturing and recycling and the total costs of investment, operations, inventory holding, transportation, and procurement. The model allows for multiple products, explicitly representing them as consisting of multiple components. The authors apply the model to a case study of a reverse supply chain for washing machines and tumble dryers in Germany over a 5-year horizon and investigate, among others, the value of dynamic planning and robustness of optimal network design w.r.t. to future scenarios. The model permits solution in reasonable time with a commercial state-of-the-art MILP solver.

Alshamsi and Diabat extend this approach by including various transportation options in the model [Alshamsi, Diabat 2015]. These may differ with respect to vehicle capacity and cost structure, and can be used to represent operation of a private fleet as well as transport outsourcing options. Alshamsi and Diabat further propose a genetic algorithm for solving the model in a real-world application [Alshamsi, Diabat 2017]. Gomes with co-authors take a similar approach to design a 2-stage reverse supply-chain network for electric and electronic waste recycling in Portugal that minimizes total costs subject to a minimum recycling target [Gomes et al., 2011]. Similarly, Ayvaz with co-authors address a 4-stage network design problem for electric and electronic waste recycling in Turkey, in which collection, sorting and recycling facilities need to be established so as to maximize total supply-chain profit [Ayvaz et al., 2015]. Differently from the above studies, the authors assume that facilities are being located under uncertainty about unit transportation costs and the volume and quality of returns; the uncertainty becomes resolved first after the facilities have been established. Thus, the problem is characterized by a *stochastic* modelling of supply and a *static* planning of facility locations. The authors model the problem in terms of a *two-stage stochastic mixed-integer program with recourse* and use the sample average approximation method [Louveaux, Schultz, 2003; Laporte, Louveaux, 1993] to solve the problem in a real-world setting assuming a continuous multivariate probability distribution of uncertain parameters.

Closed-loop supply-chain network design. Sahyouni with co-authors study a single-stage closed-loop supply-chain network design problem with deterministic demand and supply, static planning, and multi-source structure of product flows [Sahyouni et al., 2007]. They seek to determine location of distribution centres (DCs) for serving customer demand and location of collection centres (CCs) for receiving used products back from customers, with the objective of minimising the total of facility and transportation costs per period. Both kinds of facilities can be co-located, which gives a certain cost saving due to economy of scope. Interestingly, the problem can easily be restricted to either a *forward-dominant* form, in which CCs can only be co-located with DCs (suitable at the beginning of the product life-cycle), or to a *reverse-dominant* form, in which DCs can only be co-located with CCs (suitable for the end of the product life cycle). The authors model the problem in terms of a mixed-integer linear program that can be solved with a general-purpose MILP solver. They further develop a Lagrangean relaxation approach [Fügenschuh, Martin, 2005] for solving large problem instances, and investigate the value of the integrated network design in a numerical study.

Özkır and Başlıgil consider a problem of designing a 3-stage closed-loop supply-chain network, in which used products return from customers to collection points (CPs), from where they are transported to reverse centres (RCs) for inspection (Figure 3) [Özkır, Başlıgil, 2012]. The inspection determines a further route for a product depending on

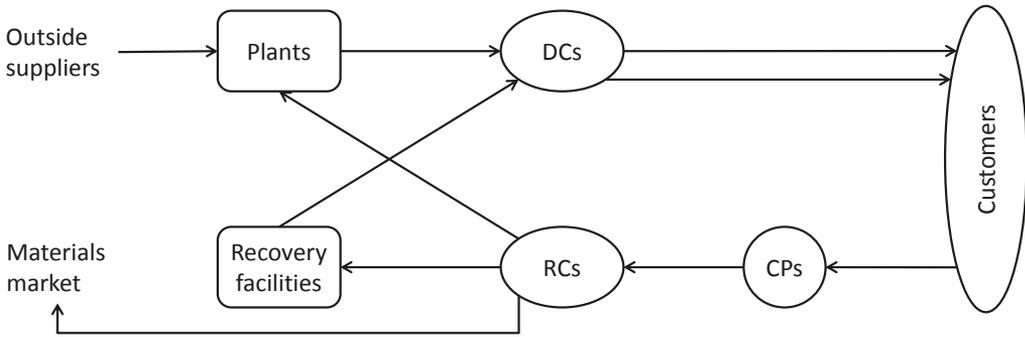


Figure 3. Product flows in the 3-stage network design problem of Özkır and Başlıgil.

Key: CPs — collection points, DCs — distribution centres, RCs — reverse centres.

Note: adapted from: Özkır V., Başlıgil H. Modelling product-recovery processes in closed-loop supply-chain network design // International Journal of Production Research, 2012. Vol. 50, no. 8. P. 2218–2233.

its quality condition: it can either be sent to a recovery facility for remanufacturing, or disassembled into components, or recycled. Components are being sent further to a plant for recovery and new product manufacturing, while recycled materials are being sold on a market. Plants produce new products from recovered components and also from new components purchased from outside suppliers. Plants and recovery facilities ship new and remanufactured products to distribution centers, from where the products are transported to customers for satisfying their demand. The problem is characterized by multi-source product flows, deterministic demand and supply, and dynamic planning over a finite horizon. It further distinguishes between demands for new and remanufactured products that are assumed to be met at pre-specified prices. The problem is modeled in terms of a MILP and requires to determine which of the CPs, RCs, DCs, plants and recovery facilities need to be established at the candidate locations so as to maximize the total profit over the entire horizon. The authors conclude from numerical experiments that variations in the product return rate have a stronger impact on the overall supply chain profit in their setting than variations in the quality of returning products.

