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Multi-criteria decision making approaches for green supply chains: a review

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Abstract Designing Green Supply Chains (GSCs) requires complex decision-support models that can deal with multiple dimensions of sustainability while taking into account specific characteristics of products and their supply chain. Multi-Criteria Decision Making (MCDM) approaches can be used to quantify trade-offs between economic, social, and environmental criteria i.e. to identify green production options. The aim of this paper is to review the use of MCDM approaches for designing efficient and effective GSCs. We develop a conceptual framework to find relevant publications and to categorise papers with respect to decision problems, indicators, and MCDM approaches. The analysis shows that (1) the use of MCDM approaches for designing GSCs is a rather new but emerging research field, (2) most of the publications focus on production and distribution problems, and there are only a few inventory models with environmental considerations, (3) the majority of papers assume all data to be deterministic, (4) little attention has been given to minimisation of waste, (5) numerous indicators are used to account for eco-efficiency, indicating the lack of standards. This study, therefore, identifies the need for

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more multi-criteria models for real-life GSCs, especially with inclusion of uncertainty in parameters that are associated with GSCs.

Keywords Multi-criteria decision making · Supply chain management · Quantitative methods · Sustainable manufacturing · Eco-efficiency · Resource efficiency

1 Introduction

Until recently, supply chains focused mainly on delivering high quality products at low costs and gave only secondary attention, if any, to environmental impact and depletion of natural resources. However, natural resources (like energy, water, minerals, metals and land) are becoming scarce, and their demand is expected to increase because of the growing world population (PWC 2011). Additionally, society puts more pressure on companies to apply environmentally friendly practices due to the growing awareness of climate change caused by greenhouse gas emissions. Escalating deterioration of the environment leads to growing interest of researchers and practitioners in Green Supply Chains (GSCs), which extend the traditional supply chains to include activities that minimize environmental impact of a product throughout its entire life cycle (Beamon 1999). To satisfy the future needs of growing population, supply chains are challenged to increase productivity and eliminate current inefficiencies. To achieve this, decision support tools, which account for characteristics of products, such as e.g. increased risks related to uncertainty of the market and productivity, can be used to assess technical innovations at chain level and optimize the current logistic management (i.e. production, distribution and inventory management).

Eliminating inefficiencies and designing GSCs imply quantification of what is feasible from a technical point of view and calculation of trade-offs between economic and environmental indicators (Dekker et al. 2012). This leads to a concept of eco-efficiency, which we define as 'maintaining or increasing the value of economic output while simultaneously decreasing the impact of economic activity upon ecological systems' (Braungart et al. 2007). Eco-efficiency, therefore, combines environmental and economic demands (Govindan et al. 2014b), and an 'eco-efficient solution' is one where further environmental damage can only be prevented at higher costs (Dekker et al. 2012; Quariguasi Frota Neto et al. 2009).

Studying eco-efficiency in GSCs requires the consideration of multiple conflicting criteria, as any design of a Supply Chain (SC) usually involves trade-offs among different conflicting objectives (Wang et al. 2011). Inclusion of multiple criteria in supply chains is a natural way of dealing with different dimensions of sustainability (Eskandarpour et al. 2015; Kannegiesser et al. 2015). Multi-Criteria Decision Making (MCDM), refers to a general class of Operations Research models (Pohekar and Ramachandran 2004), which aim to quantify feasible production alternatives and support decision makers in selecting (a subset of) alternative options based on two or more criteria (Wallenius et al. 2008). MCDM approaches have already been applied successfully in various research areas, such as energy fuels, management, or ecology (Zavadskas et al. 2014). Although literature reviews have been carried out on quantitative approaches for Supply Chain Management (SCM) with environmental concerns (Seuring 2012; Dekker et al. 2012; Brandenburg et al. 2014; Eskandarpour et al. 2015), to the best of our knowledge, no reviews specifically focus on MCDM approaches in eco-efficient GSCs and related production, distribution and inventory problems.

The aim of this paper is to review MCDM approaches that have been used for the design of Green Supply Chains. A conceptual framework is developed in Sect. 2 to categorise indicators and decision problems in GSCs based on existing literature reviews and to outline MCDM approaches and requirements for modelling GSCs. The approach we use to structure and design the literature review, including the search queries, is presented in Sect. 3. The results of the literature review are presented in Sect. 4, where publications are categorised according to the conceptual framework. Finally, Sect. 5 proposes research opportunities for MCDM approaches in eco-efficient GSCs and presents concluding remarks.

2 Conceptual framework

We started this research by identifying recent and relevant literature reviews on the topic of green supply chain management, which refers to integrating environmental thinking in SCM (Srivastava 2007). This resulted in 10 review articles which were used as a basis for the development of the conceptual framework for this study. First of all, Dekker et al. (2012) discussed issues related to green logistics, and revealed Operations Research contributions to supply chains with environmental considerations. Seuring (2012) and Brandenburg et al. (2014) focused on forward supply chains and reviewed modelling approaches used for SCs with sustainability considerations. Seuring and Müller (2008) reviewed literature on forward sustainable supply chain management. Srivastava (2007) presented a state of the art literature review on green supply chain management with a focus on reverse logistics, whereas Carter and Rogers (2008) and Ashby et al. (2012) reviewed and discussed literature on supply chain management within the context of sustainability. Three review articles focused on perishable products. Perishability is an important source of inefficiency because it contributes to production of waste. Food production chains are characteristic example of supply chains where perishability and changing product quality is evident. Akkerman et al. (2010) reviewed quantitative approaches used for distribution management of food products and focus on quality, safety and sustainability; Shukla and Jharkharia (2013) reviewed literature in agri-fresh produce SCs and discussed operational issues causing post-harvest wastage; and Soysal et al. (2012) reviewed quantitative models used for sustainable food logistics management.

Analysing the key words and frameworks used in the ten reviews and mapping these on the use of MCDM approaches in GSCs, we developed a conceptual framework for the literature analysis. This framework identifies which economic and environmental performance indicators are used to account for sustainability, categorise decision problems in SCs, and outline the impact of specific product characteristics on the decision problems and indicators (Fig. 1). These characteristics are further explored as they should be included in MCDM models developed for GSCs. The proposed framework is used to identify relevant articles and conduct the literature review.

