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# Green supply-chain management: A state-of-the-art literature review

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There is a growing need for integrating environmentally sound choices into supply-chain management research and practice. Perusal of the literature shows that a broad frame of reference for green supply-chain management (GrSCM) is not adequately developed. Regulatory bodies that formulate regulations to meet societal and ecological concerns to facilitate growth of business and economy also suffer from its absence. A succinct classification to help academicians, researchers and practitioners in understanding integrated GrSCM from a wider perspective is needed. Further, sufficient literature is available to warrant such classification. This paper takes an integrated and fresh look into the area of GrSCM. The literature on GrSCM is covered exhaustively from its conceptualization, primarily taking a 'reverse logistics angle'. Using the rich body of available literature, including earlier reviews that had relatively limited perspectives, the literature on GrSCM is classified on the basis of the problem context in supply chain's major influential areas. It is also classified on the basis of methodology and approach adopted. Various mathematical tools/techniques used in literature *vis-à-vis* the contexts of GrSCM are mapped. A timeline indicating relevant papers is also provided as a ready reference. Finally, the findings and interpretations are summarized, and the main research issues and opportunities are highlighted.

## Introduction

In early environmental management frameworks, operating managers were involved only at arm's length. Separate organizational units had responsibility for ensuring environmental excellence in product development, process design, operations, logistics, marketing, regulatory compliance and waste management. Today, this has changed. As in the quality revolution of the 1980s and the supply-chain revolution of the 1990s, it has become clear that the best practices call for integration of environmental management with ongoing operations.

Green supply-chain management (GrSCM) is gaining increasing interest among researchers and practitioners of operations and supply-chain management. The growing importance of GrSCM is driven mainly by the escalating deterioration of the environment, e.g. diminishing raw material resources, overflowing waste sites and increasing levels of pollution. However, it is not just about being environment friendly; it is about good business sense and higher profits. In fact, it is a business value driver and not a cost centre (Wilkerson 2005). In addition, the regulatory requirements and consumer pressures are driving GrSCM. Hence, the scope of GrSCM ranges from reactive monitoring of the general environment management programmes to more proactive practices implemented through various Rs (Reduce, Re-use, Rework, Refurbish, Reclaim, Recycle, Remanufacture, Reverse logistics, etc.).

Sufficient literature exists about various aspects and facets of GrSCM. Comprehensive reviews on green design (Zhang *et al*. 1997), repairable inventory (Guide *et al*. 1997c, 1999a), production planning and control for remanufacturing (Bras and McIntosh 1999; Guide 2000; Guide *et al*. 1997b,c), issues in green manufacturing and product recovery (Guide *et al*. 1996; Gungor and Gupta 1999), reverse logistics (RL) (Carter and Ellram 1998; Fleischmann *et al*. 1997) and logistics network design (Fleischmann *et al*. 2000, 2001; Jayaraman *et al*. 2003) have been published.

In addition, Bloemhof-Ruwaard *et al*. (1995) deal with interactions between operational research and environmental management, and Roy and Whelan (1992) discuss recycling through value-chain collaboration. Min *et al*. (1998) and Lippmann (1999) discuss combined location-routing problems and elements for success in GrSCM, while Dowlatshahi (2000) develops a theory of RL. Sufficient literature also exists in the related areas of green purchasing (Zhu and Geng 2001), industrial ecology and industrial ecosystems (Bey 2001; Boustead 1979; Cairncross 1992; Frosch and Gallopoulos 1989; Graedel 2002; Hui *et al*. 2001; Kaiser *et al*. 2001; Klassen 2001; Min and Galle 2001; Nasr 1997; Owen 1993; Sarkis 1998, 1999, 2001; Sarkis and Cordeiro 2001; van Hoek 1999; Zhang *et al*. 1997; Zhu and Sarkis 2004).

Earlier works and reviews have a limited focus and narrow perspective. They do not cover adequately all the aspects and facets of GrSCM. For example, Bey (2001) presents a critical appraisal of developments in the field of industrial ecology only, while Zhang *et al*. (1997) focus only on green design. Much of the work is empirical and does not focus adequately on modelling and network design related issues and practices. Our objective is to present a comprehensive integrated view of the published literature on all the aspects and facets of GrSCM, taking a ‘reverse logistics angle’ so as to facilitate further study, practice and research.

To meet this objective, we define a few relevant terms in this section. Either these have been taken from the existing literature, or we define them appropriately. The second section portrays the research methodology applied. Qualitative analysis was applied to classify the existing literature on the basis of problem context and the methodology/approach adopted. We also map the tools/techniques *vis-à-vis* the problem context classification. Finally, we provide a timeline indicating relevant papers for the benefit of academicians, researchers and practitioners. At the end of the paper, we draw certain conclusions and identify potential issues and opportunities in the realm of GrSCM.