The problem studied by Diabat with co-authors takes into account uncertainty of daily demand and return volumes [Diabat et al., 2015]. Their problem setup includes a single plant that manufactures new products and new parts needed for product remanufacturing. It supplies new products to DCs who in turn distribute them to retailers with fluctuating product demand. A decision needs to be made about which DCs to open and how to assign retailers to them, assuming that each retailer is to be supplied by a single DC. A fraction of used products return back and have to be transported from the retailers to remanufacturing centres (RCs). RCs can only be co-located with DCs. An RC remanufactures used products by replacing certain parts in them with new parts, supplied to the RC by the plant. Both demand and return volumes are assumed to be normally distributed and uncorrelated between retailers and over time. At a DC, this requires holding some safety stock in order to guarantee a certain service level to the retailers. Furthermore, the presence of fixed ordering and inventory holding costs requires using an *inventory control policy* [Silver et al., 2016] — a rule that guides the DC with regard to when and how much product to order from the plant. For each DC, the authors assume an order-point, order-quantity policy that can be determined reasonably well using the classical economic

order quantity model [Silver et al., 2016]. In a similar way, the RCs need to determine a control policy for the parts inventory required for remanufacturing of used products. This setup leads to a 2-stage closed-loop supply-chain network design problem with stochastic demand and supply, static planning, and a single-source structure of product flows. Taking inventory holding costs into account leads in this problem setting to a nonlinear, non-convex mixed-integer optimization problem that is notably difficult to solve to optimality. To this end, Diabat with co-authors propose a Lagrangean relaxation approach and illustrate its performance on a number of data sets with up to 150 candidate locations for DCs and RCs [Diabat et al., 2015]. Interestingly, the cost trade-off in their problem setting includes, apart from the usual cost factors discussed above, also (i) economies of scale in stock replenishment, and (ii) *statistical economies of scale* that arise due to the *risk pooling* effect [Oeser, 2015]. In particular, the latter effect arises because fluctuations of demands (returns) from multiple retailers, when served by the same DC (RC), tend to smoothen each other, thus reducing the safety stock requirements at the respective facility. Both kinds of economies of scale thus favour provision of service to multiple retailers from the same facility — so that increasing inventory holding costs tends to drive down the number of DCs and RCs that become opened.

We refer the reader to Khatami with co-authors for a different approach to modelling demand and supply uncertainty in a closed-loop supply-chain network design setting [Khatami et al., 2015]. They take an approach similar to Ayvaz with co-authors (discussed above in the context of reverse supply-chain network design) by representing the uncertainty in terms of future scenarios and modelling the problem in terms of a two-stage stochastic mixed-integer program with recourse [Ayvaz et al., 2015]. The reader is further referred to Govindan with co-authors for an overview of methods used for supply-chain network design under uncertainty [Govindan et al., 2017], to Akçalı and Çetinkaya — for a comprehensive treatment of literature on inventory and production planning in closed-loop supply chains [Akçalı, Çetinkaya 2011], and to Kumar with co-authors — for a vehicle routing approach in a closed-loop supply-chain network using methods of swarm intelligence [Kumar et al., 2017].

3.2. Design stream

While research in the previous stream is typically focusing on a single decision-maker, disregarding the product life-cycle and making simplifying assumptions about the relationship between used and new products, Stream 2 addresses these issues by taking a more holistic perspective at closed-loop supply chain management. Specifically, research in this stream presents studies acknowledging that (i) a closed-loop supply chain may involve multiple self-interested parties, (ii) acquisition of used products may need to be aligned with decisions related to the forward flow of goods, and (iii) the product may have a limited durability and a restricted life-cycle [Atasu et al., 2008]. We will below discuss selected work that addresses these aspects.

3.2.1. Closed-loop supply-chain coordination and design

The presence of multiple self-interested parties implies a decentralised control in a closed-loop supply chain — such that each supply-chain member seeks to maximise its own performance and acts accordingly. This may result in the overall supply-chain perfor-

mance below the level that it would have achieved when being under a centralised control of a single decision-maker. In such a case, the supply chain is said to lack *coordination*, and it thus becomes of interest to find mechanisms — such as contracts — that would help the parties to align their individual incentives with that of the entire supply chain so as to achieve coordination and improve their performance as a whole [Cachon, 2003]. An important insight from this stream of research is that supply-chain performance under decentralised control depends on the supply-chain *design* — that is, delegation of tasks to its individual members. Overall, we can divide the respective research work into three areas, as follows below.

Closed-loop coordination and design. The seminal paper by Savaskan with co-authors has laid down foundations for much of the subsequent work on coordination in closed-loop supply chains [Savaskan et al., 2004]. They consider a problem setting with three possible supply-chain designs under decentralised control that differ with respect to which party is responsible for collecting used products — retailer, manufacturer, or a 3rd party (Figure 4). It is assumed that the return rate of used products depends on the costly collection effort spent by the respective party; the effort cost grows disproportionately high with the increasing return rate. The interaction between the parties is modelled in terms of a sequential game [Osborne, Rubinstein, 1994], in which the most powerful player — the manufacturer — moves first. Consider the *R-design* with the retailer collecting. First, the manufacturer sets the wholesale price in the forward channel and the buyback price in the reverse channel. The retailer moves next by choosing (i) a retail price, which determines the volume of customer demand, and (ii) the collection effort, which determines the return rate. The manufacturer buys used products from the retailer at a pre-announced buyback price. Used products can be remanufactured to as-good-as-new ones, which serve customer demand on a par with the new products. In the *M-design* with the manufacturer collecting, there is no need for a buyback price; the manufacturer decides directly on the collection effort. In the *3P-design* with the 3rd party collecting, the latter is the least powerful party, who chooses a collection effort by moving last.

The authors derive optimal strategies of the firms in closed form and express the firms' and the supply chain's performance in terms of three indicators: (i) the profit generated, the retail price offered to the customers, and (iii) the collection rate of used products. By comparing supply-chain performance in each of the three designs, the authors obtain a striking result that the R-design is outperforming M- and 3P-designs in terms of all three indicators — that is, in terms of economic performance, product availability, and environmental friendliness. The conclusion they draw is that the closer the collecting agent to the sales market, the better is the supply-chain performance. The principal economic insight into this observation is that the retailer, who collects used products in the R-design, can increase the sales volume directly by decreasing the retail price, and will be interested in exerting collection effort for collecting a bigger fraction of used products and selling them back to the manufacturer. The analysis reveals that, in order to entice such a behaviour, the manufacturer sets the buyback price to its highest level, thus foregoing any direct savings from remanufacturing; still, the manufacturer is better off because of a higher sales volume generated by the retailer as a consequence.

The analysis further reveals that even in the R-design, the supply-chain performance is still below best possible as compared to the case of a centralised control — so that the supply chain lacks coordination. To achieve coordination in the R-design, the authors pro-

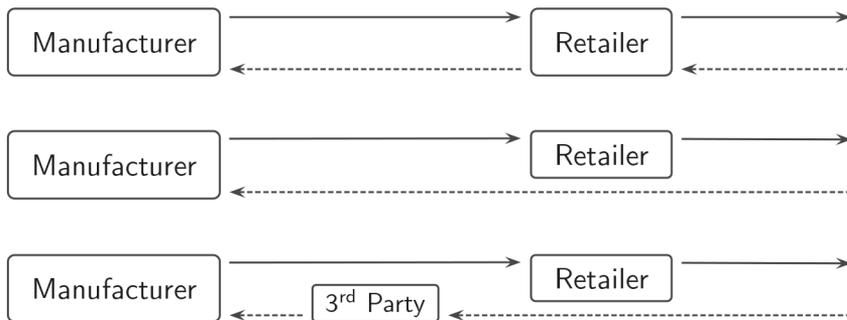


Figure 4. Three possible designs of a closed-loop supply chain due to Savaskan et al.