2.1 Eco-efficiency indicators in supply chains

During the production of final products from raw materials, and the delivery of products to final customers, supply chains inevitably harm the environment (Tang and Zhou 2012). In Supply Chain Management with environmental concerns, the main business objectives are cost reduction, responsiveness improvement, and avoidance of permanent environmental damage (Soysal et al. 2012). In order to quantify the economic and environmental impact of supply chain activities and to improve environmental and economic performance, a set of indicators for eco-efficiency must be selected and considered to support decision making at SC level. Apart from commonly used indicators for economic performance of supply chains, such as total costs or profit, the analysis of the 10 review papers shows that important indicators to account for eco-efficiency are greenhouse gas (GHG) emissions, energy consumption and water consumption (Dekker et al. 2012; Seuring 2012; Soysal et al. 2012).

Each supply chain is unique in its characteristics. Products are characterised by quality, fluctuations in demand and prices, seasonality, and perishability (Akkerman et al. 2010; Quariguasi Frota Neto et al. 2009; van der Vorst et al. 2009). These factors are associated with uncertainty. For instance, in Food Supply Chains (FSCs) these various sources of uncertainty lead to production of substantial amount of losses (Shukla and Jharkharia 2013). Perishability and continuous quality change of products over time is not exclusively associated with food products, but holds for other products as well, e.g. other fast moving consumer goods. Quality change over time is also associated with uncertainty because the change in quality is usually not precisely known as it depends on environmental conditions. We conclude that

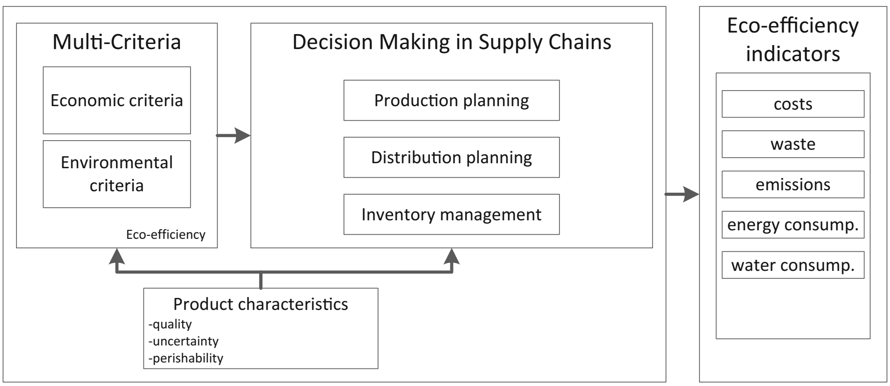

Fig. 1 Conceptual framework for multi-criteria decision making in eco-efficient supply chains

product quality, uncertainty, and perishability should be taken into account when designing eco-efficient GSCs.

2.2 Decision problems in supply chain management

Research has been focusing on improving the environmental performance of SCs (Brandenburg et al. 2014). To categorise decision problems in the conceptual framework we adapt the classification proposed by Shukla and Jharkharia (2013), and distinguish between three decision problems that have an impact on eco-efficiency in GSCs: production planning, distribution planning, and inventory management.

Production planning commonly refers to decisions on how the production is organised, how, when, and how many products are produced, and when the products become available, to minimise operational costs of production and simultaneously use available resources and capacities efficiently. Within production planning two aspects play an important role (Dekker et al. 2012). The first aspect is the production process and the way the product is produced, i.e. what resources are used to make the product and what is the environmental impact related to production. Associated decisions include e.g. which raw materials and technology to use at which location to create the right number of finished products on time to satisfy the customer's demand. These decisions have an impact on eco-efficiency as they determine the amounts of (raw) material, energy, water, and fuel use, as well as the total amount of waste produced. The second relevant aspect with respect to production planning is whether a product's value can be (partly) recovered after its use. This issue is relevant also for FSCs, as products that cannot be sold (due to quality requirements) and are considered as post-harvest losses often still possess valuable nutrients. If products (or their components) can be processed and reused, it might improve eco-efficiency by reducing the total amount of waste and reducing the need for using other raw materials.

A second decision problem affecting the performance of a supply chain is *distribution planning*, which refers to two main topics: facility selection and transportation. Facilities are physical locations in a supply chain, comprising of production sites, distribution centres, airports, railway stations or ports. Related decisions on role, location, size and number of facilities have a substantial impact on the performance of a supply chain (Chopra and Meindl 2013). Decisions concerning facilities affect not only total operating costs, but also the energy use of facilities. Additionally, the location and the number of facilities determine the total travelling distance of a product before reaching the final destination. Facility decisions therefore have an effect on the total time needed to reach the final customer, which is an important aspect in relation to products that degrade in quality over time. With respect to technological innovations, such as extending the shelf-life of products, a redesign of existing networks might bring economic and environmental benefits. A second aspect in distribution planning is transportation, which refers to the movement of products between facilities. Decisions in transportation include the selection of transportation mode, type and size of transportation unit, fuel choice, loading and routing of vehicles (Chopra and Meindl

2013). Transportation activities account for 15% of total GHG emissions worldwide (TSP 2010) and account at the same time for up to two-thirds of the total logistic costs (Akkerman et al. 2010). Due to handling and deterioration of food products, transportation is also the biggest cause of food waste in FSCs (Shukla and Jharkharia 2013). This shows that choices of transportation have a substantial impact on environmental and economic performance. New transportation equipment enables to reduce fuel consumption as observed in airplanes or ships (Dekker et al. 2012), and technological innovations allow the transportation of products in cooled or frozen conditions. This permits the control of the product's quality degradation over time but at the same time leads to additional energy consumption. These technological innovations make the transportation problems a highly dynamic environment requiring frequent reconsiderations of previously made choices (Akkerman et al. 2010).

The third decision problem closely related to performance of the supply chain is related to *inventory management* decisions and to the way the inventory is controlled, e.g. using a periodical or continuous reviewing system, determining safety stock levels, reorder points or reorder quantities. Decisions in inventory management determine how long the product is waiting before use. In relation to products with limited shelf-life, the most important factor in inventory models is to take into account the deterioration of produce over time (Shukla and Jharkharia 2013). Inventory holding is associated with holding costs, and in the case of controlled holding conditions (such as frozen, cooled, or heated storage), which is often used for perishable products, inventory holding is also associated with environmental impact because of energy consumption (Dekker et al. 2012) and other issues such as buildings or equipment.