Note: adapted from: Savaskan R. C., Bhattacharya S., Van Wassenhove L. N. Closed-Loop Supply Chain Models with Product Remanufacturing // Management Science, 2004. Vol. 50, no. 2. P. 239–252.

pose a contract with a two-part tariff between the manufacturer and the retailer, in which the wholesale price is made contingent on the collection rate in such a way that makes the retailer internalise the consequences of his actions and aligns the retailer's incentives with that of the supply chain.

The study by Savaskan with co-authors has spawned a considerable body of the follow-up research that has explored decentralised control in closed-loop supply chains in a variety of related settings [Savaskan et al., 2004]. Table 1 presents an overview of selected studies with their key features. As we can see in the table, most of the work shown adopts the assumption of a linear price-dependent demand function by Savaskan with co-authors [Savaskan et al., 2004]; at the same time, some authors consider also additional factors that influence the demand — such as sales and collection effort, product quality, and the return rate [Gao et al., 2016; Maiti, Giri, 2015; Maiti, Giri, 2017; De Giovanni et al., 2016]. Furthermore, in line with Savaskan and co-authors most of the studies assume a costly promotional effort for collecting used products but disregard scale effects in the logistics costs of product collection [Savaskan et al., 2004]. An exception is the work by Atasu with co-authors who studied economies and diseconomies of scale in the used product collection and have shown that the results quite depend on the nature of scale effects, so that the manufacturer may prefer to manage collection of used products when the volume-dependent logistics costs exhibit diseconomies of scale [Atasu et al., 2013]. Further, Saha with co-authors assume reward-driven product returns [Saha et al., 2016].

We can further observe that most of the studies in Table 1 assume leadership of the manufacturer in the supply chain. Differently from that, Choi with co-authors explore decentralized control under three different leadership structures and perform comparison between supply chain performance in terms of profit, retail price and collection rate [Choi et al., 2013]. They find the supply chain under the retailer leadership most profitable, with the collection rate exceeding that of the supply chain under centralised control, a questionable result. Maiti and Giri obtain similar insights using a numerical study in a setting with quality-dependent demand, yet under the assumption of fixed buyback prices [Maiti, Giri 2015; Maiti, Giri, 2017]. Assuming effort-dependent demand, Gao with co-authors show that the most beneficial leadership structure generally depends on the effectiveness of the sales and collection effort; under certain conditions, absence of a leader may give the best outcome [Gao et al., 2016].

Table 1 also reveals that most of the studies do not differentiate between new and remanufactured products, assuming them to be perfect substitutes. The work by Xiong with co-authors is a notable exception [Xiong et al., 2013; Xiong et al., 2016]. They use a standard demand modelling approach for new and remanufactured products [Ferguson, Toktay, 2006] and assume that used products can be remanufactured only once. Consider a setting in which the retailer collects used products and remanufactures them directly, without sending them to the manufacturer. The authors derive a counterintuitive insight that a stronger willingness to pay for the remanufactured product by the customers does not need to imply an increase in the retailer's remanufacturing activity; instead, the retailer may end up foregoing remanufacturing completely. Reason being that the sales of remanufactured product may cannibalise the new product sales far too much, which makes the manufacturer raise the wholesale price of new products in order to prevent remanufacturing by the retailer. The authors further show that the retailer can be better off by letting the manufacturer collect and remanufacture used products due to complementarity between new and remanufactured products regarding their pricing by the manufacturer.

We can see in Table 1 that most of the studies consider a static, steady-state period analysis, with the exception of De Giovanni and Zaccour [De Giovanni, Zaccour, 2014] and De Giovanni with co-authors [De Giovanni et al., 2016] who consider time-dynamic decisions over a finite and infinite horizon respectively, and Aydin with co-authors [Aydin et al., 2016] who study a two-period setup with a two-objective decision problem of the manufacturer, which they solve using a genetic algorithm approach in an industry application. A few studies consider collection of used products via multiple channels [Savaskan, Van Wassenhove, 2006; Hong et al., 2013; Maiti, Giri, 2017]; notably, Saha with co-authors address dual-channel sales [Saha et al., 2016]. We can also see that about a half of the studies in Table 1 seek to find a coordination mechanism, and about a half of studies is concerned with determining an optimal supply-chain design.

Coordination in a reverse supply chain. Several studies included a number of additional features in the analysis by restricting attention to the reverse channel only. For example, Govindan and Popiuc consider a reverse supply chain with three members — a manufacturer, a distributor, and a retailer [Govindan, Popiuc, 2014]. The latter collects used products from customers and rewards them with a discount that they receive for a future purchase. The amount of the discount determines the customers' willingness to return used products, and thus the return rate. This dependence is assumed to be linear. The retailer sells used products to the distributor who in turn re-sells them to the manufacturer. The manufacturer generates revenue by remanufacturing eligible products and selling them on the market at a fixed price. Given fixed exchange prices between supply-chain members, the authors derive an optimal amount of customer discount and introduce revenue-sharing contracts between the partners [Cachon, 2003] so as to achieve supply-chain coordination. A sensitivity analysis shows that increasing unit remanufacturing cost decreases the amount of the customer discount while increasing the manufacturer's fraction in revenue sharing.

Zeng considers a two-member reverse supply chain with a manufacturer and a retailer who operate in a setting similar to the above (see Figure 5) [Zeng, 2013]. A major feature that distinguishes this work from the previously discussed literature is the model of incentives provided to the customers for stimulating return of used products. Based on a field survey of consumer attitudes towards used product return, Zeng identifies three

Table 1. Selected studies of decentralised control in closed-loop supply chains

Study	Linear demand function	Other demand factors	Differentiated products	Time dynamics	Collection effort	Logistics / reward	Number of firms ¹	Leadership ²	Multiple channels ³	Competitive remanufacturing	Design	Design-dependent collection	Coordination
Savaskan et al., 2004	X				X		***	M			X		X
Savaskan, Van Wassenhove, 2006	X				X		***	M	F, R		X		X
Hong et al., 2013	X				X		***	M	R		X		X
Atasu et al., 2013	X				X	X	***	M			X		
De Giovanni, Zaccour, 2014	X			X	X		***	M			X	X	
De Giovanni et al., 2016	X	X		X	X		**						X
Aydin et al., 2016				X			**	M					
Choi et al., 2013	X				X		***	M, R, 3P					X
Maiti, Giri, 2015	X	X			X		***	M, R, 3P, -					
Maiti, Giri, 2017	X	X					**	M, R, -	R				X
Gao et al., 2016	X	X			X		**	M, R, -					X
Saha et al., 2016	X					X	***	M	F		X		X
Xiong et al., 2013	X		X				**	M		X			
Xiong et al., 2016	X		X				**	M		X	X		

¹ Number of asterisks indicates the number of firms in the study. Spacing before the 3rd asterisk indicates modelling with as well as without a 3rd party.

² Leadership designates the most powerful supply-chain member: manufacturer (M), retailer (R), or the 3rd party (3P). A dash ‘-’ represents the case of no leadership, when all parties move simultaneously, and the solution is defined in terms of a Nash equilibrium [Osborne, Rubinstein, 1994]. No entry in this column represents the case of a cooperative solution approach.

³ ‘F’ and ‘R’ indicate multiple forward and reverse channels, respectively.

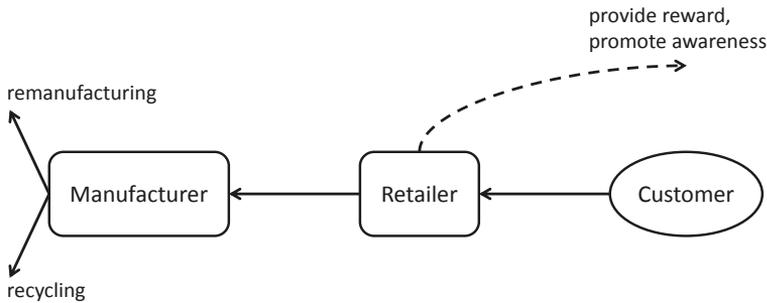


Figure 5. Schematic representation of the reverse supply chain due to Zeng

Note: adapted from: Zeng A.Z. Coordination mechanisms for a three-stage reverse supply chain to increase profitable returns // Naval Research Logistics, 2013. Vol. 60, no. 1. P.31–45.

customer segments: those who are *reward-driven*, returning the product against a reasonable reward; those who are *awareness-driven*, returning the product out of environmental considerations; and *ignorant* — who do not return used products. The first and the second segments may overlap. Based on these considerations, Zeng suggests that different incentive mechanisms need to be used for attracting returns from different segments and represents the return rate from the first segment as a concave increasing function of the reward amount, and from the second segment — as a concave increasing function of promotional effort. The retailer needs to decide about the volume of spending on rewards and promotion of returns. To give the retailer an incentive, the manufacturer shares a fraction of his revenue from remanufacturing and sale of used products. By modelling the interaction between the parties in the form of a Stackelberg game [Osborne, Rubinstein, 1994] with the manufacturer as the leader, Zeng derives the retailer's best response to the manufacturer's choice of the revenue-sharing fraction in closed form, and then numerically determines the manufacturer's profit-maximising revenue-sharing decision. Her analysis reveals that the manufacturer's profit is concave in the decision variable, which simplifies the numerical solution. Numerical experiments indicate that the manufacturer's optimal revenue-sharing fraction is increasing in the size of the first customer segment but decreasing in the size of the second. Furthermore, while the manufacturer's profit has been observed to increase in the size of these segments, the retailer's profit depended on the size of the second segment in a non-monotonic way.

Closed-loop coordination and operations. While the above work on closed-loop supply-chain coordination and design typically adopts a marketing channel perspective [Savaskan et al., 2004], a further stream of work has introduced operational considerations into the analysis by explicitly modelling manufacturing and remanufacturing operations and including inventory-related costs in the decision model. The work by Pishchulov with co-authors [Pishchulov et al., 2014] combines in this regard essential elements of the conventional *joint economic lot size* problem [Banerjee, 1986], the economic order quantity model for a production–inventory system with product recovery and disposal [Richter, 1996], and the closed-loop supply-chain coordination model as per Savaskan with co-authors [Savaskan et al., 2004]. Specifically, Pishchulov with co-authors consider a closed-loop supply chain comprising a manufacturer and a retailer (see Figure 6) [Pishchulov et al., 2014]. The manufacturer can produce new products and remanufacture used ones

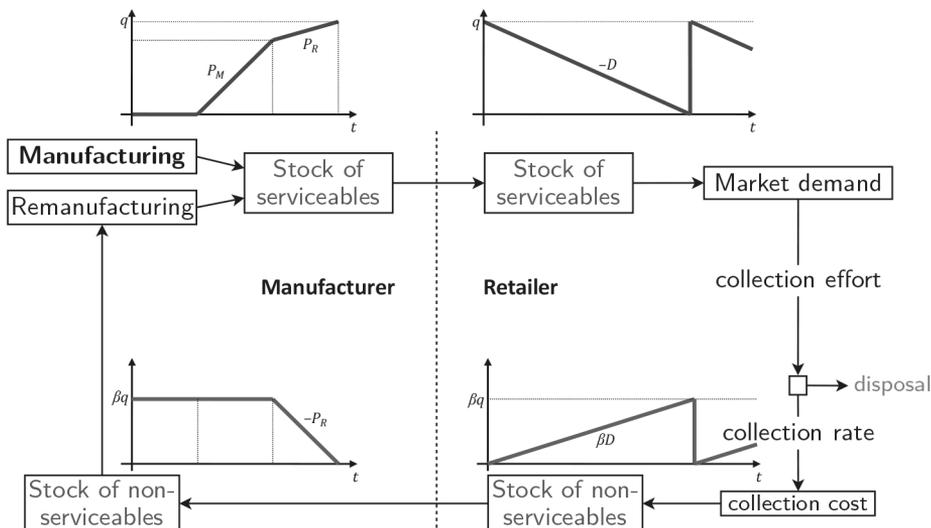


Figure 6. Product flows and stock levels in the closed-loop supply chain model due to Pishchulov et al.