It should be mentioned that apart from the three aggregate categories of decision problems considered in this paper (i.e. production planning, distribution planning, inventory management), other decision problems can be found in literature too, e.g. supplier selection, procurement planning, or combinations of decision problems, such as inventory routing, or production–distribution. These topics have also been investigated, but are categorized into one of the three main decision themes, i.e. distribution, production, and inventory. The topic of procurement planning can be characterized by making links between the buyer and the supplier, and supplier selection influences the physical location of links in a supply chain. Once physical locations of supply chain links are known, they can be translated into distances. Therefore, for simplification and to facilitate presentation, supplier selection and procurement planning are assigned to decision problems in the distribution planning category.

The environmental impact of a SC can be improved by practices such as reuse, repair, recycle, remanufacture and reverse logistics (Chaabane et al. 2012; Paksoy et al. 2011; Jayaraman 2006). Thus, not only forward flows of products in a SC, but also reverse and closed loop supply chains (integrated forward and reverse supply chains) are investigated to improve the environmental impact. The investigation can be divided into the three types of decision problems described above.

2.3 MCDM model characteristics and requirements

Decision makers in GSCs are confronted with multiple and mostly conflicting criteria of economic and environmental performance, which by definition implies that MCDM approaches are appropriate tools for decision support. Hence it is not surprising that MCDM approaches have already been used to address different decision problems in SCs and to test the efficiency of various SC configurations and operating strategies (Aramyan et al. 2011; Ramudhin et al. 2010). Within the MCDM field, existing approaches are divided in literature into two categories based on the number of feasible solutions (Hwang et al. 1980; Mendoza and Martins 2006; Wallenius et al. 2008): (1) a small and finite set of solutions, called Multi-Attribute Decision Making (MADM), and (2) a large and infinite set of alternatives, referred to as Multi-Objective Decision Making (MODM) or Multi-Objective Programming (MOP). MADM approaches aim at identifying the best option based on the known attributes of a limited number of alternatives, whereas MODM approaches aim to find the best solution that satisfies the decision maker's desires (Scott et al. 2012). Some of the MADM approaches include analytic hierarchy process (AHP), analytic network process (ANP), decision-making trial and evaluation laboratory (DEMATEL), elimination and choice expressing reality (ELECTRE), preference ranking organization method for enrichment of evaluations (PROMETHEE), technique for order of preference by similarity to ideal solution (TOPSIS), utility additive (UTA) method (Fig. 2). For a description of MADM approaches see Tzeng and Huang (2011). Some basic MODM approaches are Weighting Method, ε-constraint, and Goal Programming. For a description of MODM methods see Miettinen (2008). The specific MCDM approach used to support decision making in GSCs depends on the case study and scope of the analysis. Additionally, MCDM approaches differ in complexity and model characteristics.

Within MCDM a distinction can be made depending on how data are taken into account. Deterministic data is often assumed for modelling simplicity and computational effort needed to arrive at a solution. In real-world optimisation problems however, the data are not exactly known at the time the problem is being solved, due to measurement, estimation and implementation errors (Ben-Tal et al. 2009). Uncertainty in SCs is related to 'situations in which a decision maker lacks effective control actions or is unable to predict accurately the impact of possible control actions on system behaviour due to a lack of (1) information (or understanding) of the environment or current SC state, (2) a consistent model of

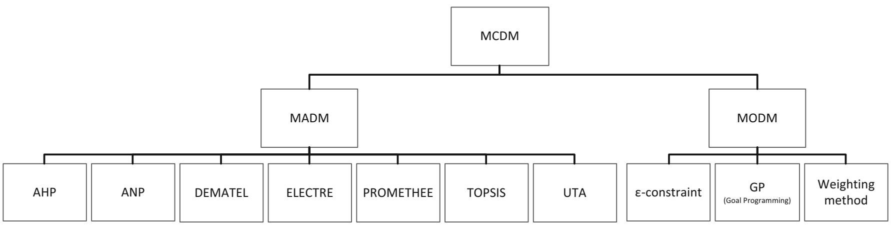

Fig. 2 Some existing MCDM approaches, based on Tzeng and Huang (2011) and Miettinen (2008)

the SC presenting the relationships between SC redesign variables and SC performance indicators' (van der Vorst 2000). In SCs uncertainty can be related to supply of raw materials, demand for final products, processing parameters, prices, and in the light of reverse logistics quantity and quality of returned products (Ahumada and Villalobos 2009; Soysal et al. 2012; Tang and Zhou 2012). Due to the importance of uncertainty in SCs, in our literature review we differentiate between deterministic models and models taking uncertainty into account.

Specific characteristics of products, such as quality changes, demand and prices variability require model representations of the system dynamics and the interactions between time periods. For that reason, another characteristic of reviewed MCDM approaches is related to whether and how time is taken into account.

3 Literature review method

To review scientific literature concerned with applications of MCDM approaches to support decision making processes for establishing eco-efficient GSCs, we defined three categories of keywords: Multi-Criteria Decision Making, Supply Chain Management, and eco-efficiency. Based on the conceptual framework (Sect. 2), we created a set of keywords for each category. Within the eco-efficiency category, keywords are included that automatically entail simultaneous consideration of economic and environmental criteria, i.e. keywords such as "eco-efficient" or "sustainability", instead of using specific indicators or criteria as keywords. The intention is to find articles that position themselves under the umbrella of GSCs, instead of finding articles that focus on a specific aspect of environmental protection. A set of keywords for each category together form a search string that was used to explore existing literature in the ISI Web of Science database, one of the highest regarded science databases, which covers more than 11,000 journals from multiple disciplines, allowing in-depth exploration of the literature.

A search for scientific publications fitting each of the three categories was conducted. The following search string was used:

> (multicriteria OR multi-criteria OR multiobjective OR multi-objective OR multiattribute OR multi-attribute OR trade-off*)
> AND ("supply chain" OR logistics or "network design" OR "production planning" OR "inventory management" OR "supplier selection" OR "distribution management" OR "distribution planning")
> AND (green OR sustainable OR sustainability OR eco-efficien* OR "resource efficient")

Within the results found, we selected the articles that fit the scope of our analysis: i.e. those articles that concern quantitative models for supporting decision making in supply chains in a multi-criteria decision making context, while taking into account eco-efficiency considerations. We excluded publications concerned with non-quantitative analysis, publications describing non-MCDM approaches (e.g. simulation approaches, regression analysis, and single-objective inventory models), publications that do not describe supply chain analysis, and publications that do not include an indicator associated with eco-efficiency (e.g. models including carbon emission trading scheme in costs only).

4 Results

This section presents the results of the literature review. Publications that fit in each of the three categories (MCDM, Supply Chain Management, and eco-efficiency) are discussed in line with the developed conceptual framework. Additionally, these publications are analysed to determine the trends in literature with respect to indicators used to account for eco-efficiency, decision problems tackled, and approaches used.