Note: adapted from: Pishchulov G., Dobos I., Gobsch B., Pakhomova N., Richter K. A vendor–purchaser economic lot size problem with remanufacturing // Journal of Business Economics, 2014. Vol. 84, no. 5. P. 749–791.

at production rates P_M and P_R respectively. Remanufactured products serve the retailer’s demand on a par with the new ones. After receiving an order of the size q from the retailer, the manufacturer produces the lot while accumulating the items in stock and then ships it to the retailer. The retailer’s stock is being depleted by the customer demand at the rate D , which makes the retailer repetitively re-order the product from the manufacturer. The retailer also exerts a collection effort for getting used items back, which determines their return rate β . Returning products are being accumulated at the retailer as non-serviceable inventory and shipped to the manufacturer in batches. The manufacturer keeps them in the non-serviceable stock that becomes subsequently depleted during remanufacturing. The authors derive optimal decisions of the parties with regard to lot sizing, collection effort, and refunding the retailer for the used items in a Stackelberg and a cooperative setting. They demonstrate that coordination can be difficult to achieve with conventional, simple contracts between supply-chain members, and propose to this end a contract form with a three-part tariff and a refund amount.

A number of studies have addressed similar settings, for which we provide an overview in Table 2. Dobos with co-authors [Dobos et al., 2013] study a setting closely related to Pishchulov with co-authors [Pishchulov et al., 2014] while assuming cooperative as well as competitive action of supply-chain members. Both these works assume at most one manufacturing and one re-manufacturing batch per production cycle. Jaber with co-authors [Jaber et al., 2014] expand the modelling approach in this regard by permitting multiple manufacturing and remanufacturing batches and adopting a *consignment stock* policy [Braglia, Zavanella, 2003], which assumes that the stock at the retailer’s side is managed by the manufacturer and remains in his ownership until being actually used by the retailer. These authors assume, however, a fixed collection rate of used products and a centralised decision making by the supply-chain partners. Bazan with co-authors expand this

Table 2. Selected studies of coordination in closed-loop supply chains with operational considerations

Study	Constant demand	Uncertainty	Time dynamics	Investment in product design	Collection effort	Number of firms ¹	Leadership ²	Optimal purchase quantity ³	Optimal lot size	Variable number of production batches	Design	Coordination
Pishchulov et al., 2014	X				X	**	M		X			X
Dobos et al., 2013	X		X			**	-		X			
Jaber et al., 2014	X					**			X	X		
Bazan et al., 2017	X			X		**			X	X		
Yuan, Gao, 2010	X					****	R		X	X		
Yuan et al., 2015	X					****	R, RM, RMS, RMC		X	X		
Jonrinaldi, Zhang, 2013	X					: : * : *	R, RDMC		X			
Kim, Glock, 2014	X	X		X		**			X	X		
Bhattacharya et al., 2006		X	X			***	M, MC, RM	X				X
Chuang et al., 2014		X	X		X	***	M	X			X	

¹ An asterisk in this column represents a supply-chain member, while a colon ':' — multiple firms in one supply-chain tier. Spacing before the 3rd asterisk indicates that the supply chain is modelled with as well as without a 3rd party.

² Leadership designates the most powerful supply-chain member or a coalition of members: manufacturer (M), retailer (R), collector and manufacturer (RM), retailer, manufacturer and collector (RMC), manufacturer and collector (MC), manufacturer and supplier (RMS), retailer, manufacturer and collector (RMC), or retailers, distributors, manufacturer and collector (RDMC). A dash '-' represents the case of no leadership, when all parties move simultaneously, and the solution is defined in terms of a Nash equilibrium (Osborne M. J., Rubinstein A. A Course in Game Theory. Cambridge, Massachusetts: The MIT Press, 1994, 368 p.).

No entry in this column represents the case of a cooperative solution approach or a centralised decision-making.

³ In the sense of the optimal *newsvendor* quantity (Silver E. A., Pyke D. F., Thomas D. J. Inventory and production management in supply chains. 4th ed. Boca Raton: CRC Press, 2016, 782 p.).

analysis further to investments in product durability and costs of greenhouse gas emissions in production and transportation [Bazan et al., 2017]. Yuan and Gao assume the retailer to be the most powerful supply chain member and include additionally a supplier and a collecting firm in the model [Yuan, Gao, 2010], while Yuan with co-authors explore supply-chain performance under different leadership structures [Yuan et al., 2015]. Their numerical analysis reveals that integrating the retailer in the decision-making coalition is essential for the supply-chain's as well as manufacturer's and retailer's profits. Jonrinaldi and Zhang study lot sizing in a multi-tier supply chain model with tier-1 and tier-2 suppliers, a manufacturer, distributors, retailers and a 3rd party who collects used products [Jonrinaldi, Zhang, 2013].

While the above studies assume fully deterministic settings, a number of works further address different kinds of uncertainty in closed-loop supply chains (see Table 2). For example, Kim and Glock assume a stochastic return rate of reusable containers from the retailer to the supplier under a deterministic constant demand [Kim, Glock 2014], while Bhattacharya with co-authors study a multi-period, finite-horizon model with uncertain demand [Bhattacharya et al., 2006]. The latter assumption implies that by the end of each period, there can be either unsatisfied demand (lost sales) or leftover stock at the retailer, which both are costly to the retailer. A certain fraction of returning used products and leftover stock can be remanufactured to as-good-as-new products in the next period by a 3rd party remanufacturer who then sells these to the manufacturer — from whom, in turn, the retailer orders the product. The authors use dynamic programming to derive optimal decisions of supply-chain members under different leadership structures and establish a supply-chain coordination mechanism using two-part tariffs. Chuang with co-authors [Chuang et al., 2014] consider a setting similar to Savaskan with co-authors [Savaskan et al., 2004] and Atasu with co-authors [Atasu et al., 2013], yet assuming an uncertain demand and a fixed return rate of used products, and compare the retailer's order quantity and the manufacturer's profit under different reverse channel designs and different scale effects in the logistics costs of used product collection.

Table 2 reveals that all of the studies listed adopt the assumption of either a constant or a stationary demand, and only a few include decision dynamics in the model. Also, only a few studies take into account collection effort and investments in the product design. We can also see in the table that questions of coordination mechanisms for independent supply-chain members and reverse channel design are rarely addressed. We refer the reader to Guo with co-authors [Guo et al., 2017] and Krapp and Kraus [Krapp, Kraus, 2017] for a more comprehensive overview of the literature on decentralised control and coordination in closed-loop supply chains, including asymmetric information and stochastic settings, as well as discussion of existing study gaps.