Our literature review resulted in 418 publications out of which 188 publications (45%) turned out to be relevant for our analysis and were included in the literature review. Figure 3 presents a distribution of publications considered by publication year, indicating that the considered research field is new and emerging.

The articles were published in 68 different journals. In 43 of these journals only one article of interest was found (Table 1). Publications are most frequently found in journals associated with categories: operations research and management science; industrial, chemical, and environmental engineering; and environmental sciences. However, some publications are also found in journals associated with categories such as forestry, electrochemistry, thermodynamics or computer science. The distribution of publications among numerous journals, associated with such diverse categories, shows how multi-disciplinary the topic is. It is also observed that the number of conceptual studies from operations management and supply chain management journals is limited, providing a research opportunity to include green supply chain considerations within MCDM context.

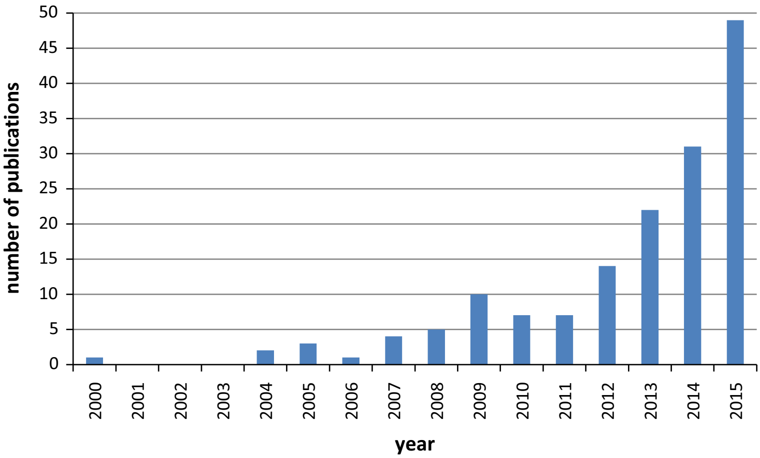

Fig. 3 Distribution of publications between 2000 and 2015. Relevant publications include application of MCDM approaches to support decisions in inventory, production and distribution in green supply chains

Table 1 Distribution of papers across journals

Journal	Articles	Year
Journal of Cleaner Production	18	2009–2016
International Journal of Production Economics	15	2008–2015
International Journal of Production Research	14	2007–2016
European Journal of Operational Research	9	2004–2016
Expert Systems with Applications	9	2011–2016
Computers and Chemical Engineering	8	2000–2016
Sustainability	8	2014–2016
Acs Sustainable Chemistry and Engineering	6	2013–2015
Aiche Journal	6	2009–2015
Transportation Research Part E-Logistics and Transportation Review	6	2014–2016
Computers & Industrial Engineering	5	2005–2016
Mathematical Problems in Engineering	5	2013–2016
International Journal of Environmental Science and Technology	4	2009–2016
Journal of Manufacturing Systems	4	2015–2016
Resources Conservation and Recycling	4	2009–2016
Computers and Operations Research	3	2015
Industrial and Engineering Chemistry Research	3	2008–2016
International Journal of Hydrogen Energy	3	2005–2014
Production Planning & Control	3	2011–2016
Applied Energy	2	2013–2014
Decision Support Systems	2	2009–2011
Energy	2	2012–2016
Flexible Services and Manufacturing Journal	2	2014–2016
Journal of Manufacturing Technology Management	2	2015
Journal of the Operational Research Society	2	2016
Journals with one article[a]	43	2004–2016

[a] Abstract and Applied Analysis, Annals of Operations Research, Applied Mathematical Modelling, Applied Soft Computing, Applied Thermal Engineering, Arabian Journal for Science and Engineering, Biofuels Bioproducts and Biorefining-Biofpr, Biomass and Bioenergy, Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere, Computers in Industry, Croatian Journal of Forest Engineering, Ecological Indicators, Energy Conversion and Management, Energy Policy, Environment and Planning A, Environment and Planning B-Planning and Design, Environmental Science and Technology, Environmental Technology, Human and Ecological Risk Assessment, Ieee Transactions on Engineering Management, Information Sciences, Intelligent Decision Technologies-Netherlands, International Journal of Advanced Manufacturing Technology, International Journal of Sustainable Transportation, Journal of Advanced Mechanical Design Systems and Manufacturing, Journal of Food Engineering, Journal of Intelligent and Fuzzy Systems, Journal of Natural Gas Science and Engineering, Journal of Scientific and Industrial Research, Kybernetes, Mathematical and Computer Modelling, Omega-International Journal of Management Science, OR Spectrum, Proceedings of the Romanian Academy Series a-Mathematics Physics Technical Sciences Information Science, Processes, Renewable and Sustainable Energy Reviews, Renewable Energy, Scientia Iranica, Scientific World Journal, Springerplus, Tehnicki Vjesnik-Technical Gazette, Transportation Research Part D-Transport and Environment, Waste Management

4.1 Decision problems

Production and distribution planning models represent the majority of the publications. We found 69 articles concerned with distribution planning (Fig. 4) and the associated decision problems related to supplier selection, reverse logistics project selection, third party contractor selection, facility location and transportation planning. Production planning problems were found in 39 papers. The related problems are e.g. capacity planning and technology selection, manufacturing, and scheduling. In 70 publications both production and distribution planning decisions are considered. These articles concern network design and associated production decisions, such as technology selection, or decisions on the quantity of products to be produced.

Inventory management with an environmental objective is hardly treated with MCDM models. Only ten publications include inventory management decisions while considering economic and environmental criteria. Bouchery et al. (2012) present the Sustainable Order Quantity, which is a multi-objective formulation of an Economic Order Quantity (EOQ) model, including economic, environmental and social objectives. An extension to multiple echelons is proposed, and the eco-efficient frontiers are characterised analytically. Andriolo et al. (2015) also propose a bi-objective EOQ optimization model, and develop a haulage-sharing lot sizing model to discuss the benefits of cooperation for cost and emission reduction. Konur and Schaefer (2016) model multi-item joint replenishment problem under indirect and direct grouping strategies. Chan et al. (2013) study vendor-buyers co-ordination and illustrate its benefits on economic and environmental performance.

Six publications are assigned to inventory and distribution problems. Jamshidi et al. (2012) present a bi-objective network design model with periodic review inventory replenishment policy (with back-ordering) in warehouses and distribution centres. Sazvar et al. (2014) develop a model to select the best transportation vehicles and to optimally replenish a deteriorating product in a two-echelon centralized supply chain under partial backorder assumption. Marti et al. (2015) use a continuous review inventory policy in the considered supply chain network design model with facility location, procurement and transportation decisions. The developed model is used to analyse the effects of different carbon policies, and

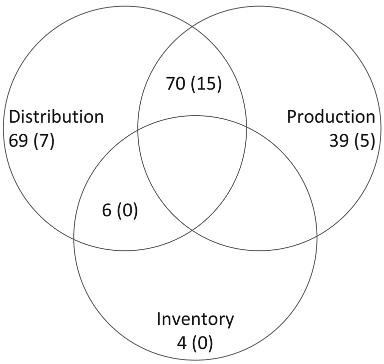

Fig. 4 Number of publications for each decision problem; numbers in *brackets* indicate the number of publications considering reverse logistics or closed loop supply chains

allows distinguishing between functional or innovative products. Schaefer and Konur (2015) study continuous review inventory control systems with explicit transportation considerations, and consider models with less-than-truckload transportation and truckload transportation. Bouchery et al. (2016) formulate a model with simultaneous optimization of decisions on transportation mode and order quantity and propose analytical results to identify the efficient frontier when multiple transportation modes are available. Tang et al. (2016) propose a supply chain network design model to select number and location of warehouses and to select routes from manufacturers to warehouses and from warehouses to retailers, while using continuous review inventory policy. We observe that no publications are found that consider simultaneously production and inventory decisions in the context of eco-efficiency. These findings show that gaps in literature exists concerning the use of MCDM approaches to support inventory management decisions with respect to economic and environmental criteria.

Reverse logistics is considered in 27 publications, while only 11 papers combined forward and reverse logistics to support decision making in a closed-loop supply chain (Govindan et al. 2016a; Garg et al. 2015; Ghayebloo et al. 2015; Mota et al. 2015; Devika et al. 2014; Kannegiesser and Gunther 2014; Oh and Jeong 2014; Pishvaee et al. 2014; Ozkir and Basligil 2013; Paksoy et al. 2012; Quariguasi Frota Neto et al. 2010). Only few of the papers dealing with modelling material flows in a closed-loop supply chain presents a case study with realistic data. This shows that the actual economic and environmental implications of closing loops in real-life case studies still require investigation. Additionally, it is observed that none of the analysed papers concerning food products takes the principles of reverse logistics or closed loop into account.

4.2 Key performance indicators

The analysis shows that the number and types of indicators considered are closely related to the applied MCDM approach. In MADM approaches (in which decision makers interactively assess alternatives with respect to multiple attributes or indicate their perceived importance of each criterion e.g. on a Likert scale), numerous economic, technological, environmental and social indicators are used. In each publication dealing with an MADM approach, a unique set of indicators is developed, which renders clustering and aggregating of these indicators problematic. For this reason we only outline the number of indicators used. The average number of indicators used in MADM approaches is 9.9; the largest number of indicators used is 31 in Govindan et al. (2015b); and the smallest number of indicators used is two in Validi et al. (2015). The largest number of objectives in papers concerned with MODM models is considered in Kostin et al. (2015) (15 objectives for two case studies presented), where an approach is proposed to reduce the number of objectives to a comprehensible number. In articles in which the ultimate goal is to derive a Pareto-efficient frontier, authors focus on two or three objectives. The most commonly used objectives in these studies are minimization of total costs and GHG emissions.

In MODM approaches the indicators (treated as objectives) most commonly used to account for economic performance are costs, profit, Net Present Value, expected return, economic output, financial risk, and total value of purchasing (Table 2). In seven publications assigned to production planning no economic indicators were used. Publications that did not use an economic indicator in production planning, focused on balancing between either energy consumption and total completion time (Mansouri et al. 2016; Yildirim and Mouzon 2012; Mouzon et al. 2007), energy consumption and tardiness (Liu et al. 2014b), carbon emissions and total completion time (Liu et al. 2014a), or focused on environmental indicators objectives only in pinch analysis (Geldermann et al. 2006, 2007). In some publications two economic indicators are used simultaneously, e.g. profit and risk (Cruz 2009, 2013; Cruz and Matsypura 2009).

With respect to environmental indicators, some form of greenhouse gas (GHG) emissions, such as CO_2-equivalent, CO_2 emission per capita, embodied carbon footprint, air pollution, or impact on global warming is most commonly used.

Table 2 Number of publications with a given indicator used in MODM approaches for different decision problems

	Indicator	Decision problem					Total
		P	D	I	P + D	D + I	
Economic	Costs	13	20	4	37	5	79
	Profit	2	–	–	21	1	24
	NPV	4	–	–	11	–	15
	Other economic[a]	6	3	–	6	–	15
Environment	GHG	12	14	4	42	6	78
	Energy	12	2	1	2	–	17
	LCA based	2	1	–	13	–	16
	Water	10	1	–	1	–	12
	Waste	–	4	1	6	–	11
	Other environmental[b]	7	5	–	6	–	18
Other	Service level	6	7	–	5	–	18
	Social	3	3	1	21	–	28
Number of MODM publications		31	21	4	67	6	129

P production planning, *D* distribution planning, *I* inventory management

[a] Other economic indicators include: economic score, economic output, economic value added, expected return, financial risk, production, revenue, total credit, total value of (1) purchasing performance, (2) production performance, (3) delivery and logistics performance

[b] Other environmental indicators include: ecocosts, environmental certification, environmental efficiency, environmental index, environmental score, exergy losses, greenness, green appraisal scores, hazardous waste management, non-renewable resources consumption, recycling rate, relative direct sustainability index, relative total sustainability index, remanufacturing activity, reverse logistics program, soil erosion, volatile organic compounds

Greenhouse gasses were used as an indicator in 60% of publications, and were most frequently used in distribution planning models (67% of publications), and in combination of distribution and production planning models (63%). Energy consumption is used in 13% of publications, and was most frequently used in production planning models (39%). LCA based indicators, such as ReCiPe 2008, Impact2002 + or EcoIndicator, are used in 12% of publications, water is used in 9% of publications, and waste is used as an indicator in 9% of publications. Other environmental indicators, e.g. green appraisal scores, environmental efficiency, environmental index, volatile organic compounds emissions, or exergy losses are used in 14% of the papers. Note that number of (environmental) indicators is larger than number of publications. This is because in some publications more than one indicator is used. Notably, none of the studied articles on FSCs use the amount of food waste as an objective.