3.2.2. Acquisition and remanufacturing policies for used products

While most of the above reviewed work makes simplified assumptions about the nature of product returns, used products may in fact return in a highly variable condition, which typically implies different costs of remanufacturing them to serviceable products. What is more, in many real-world settings, the actual quality condition of a returned product remains uncertain until the product undergoes inspection, first after which a decision about remanufacturing can be made. Such a situation requires using an acquisition policy

for used products that takes into account both their uncertain quality condition and the subsequent remanufacturing decisions. In this regard, Teunter and Flapper study a setting in which used products are being acquired in bulk at an equal price and sorted into several quality grades after inspection [Teunter, Flapper, 2011]. Each quality grade implies a specific unit remanufacturing cost, which is lowest for the highest quality grade. Further, each quality grade has a known probability of occurrence; however, the actual fraction of products of any quality grade in the acquired batch is uncertain. Given a deterministic demand for the remanufactured product, a decision needs to be made about the acquisition volume of used products, taking into account the opportunity to remanufacture then only the higher-quality ones and dispose of the rest. The authors derive the expected cost expression associated with any given acquisition volume and give a numerical example demonstrating the expected cost difference between the optimal acquisition decision and the one that is based on the assumption of a fixed fraction of products of each grade in the batch. This analysis is further extended to the case of a stochastic product demand, which in addition requires to determine the remanufacture-up-to levels for different quality grades ahead of the realisation of uncertain demand. The authors' solution approach permits a straightforward implementation on a spreadsheet.

The work by Bulmuş with co-authors [Bulmuş et al., 2014b] extends the analysis to

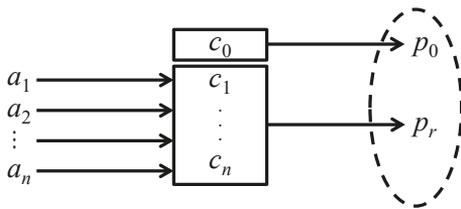


Figure 7. Price variables a_i , p_0 , p_r and cost parameters c_i in the problem setting by Bulmuş et al.

Note: based on: Bulmuş S. C., Zhu S. X., Teunter R. H. Optimal core acquisition and pricing strategies for hybrid manufacturing and remanufacturing systems // International Journal of Production Research, 2014 b. Vol. 52, no. 22. P. 6627–6641.

a setting that excludes demand and quality uncertainty from consideration but involves pricing decisions with regard to used, remanufactured, and new products. Specifically, it allows for differentiated acquisition of products of different quality grades, whose acquisition volumes are determined by the acquisition prices a_i (see Figure 7). They can be remanufactured at different unit costs c_i to an equal quality standard and sold on the market at the price p_r . In addition, new products can be manufactured at the unit cost c_0 and sold on the same market at the price p_0 . Using a standard demand modelling approach for new and remanufactured products [Fer-

guson, Toktay, 2006], the authors express the inverse demand functions, derive properties of optimal pricing policies, and devise a computational procedure for finding these. Their sensitivity analysis reveals, among others, that increase in the unit remanufacturing cost of a particular quality grade decreases its acquisition price, thus decreasing its and also the total acquisition and output volumes, while increasing other acquisition prices and the sales price p_r .

Mutha with co-authors study a setting in which acquisition of used products extends over two periods: first, when the product demand is yet uncertain, and, second, when the demand has become known [Mutha et al., 2016]. The second period is usually shorter and implies higher acquisition and remanufacturing costs. In each period, the remanufacturing firm may acquire used products in bulk — with uncertain quality condition, as well as sorted by quality grade. Sorted acquisition removes uncertainty about product quality, but implies, on average, a higher acquisition price per unit compared to the bulk purchase. In

each period, the firm has to make two consecutive decisions: how much to purchase, in bulk and sorted, and which products to remanufacture then. In view of uncertain demand (period 1), acquisition of sorted products should strike a balance between profit from remanufacturing and risk of over-investment, which may lead the firm to purchasing a mix of higher- and lower-quality products. Some of them may not be remanufactured until period 2, when product demand becomes realised, and some of them may not be remanufactured at all — either due to a low demand or due to the opportunity of purchasing more profitable products in period 2. The authors accordingly develop a four-stage stochastic programme that captures optimal decision making of the firm over the entire horizon, determine structural properties of optimal decision policies, and illustrate application of the model using empirical data of a smartphone remanufacturing company.

3.2.3. Limited product durability and restricted life-cycle

In addition to the studies reviewed by Atasu with co-authors [Atasu et al., 2008] with regard to the issues of a limited product durability and its restricted life-cycle, we refer to reader to the work by El Saadany with co-authors [El Saadany et al., 2013] who link two distinguished lot-sizing approaches due to Richter [Richter, 1997] and Teunter [Teunter, 2001] (Stream 1, Section 3.1) to the problem of a limited product durability and investment in durability improvement. They then compare cost performance of the respective production–inventory systems under the assumptions of a limited and unlimited durability using a series of numerical examples. However, all comparisons are made only for the special case of an equal manufacturing and remanufacturing cost per unit. Bazan with co-authors [Bazan et al., 2017] employ this framework in a setting with closed-loop supply-chain coordination and operations (Stream 2, Section 3.2.1), while Dobos with co-authors [Dobos et al., 2018] study a lot-sizing setting with a limited product durability, in which quality condition of used products depends on the number of remanufacturing cycles they underwent and determines their inventory holding and remanufacturing setup costs. We refer the reader further to the study by Atasu and Çetinkaya [Atasu, Çetinkaya, 2006] who address the problem of a restricted product life-cycle in a closed-loop supply chain setting with optimal timing and lot-sizing of used product returns.

3.3. Strategy stream

While the above Stream 2 considers closed-loop supply chain management from a more holistic perspective than Stream 1, Stream 3 refers to strategic competition in remanufacturing [Atasu et al., 2008]. We refer the reader to Atasu with co-authors for an exposition of foundational studies in this stream, and discuss in this section selected follow-up research [Atasu et al., 2008].