Numerous indicators were identified to account for eco-efficiency throughout the considered literature. A variety of environmental indicators is observed, and it is concluded that the exact environmental indicator used depends on the specific problem environment and case study. Moreover, attempts are made to assess the environmental impact using standardised methods (e.g. Eco-indicator). However, such newly created measures continue to emerge (e.g. environmental impact score in Inghels et al. (2016), greenness level in Ghayebloo et al. (2015)), indicating the lack of standards.

Service level indicators (e.g. total completion time, rejection rate, late delivered items, tardiness) are used in 14% of publications. Social indicators, such as number of accrued jobs, hours of employment, injury rate, satisfaction levels of stakeholders and customers, and social risks, were used in 22% of the publications

4.3 Solution approaches

It is observed that the use of MADM approaches to balance conflicting criteria in eco-efficient SCs is well represented. Numerous approaches such as AHP, TOPSIS, ANP, PROMETHEE, DEMATEL, VIKOR and their combinations are used. In 78 out of 188 studied articles (41%) one or more MADM approaches were applied. The most commonly used approach is AHP (32 publications), TOPSIS (23 publications), and ANP (16 publications). Most of the MADM approaches are applied to supplier selection or evaluation problems (44 publications, 56% of all MADM approaches), and technology or material selection (9 publications, 12%). Within the relevant publications, 129 articles (69%) use an MODM approach, mostly based on linear and non-linear programming problems. In some studies two or more approaches are presented. It is observed that MODM approaches most commonly focus on deriving a set of Pareto-efficient solutions (or Pareto-efficient frontier). Pareto efficient solutions are derived to aid a decision maker in selecting most preferable solution that balances environmental and economic objectives. The methods most frequently used are the ε-constraint method (44 papers, 34% of all MODM approaches) and weighting methods (35 papers, 27%). Some problems are solved using heuristics (in case the problem is too difficult or takes too much computational effort to solve with standard optimisation approaches), such as genetic algorithms (14 papers, 11%), other evolutionary algorithms, multi-objective gravitational search algorithm, memetic algorithm, multi-objective heuristic based on variable neighbourhood search, or greedy heuristic. Additionally, in 19 publications (10%) MADM and MODM approaches are combined to arrive at a final solution. In these articles AHP, ANP, and/or TOPSIS are used to obtain weights for multi-objective optimisation problems, and a single solution out of the efficient set is selected, e.g. in Validi et al. (2014a) an AHP constraint is introduced to include decision makers' consensus opinions for vehicles used for distribution, and TOPSIS approach is used to evaluate results generated by (three genetic algorithm-based) optimizers to highlight the best candidate to a decision maker.

Among publications assigned to MODM approaches, we included Bouchery et al. (2012) which studies the SOQ model and analyses the efficient frontier analytically. The authors also develop an interactive procedure to find a balance between the considered objectives. Five publications concerned with supply chain network equilibrium problems (Cruz 2013; Cruz and Matsypura 2009; Nagurney et al. 2007) are also assigned to MODM approaches. The authors model the behaviours of multiple decision makers in the supply chain and derive the equilibrium conditions and optimality conditions for all actors, with the variables such as product flows, prices, or levels of social responsibility activities.

Publications in which the Data Envelopment Analysis (DEA) method is used are assigned to MODM or MADM approaches depending on its context. Publications of Zeydan et al. (2011), Kuo et al. (2010) and Dobos and Vorosmarty (2014) are assigned to MADM approaches, and the authors use DEA to select the most appropriate suppliers, to rank them, and to choose a weight system. Two publications in which DEA is used are assigned to MODM approaches: Van Meensel et al. (2010) evaluate the ability of frontier approaches to support decision making and to analyse trade-offs between economic and environmental performance; Quariguasi Frota Neto et al. (2008) propose a methodology based on DEA and multi-objective programming to assess efficiency of logistic networks.

Current categorisation could be further extended by categorising the papers based on the involvement of the decision maker in selecting a solution from the efficient set. Within MCDM approaches a distinction can be made depending on when preferences of a decision maker are specified: (1) no articulation of preference, (2) 'a priori' articulation of preference information (before solution process), (3)'progressive' articulation of preferences (during solution process), and (4)'a posteriori' articulation of preferences (after solution) (Hwang et al. 1980).

4.4 Model characteristics

Within the 188 papers considered, 123 (65%) assume all data to be deterministic (Table 3), and uncertainty is included more often in publications concerned with MADM approaches compared to MODM approaches. Non-deterministic data in MADM approaches are included in 46 articles (59% of all MADM approaches), whereas in MODM approaches only 27 papers (21% of all MODM approaches) use uncertainty in parameters. Among non-deterministic models fuzzy set theory is most frequently applied to take uncertainty into account. Fuzzy set theory is used to take

Table 3 Publications with respect to each decision problem and solution approach

	MADM	MODM	MADM + MODM	Sum[b]
P	Govindan et al. (2016b, 2015b), Ravi et al. (2005), Laukkanen et al. (2004) Boutkhoum et al. (2016)[a], Singh et al. (2016)[a], Cobuloglu and Buyuktahtakin (2015)[a], Ziolkowska (2014)[a]	Igarashi et al. (2016), Kucukvar et al. (2016), Mansouri et al. (2016), Yan et al. (2016), Garcia and You (2015a), Gong and You (2015), Hombach and Walther (2015), Liu et al. (2015, 2014a, b), Manzardo et al. (2014), Gerber et al. (2013), Kravanja and Cucek (2013), Bernardi et al. (2012), Giarola et al. (2012), Oglethorpe (2010), Quariguasi Frota Neto et al. (2010), Van Meensel et al. (2010), Ayoub et al. (2009), Guillen-Gosalbez et al. (2008), Geldermann et al. (2007), Mouzon et al. (2007), Geldermann et al. (2006) Wang et al. (2016)[a], Eker and van Daalen (2015)[a], Kravanja (2010)[a], Radulescu et al. (2009, 2008)[a], Wu and Chang (2004)[a]	Inghels et al. (2016), Yildirim and Mouzon (2012)	39 (10)
D	Yu and Hou (2016), Asgari et al. (2015), Bouzarour-Amokrane et al. (2015), Galvez et al. (2015), Stas et al. (2015), Barata et al. (2014), Dobos and Vorosmarty (2014), Falatoonitoosi et al. (2014), Hsu et al. (2014), Tsui and Wen (2014), Scott et al. (2013), Dai and Blackhurst (2012), Hsu et al. (2012), Kuo et al. (2010), Hsu and Hu (2009), Chakraborty et al. (2005) Awasthi and Kannan (2016)[a], Celik et al. (2016)[a], Chen et al. (2016)[a], Liou et al. (2016)[a], Sang and Liu (2016)[a], Zhou et al. (2016)[a], Boutkhoum et al. (2015)[a], Chithambaranathan et al. (2015)[a], Govindan et al. (2015c)[a], Hashemi et al. (2015)[a], Jia et al. (2015)[a], Kannan et al. (2015)[a], Orji and Wei (2015a,b)[a], Wan and Dong (2015)[a], Wan and Li (2015)[a], Zhang and Xu (2015)[a], Senthil et al. (2014)[a], Tseng et al. (2014)[a], Wang et al. (2014)[a], Zhao and Guo (2014)[a], Govindan et al. (2013)[a], Hsueh and Yan (2013)[a], Shen et al. (2013)[a], Tuzkaya (2013)[a], Buyukozkan (2012)[a], Buyukozkan and Cifci (2012)[a], Awasthi et al. (2011)[a], Buyukozkan and Cifci (2011)[a], Zeydan et al. (2011)[a], Tuzkaya et al. (2009)[a], Lu et al. (2007)[a]	Colicchia et al. (2016), Boonsothonsatit et al. (2015), Yang et al. (2015), Harris et al. (2014), Ramos et al. (2014), Soysal et al. (2014), Validi et al. (2014b), Tang et al. (2013), Wang et al. (2011)	Aktin and Gergin (2016), Wu and Barnes (2016), Validi et al. (2015, 2014a), Ravi et al. (2008) Govindan and Sivakumar (2016)[a], Azadnia et al. (2015)[a], Cao et al. (2015)[a], Ashlaghi (2014)[a], Paksoy et al. (2012)[a], Kannan et al. (2013)[a], Shaw et al. (2012)[a]	69 (39)
I	Ø	Konur and Schaefer (2016), Andriolo et al. (2015), Chan et al. (2013), Bouchery et al. (2012)	Ø	4 (0)

Table 3 continued

	MADM	MODM	MADM + MODM	Sum[b]
P + D	Kuhmaier and Stampfer (2012) Rostamzadeh et al. (2015)[a], Ren et al. (2013)[a]	Bortolini et al. (2016), Chibeles-Martins et al. (2016), d'Amore and Bezzo (2016), Govindan et al. (2016a), Miret et al. (2016), Yue et al. (2016), Zhong et al. (2016), Boukherroub et al. (2015), Gao and You (2015), Garcia and You (2015b), Garg et al. (2015), Ghayebloo et al. (2015), Kostin et al. (2015), Mota et al. (2015), Nagurney (2015), Santibanez-Aguilar et al. (2015), Shimizu et al. (2015), Tognetti et al. (2015), Yu et al. (2015), Yue et al. (2015), Devika et al. (2014), Govindan et al. (2014a), Kannegiesser and Gunther (2014), Martinez-Guido et al. (2014), Oh and Jeong (2014), Santibanez-Aguilar et al. (2014), Yue et al. (2014), Zhang et al. (2014), Cruz (2013), Eskandarpour et al. (2013), Kanzian et al. (2013), Ortiz-Gutierrez et al. (2013), Sadrnia et al. (2013), Sahay and Ierapetritou (2013), Santibanez-Aguilar et al. (2013a, b), Shaw et al.(2013), Yue et al. (2013), Perez-Fortes et al. (2012), You et al. (2012), Chaabane et al. (2011), Giarola et al. (2011), Yeh and Chuang (2011), Guillen-Gosalbez et al. (2010), Bojarski et al. (2009), Cruz (2009), Cruz and Matsypura (2009), Quariguasi Frota Neto et al. (2009), Cruz (2008), Quariguasi Frota Neto et al. (2008), Nagurney et al. (2007), Hugo et al. (2005) Bairamzadeh et al. (2016)[a], Fahimnia and Jabbarzadeh (2016)[a], Azadeh et al. (2015)[a], Brandenburg (2015)[a], Gonela et al. (2015)[a], Govindan et al. (2015a)[a], Pishvaee et al. (2014)[a], Ozkir and Basligil (2013)[a], Guillen-Gosalbez and Grossmann (2010, 2009)[a]	Almaraz et al. (2014), Chen and Andresen (2014), Dehghanian and Mansour (2009), Zhou et al. (2000) Jakhar (2015)[a]	70 (13)
D + I	Ø	Bouchery et al. (2016), Tang et al. (2016), Jamshidi et al. (2012) Marti et al. (2015)[a], Schaefer and Konur (2015)[a], Sazvar et al. (2014)[a]	Ø	6 (3)
Sum[b]	59 (38)	110 (19)	19 (8)	188 (65)

[a] Publication with non-deterministic parameter(s)

[b] Number in brackets indicates number of publications with non-deterministic parameter(s)

uncertainty into account in weights of decision makers, demand, capacities, prices of products, and customer satisfaction levels. Fuzzy set theory was combined with AHP, ANP, TOPSIS and Multi-Objective Optimisation models. In publications concerned with MADM approaches, fuzzy set theory is applied in majority of papers to treat uncertainty, and other approaches are used in five papers only. Liou et al. (2016), Chithambaranathan et al. (2015), Hashemi et al. (2015), and Wang et al. (2014) apply grey system theory based approach to integrate uncertainty in decision making process. In Cobuloglu and Buyuktahtakin (2015) stochastic AHP is proposed to treat uncertain information obtained from decision makers.