We first refer to the study by Ferrer and Swaminathan who consider a single-firm, two-period setting with manufacturing and remanufacturing [Ferrer, Swaminathan, 2006]. Specifically, in the first period, new products are being manufactured. Returns collected by the end of that period can be remanufactured in the second period to as-good-as-new products. In addition, new products can be manufactured as well, but at a higher unit cost compared to remanufacturing. The firm has to optimally decide pricing of the product on the market in each period. The analysis by the authors reveals that maximising

the profit in the first period straight on can be sub-optimal; instead, the firm may consider selling the product in the first period at a low price in order to generate a high demand volume, which will provide a higher volume of returns, and thus generate bigger savings from remanufacturing in the second period — that can surpass the profit sacrificed in the first period. This shows that new and remanufactured products are not only *substitutes* but also *complements* of one another [Atasu et al., 2008]. Ferrer and Swaminathan further extend their analysis to a setting in which the manufacturer competes with a 3rd party who collects remaining used products by the end of the first period and remanufactures them in the second period to a low-quality product, which the customers value less than the product remanufactured “genuinely” by the original manufacturer [Ferrer, Swaminathan, 2006]. Under these assumptions, the authors derive Nash equilibrium strategies of the players in dependence of the model parameters and prove that under certain conditions, competition is forcing the manufacturer to charge lower prices either in the second or in both periods, compared to the case without competition. This analysis is further extended to a multi-period and infinite-horizon settings.

Ferguson and Toktay similarly address a two-period setting but assume that customers distinguish between new and remanufactured products [Ferguson, Toktay, 2006]. Furthermore, customers are heterogeneous with regard to their valuation of the new product, and each has a respectively lower valuation of the remanufactured version. The firm thus needs to decide about joint pricing of both kinds of product, taking into account that each sale of the remanufactured product *cannibalizes* a new product sale [Atasu et al., 2010], which thus reflects *competition* between the two product versions [Ferguson, Toktay, 2006]. The authors accordingly derive the inverse demand functions for new and remanufactured products (the same approach has also been adopted by a number of studies in Stream 2, see Sections 3.2.1 and 3.2.2). Assuming the presence of a fixed collection and remanufacturing cost, they further obtain conditions under which a monopolist firm will not collect and remanufacture used products. They then expand the analysis to the case where a 3rd party remanufacturer may enter the market and collect used products, which would create an external competition to the manufacturer, and which makes him collect and remanufacture used products for deterring the competitor's entry.

Ferrer and Swaminathan further extend their earlier analysis of a monopolist firm to a multi-period setting, in which customers distinguish between new and remanufactured products [Ferrer, Swaminathan, 2010], while Subramanian with co-authors study competition between a manufacturer and a 3rd party, in which the manufacturer can use product design as a strategic instrument [Subramanian et al., 2013]. In their study setting, two product variants (high-end and low-end) may share common components. This would, on the one hand, simplify operations and supply chain management to the manufacturer, but on the other, increase unit cost of the low-end product. Further, it would reduce the customers' valuation of the high-end product while increasing their valuation of the low-end product. Finally, component commonality would reduce the cost of remanufacturing a high-end product for the manufacturer, but also for a 3rd party competitor. The manufacturer therefore needs to strike a balance between these effects when deciding about component commonality in the product design. The authors derive equilibrium strategies of the firms and conduct a large-scale numerical study to generate insights into situations, in which remanufacturing and competition reverse the manufacturer's component commonality decision. They further provide a real-world illustration of their analysis on

the example of the Apple iPad™ product family. We refer the reader to a similar study approach by Örsdemir with co-authors who consider product quality level as strategic instrument and further investigate the impact of competition with a 3rd party remanufacturer on the environment and on consumer and social surplus [Örsdemir et al., 2014]. Interestingly, their results show that competitive remanufacturing can lead to a lower consumer and social surplus compared to the case of no remanufacturing, which happens due to the manufacturer's quality level choice under the pressure of competition.

Differently from the above studies, Bulmus with co-authors study competition between a manufacturer and a 3rd party remanufacturer, which takes place both in sales of the serviceable products and in the acquisition of used products [Bulmus et al., 2014a]. They consider a two-period setting where the manufacturer produces new product in the first period, and both parties can collect used products at the beginning of the second period by choosing their acquisition prices. Collected products are being remanufactured in the same period; in addition, the manufacturer can also produce new products. They determine equilibrium strategies of the parties in the second period and, based on that, obtain the manufacturer's optimal production quantity in the first period. The authors explore three cases: (i) when customers do not distinguish between new and remanufactured products, (ii) when they do, and (iii) when they do not distinguish between the new and remanufactured products of the manufacturer but distinguish them from the products remanufactured by the 3rd party. A numerical study reveals, among other insights, that a larger market size in the second period may in fact decrease the manufacturer's production in the first period — when used products are difficult to collect for the manufacturer but are easy to for the 3rd party, so that the manufacturer protects its market share by cutting the number of products available for remanufacturing.

Unlike the above work, Wu and Zhou study competition between two closed-loop supply chains [Wu, Zhou, 2017]. Each supply chain is modelled according to Savaskan with co-authors [Savaskan et al., 2004] while assuming that competition between them takes place in sales only. Each supply chain has to adopt a particular design — that is, choose whether the manufacturer or the retailer will collect used products (Section 3.2.1), as decided by the manufacturer in each supply chain. While the study by Savaskan with co-authors [Savaskan et al., 2004] shows that collection by the retailer represents the most beneficial design in the absence of competition, the analysis by Wu and Zhou [Wu, Zhou, 2017] reveals that in certain situations, competition may entail one of the two manufacturers to undertake collection of used products — which happens when the unit cost saving from remanufacturing is high enough, or when used products can be collected with a low effort, or both. When both retailers are collecting in such circumstances, sales competition between them is intensified, which drives down the retail price. As both manufacturers in this supply-chain design pass on direct savings from remanufacturing to their retailers (Section 3.2.1), they inevitably have to decrease their wholesale prices — to the extent that one of the manufacturers switches to collecting himself in equilibrium. Interestingly, the authors further show that collection by both retailers may actually represent an equilibrium situation in the *prisoner's dilemma* [Osborne, Rubinstein, 1994, p. 16] — in which both manufacturers could have gained by collecting themselves, but these strategies do not form an equilibrium.

3.4. Behavioural stream

Atasu with co-authors classify research in Stream 4 as the studies addressing behavioural aspects pertaining to product returns and perception of remanufactured products [Atasu et al., 2008]. In addition to the work reviewed by Atasu with co-authors [Atasu et al., 2008], we discuss the following studies in this stream.