In 14 publications associated with MODM approaches uncertainty in parameters is treated with an approach different from fuzzy set theory. Eker and van Daalen (2015) consider multiple sources of uncertainty associated with biomethane production (e.g. resource availability, demand, capacity) and formulate a multi-objective robust optimization model. Brandenburg (2015) studies supply chain design problem under uncertain demands, and solves the proposed two-stage stochastic programming model with discrete number of scenarios to support production and transportation decisions. Gonela et al. (2015) consider uncertain parameters related to bioethanol price, demand, and biomass yield. A two-stage stochastic programming model is proposed to support design and production decisions in bioethanol supply chain. Govindan et al. (2015a) consider uncertain demand of retailers, and develop a scenario-based two-stage stochastic programming network design model including transportation and manufacturing decisions. Fahimnia and Jabbarzadeh (2016) apply a two-stage stochastic fuzzy goal programming approach to design a resiliently sustainable supply chain by considering a set of disaster scenarios. Kravanja (2010) includes uncertain parameters related to processing, and the non-linear problem including uncertainty is solved with the developed synthesizer to derive Pareto-efficient solutions. Radulescu et al. (2009) formulate a multi-objective stochastic programming model with random vectors (with multivariate normal distribution) in the objective function and solve the presented model with a genetic algorithm. Radulescu et al. (2008) solve a stochastic programming model (with random selling price coefficients) with optimisation software maximising one objective at a time. Wu and Chang (2004) use the grey system theory to account for uncertainty, and solve their problem with grey compromise programming approach. Guillen-Gosalbez and Grossmann (2009, 2010) include uncertainty related to environmental damage and use a chance constraint indicating that environmental impact must be within a given bound at a given probability. Three papers include uncertainty in demand in inventory models. Marti et al. (2015), and Schaefer and Konur (2015) consider uncertain demand while using a continuous review inventory policy. Sazvar et al. (2014) also consider uncertain demand and propose a two-stage stochastic programming model. Limited number of papers shows an opportunity for future research to consider uncertainty in parameters in MCDM approaches.

It can be observed that in eight out of ten papers concerned with food products, all data are assumed to be deterministic. Ziolkowska (2014) uses fuzzy set theory to evaluate linguistic variables assigned by decision makers to assess the relation between each production alternative and each attribute. Also in Azadnia et al.

(2015) experts' (linguistic) evaluations are quantified based on fuzzy set theory. None of the sources of uncertainty listed in the conceptual framework related to food production (e.g. production yields or demand) are included papers that model food supply chains.

The time aspect is taken into account in 51 publications. Perishability and degrading product quality, however, is taken into account in only five publications associated with food products. Soysal et al. (2014) and Govindan et al. (2014a) take perishability into account by allowing a maximum number of consecutive time periods that a food product can be stored. You et al. (2012) take into account a given degradation rate during storage, i.e. it is assumed that during each time period a given fraction of stored products deteriorates and cannot be used. Miret et al. (2016) take into account biomass deterioration during the storage by considering a given (fixed) deterioration rate for each product. To consider perishability Bortolini et al. (2016) propose a quality function, which describes shelf life, to evaluate the quality decrease over the time and the related market purchase probability.

5 Discussion and conclusions

As observed by Dekker et al. (2012), environmental performance can often be improved substantially at a marginal expense of economic performance, and MCDM approaches can be very useful within this context. To the best of our knowledge, no reviews have specifically focused on MCDM approaches in GSCs and related production, distribution, and inventory problems. The aim of this paper was to review studies and to identify research opportunities in this field. While MCDM approaches are important to identify solutions balancing environmental and economic concerns, there are other approaches that can be used to take environmental issues into account, e.g. financial evaluation of environmental criteria, for instance carbon tax as presented in Chaabane et al. (2008), or using economic objective and environmental constraints (or vice versa). In this manuscript, however, we focused on papers that as a starting point apply MCDM approaches to balance (conflicting) criteria of economic and environmental performance.

We found that MCDM approaches to support production, distribution and inventory decisions in GSCs gain an increasing interest in recent years. However, using MCDM approaches to design green supply chains is currently absent in many Operations Management and Supply Chain Management journals, which shows a gap in literature. Most of the studied publications focus on production and distribution problems. There are not many MCDM studies focusing on inventory management. The reason may be that inventory management decisions do not heavily influence the environmental impact. Storage of food products, however, often requires temperature controlled conditions that are associated with energy consumption. Nonetheless, we did not find any publications on inventory management for food products, which shows a gap in literature. In fact, multi-criteria approaches in green food supply chains are especially scarce, despite the perishability of the products that often results in trade-offs between quality decay and costs. It is also surprising that no attention has been given to the closed loop principles in publications concerned with perishable products, as we are aware of technologies that can process agri-food waste into raw materials used in the same supply chain, as presented in e.g. Zisopoulos et al. (2015).

It is observed that numerous indicators are used to account for environmental performance in supply chains, indicating a lack of standards. We observe attempts to assess the environmental impact of a SC by using standardised methods such as Eco-Indicator, Impact2002, or environmental index. It appears, however, that there is no agreement on a unified indicator to be used to account for environmental damage, as newly created measures aggregating some indicators continue to emerge. Notably, none of the publications concerned with food products take food waste as an indicator. This is surprising knowing that food waste is a major concern in food supply chains (Shukla and Jharkharia 2013), and one-third of all food produced for human consumption is lost or wasted (FAO 2013).

To assess the limited number of alternatives, multi-attribute decision making (MADM) approaches are used, mainly TOPSIS, AHP and ANP. These approaches are commonly applied to assess potential suppliers, to select most appropriate production technology, or to evaluate contractors for reverse logistics activities. Multi-objective decision making (MODM) approaches are used to find an optimal solution for a large or infinite set of alternatives. These approaches are used to support decision making in problems associated with network design, transportation planning, scheduling, and with allocation problems. Most publications concerned with MODM approaches focus on deriving Pareto-efficient solutions, which are especially informative, because they illustrate a quantified trade-off between conflicting economic and environmental performance. Pareto efficient solutions are derived to aid a decision maker in selecting most preferable solution. Weighted sum method and ε-constraint method are most commonly used to derive these efficient solutions, while other methods often require involvement of the decision maker, who may not always be available or capable to participate in weight elicitation process. In some publications Pareto-efficient solutions are derived, and an MADM approach is used to select a single solution out of the efficient set.

Notably, in the majority of papers on eco-efficient supply chains all data are assumed to be deterministic, and uncertainty is hardly taken into account. Fuzzy set theory is most commonly applied to take uncertainty into account, and the use of other approaches to treat uncertainty in a multi-criteria context is limited. We therefore conclude that there is a need for more emphasis to include uncertainty inherently associated with supply chains (in demand, prices, processing parameters, quality change in products, as pointed out in the developed framework). This can lead to the need for exploring other solution approaches that are capable of including uncertainty in various data parameters in all decision problems.

We conclude that more attempts to balance economic and environmental criteria in real-life SC decision problems are needed. In line with Brandenburg et al. (2014), we identify a need for more stochastic approaches in modelling to represent the uncertain decision environment of SCs, to take intrinsic characteristics of products into account. It will be interesting to observe which impact stochasticity in parameters has on decision making and on eco-efficient frontiers in supply chains.

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