The study by Zeng, discussed above in the context of reverse supply chain coordination (Section 3.2.1), involves an empirical investigation of consumer attitudes towards used product return [Zeng, 2013]. To this end, Zeng conducted a customer survey referring to one specific kind of product — ink cartridges [Zeng, 2013]. The results of the survey suggest that it is reasonable to divide the customer base into three segments according to the factors that make customers return used products: either a pecuniary reward, or environmental awareness, or none. Further, the first and the second segments may to some degree overlap. The results of the survey can be used for estimating, at least partly, the relative segment sizes and customer response to the efforts directed towards attracting returns from different segments.

Agrawal with co-authors conducted a behavioural experiment study revealing that the presence of remanufactured products may in fact influence customer perception of the new products [Agrawal et al., 2015]. Their study referred to two kinds of electronic products — portable audio players and consumer-grade printers, for which remanufactured versions are broadly available. The results of the study show that if a strong brand owner remanufactures its own products, this is likely to reduce the valuation of the new product by the customers. In contrast, if the product is remanufactured by a 3rd party, this tends to increase the perceived value of the new product. This provides new insights into the issues of cannibalization and competition in remanufacturing studied in the strategy stream (Section 3.3).

The study by Abbey with co-authors empirically tests the assumption made in much of the literature that customers equally discount their valuation of the remanufactured product in comparison to the new product [Abbey et al., 2017]. Referring to a strong brand of consumer electronic products, the study suggests that discounting of the remanufactured product by the customers can be attributed to a perceived risk of functional and cosmetic defects in the product; different risk preferences of the customers accordingly result in different discounting behaviours. The study obtains an empirical distribution of discounting factors for a remanufactured iPhoneTM product and employs it in an infinite-horizon monopolist pricing problem (see Section 3.3), assuming that products can be remanufactured at most once. The results demonstrate that classical linear demand modelling via a constant discount factor may lead to sub-optimal pricing and significantly underestimate the potential profit from remanufacturing, thus being potentially misleading in the strategic decision about adopting product remanufacturing.

4. Summary and outlook

We have discussed supply chain management in the context of sustainable development goals and identified main paradigms, around which related academic research has been centred: the circular economy paradigm — represented by closed-loop supply chain research, the emissions reduction paradigm — represented by green forward supply chain

management research, and a combined paradigm. We then focused on the circular economy paradigm and provided an overview of research in closed-loop supply chain management. As it would not be possible to review this body of research in its entirety here, we overviewed selected studies by adopting the research taxonomy proposed by Atasu with co-authors [Atasu et al., 2008] and aiming to address representative and recent work in four research streams. In so doing, we intended to outline essential features of analytical approaches and present key insights offered by the literature.

Apart from that, our review refines the original taxonomy and highlights various connections that have emerged between the four research streams over the past decade, which is the use of inventory management approaches (Stream 1) in supply chain coordination and limited product durability settings (Stream 2), studying supply chain coordination and design (Stream 2) under competition (Stream 3), differentiation between new and remanufactured products (Stream 3) in studying supply chain coordination and acquisition and pricing policies (Stream 2), and using behavioural models (Stream 4) for studying supply chain coordination (Stream 2) and pricing policies (Stream 3). This suggests that research is evolving towards an integrated perspective matching the definition of closed-loop supply chain management (Section 2).

While the closed-loop supply chain research agenda puts emphasis on economic benefits of product re-use [Eskandarpour et al., 2015; Geissdoerfer et al., 2017], the work centring around the emissions reduction paradigm and the combined paradigm is more explicit in emphasizing both economic and environmental dimensions of sustainability. As it would not be possible to review this work in the present article for reasons of space, we refer the reader to the following reviews addressing these paradigms. Ansari and Kant [Ansari, Kant, 2017] and Rajeev with co-authors provide a recent account of research evolution in sustainable supply chain management over the last 15 years, paying attention to all three sustainability dimensions [Rajeev et al., 2017]. Eskandarpour with co-authors focus on research work in the area of supply-chain network design [Eskandarpour et al., 2015], while Chen with co-authors overview studies addressing supply chain coordination and collaboration [Chen et al., 2017]. Jaehn offers a systematic discussion of studies addressing operational-level planning [Jaehn, 2016]. We further refer the reader to Zimmer with co-authors for an overview of methods for supplier selection, monitoring and development involving all three sustainability dimensions [Zimmer et al., 2016], and to Feng with co-authors — for an overview of literature addressing corporate social responsibility issues in the context of supply chain management [Feng et al., 2017].

Future work should be directed towards embracing both the circular economy and the emissions reduction paradigms — studies that only begin to emerge [Yenipazarli, 2016]. Furthermore, the broad adoption of the sustainability mindset by the society and the trend towards digitalisation of economy requires a better understanding of the interplay between the societal and the technological developments, which invites supply chain management research and practice integrating both these perspectives [Lopes de Sousa Jabbour et al., 2018; Koppius et al., 2014].

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Устойчивое управление цепями поставок: классификация исследований в контексте циркулярной экономики

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Социально-экологические последствия развития мировой экономики привлекают возрастающее внимание общественности на глобальном уровне. Общество ожидает от бизнеса ответственного отношения к окружающей среде и ее ресурсам, а также к людям для достижения целей устойчивого развития. Цепи поставок, рассматриваемые в качестве существенного звена современной экономики, представляют собой сети взаимосвязанных компаний, которые создают и доставляют продукты и услуги конечным потребителям. Авторы статьи предлагают классификацию исследований в области устойчивого управления цепями поставок и дают обзор научных работ в контексте циркулярной экономики, предметом которых являются так называемые замкнутые цепи поставок. На основе проведенного анализа представлена обновленная классификация работ в этой научной области, при составлении которой использован подход к структурированию исследований, первоначально предложенный А. Атасу и соавторами в 2008 г. В работе дано описание методов аналитического моделирования и поддержки принятия решений, используемых в научной литературе и на практике, а также приведены полученные с их помощью выводы. Среди источников литературы предпочтение отдается исследованиям, реализующим интегрированный подход к управлению замкнутыми цепями поставок путем решения задач проектирования и координации цепей поставок, в том числе с учетом операционных аспектов управления. Авторами выявляются взаимосвязи между возникшими с течением времени новыми направлениями исследований, а также обозначаются перспективные области анализа.

Ключевые слова: управление цепями поставок, замкнутые цепи поставок, ремануфактуринг, устойчивость.

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