### *Green Supply-Chain Management Defined*

Green supply-chain management has its roots in both environment management and supply-chain management literature. Adding the ‘green’ component to supply-chain management involves addressing the influence and relationships between supply-chain management and the natural environment. Similar to the concept of supply-chain management, the boundary of GrSCM is dependent on the goal of the investigator. The definition and scope of GrSCM in the literature has ranged from green purchasing to integrated green supply chains flowing from supplier to manufacturer to customer, and even RL (Zhu and Sarkis 2004). For the purpose of this paper, GrSCM is defined as ‘integrating environmental thinking into supply-chain management, including product design, material sourcing and selection, manufacturing processes, delivery of the final product to the consumers as well as end-of-life management of the product after its useful life'. We specifically focus on RL and mathematical modelling aspects in order to facilitate further study and research.

Green design has been used extensively in the literature to denote designing products with certain environmental considerations. It is the systematic consideration of design issues associated with environmental safety and health over the full product life cycle during new production and process development (Fiksel 1996). Its scope encompasses many disciplines, including environmental risk management, product safety, occupational health and safety, pollution prevention, resource conservation and waste management.

Green operations relate to all aspects related to product manufacture/remanufacture, usage, handling, logistics and waste management once the design has been finalized. Green manufacturing aims to reduce the ecological burden by using appropriate material and technologies, while remanufacturing refers to an industrial process in which worn-out products are restored to like-new condition (Lund 1984).

Rogers and Tibben-Lembke (1999, 2) define RL as 'the process of planning, implementing, and controlling the efficient, cost-effective flow of raw materials, in-process inventory, finished goods and related information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal', while Maruglio (1991, 57) defines waste minimization as 'the reduction ... of hazardous waste which is generated (during production and operations) or subsequently treated, stored or disposed ...'.

## Research Methodology

The objective of this paper is to identify major works on green supply-chain management research integrating environmental thinking into supply-chain management, and thereafter, to classify them so as to identify gaps, issues and opportunities for further study and research. A literature review seems to be a valid approach, as it is a necessary step in structuring a research field and forms an integral part of any research conducted (Easterby-Smith *et al.* 2002). This helps to identify the conceptual content of the field (Meredith 1993) and guides towards theory development.

Our research is driven by theoretical preconsiderations and follows a clear process, as this allows conclusions to be drawn on the reviewed literature. It may be classified as an archival research method in the framework for conducting and evaluating research suggested by Searcy and Mentzer (2003). Our process of analysis comprises the following steps:

- *Defining unit of analysis:* The unit of analysis has been defined as a single research paper/book. We further delimit the material (research paper/book) to be collected as per our scope.
- *Classification context:* We select and define the classification context to be applied in the literature review to structure and classify the material. There are two contexts: the problem context and methodology/approach context.
- *Material evaluation:* The material is analysed and sorted according to the classification context. This allows identification of relevant issues and interpretation of the results. Problem context and related methodology/approaches allow classification of the reviewed literature, which can be derived deductively or inductively.
- *Collecting publications and delimiting the field:* Our literature review focuses upon books, edited volumes and journal articles only. To establish a time span, a starting point was set at 1990. This seems justified, as the beginning of the debate on GrSCM can be traced to this period. Library databases were used where a keyword search using some important keywords such as 'green supply chain', 'remanufacturing',

 

'green purchasing', 'green design', 'industrial ecology', 'industrial ecosystems', 'RL', 'remanufacturing' and 'waste management' were conducted.

To delimit the number of publications, empirical papers mainly addressing firm-level or specific operational issues were excluded from the review. Similarly, highly technical work on topics such as life-cycle assessment, inventory, pollution prevention and disassembly was also excluded from the review. Research with a highly ecological rather than supply chain perspective (green purchasing, industrial ecology and industrial ecosystems) was also excluded. This seems to be justified when considering the objective outlined, which concentrates on integrating environmental thinking into supply-chain management.

We use the published literature from 1990 onwards to go back to other papers by cross-referencing. As the published literature is interlinked to a considerable degree, one paper (stem) leads to others (branches). So, when we pick up one thread, we are able to find others. As references accumulated, we found that some of them were more central and useful than others. We consider such references as seminal papers. These were also found to be generally referenced a number of times in subsequent literature.

Thus, within our defined objective, this work integrates and takes forward the literature on GrSCM since its conceptualization. About 1500 books, articles from journals and edited volumes have been covered. The list of 227 cited references is given at the end.

## Classification Based on Problem Context

We classify the existing GrSCM literature into three broad categories based on the problem context in supply chain design: literature highlighting the importance of GrSCM; literature on green design; and literature on green operations, as shown in Fig. 1. Green design may be looked into from the viewpoint of environment conscious design taking life-cycle assessment of the product/process into account. Similarly, green operations involve all operational aspects related to RL and network design (collection; inspection/sorting; pre-processing; network design), green manufacturing and remanufacturing (reduce; recycle; production planning and scheduling; inventory management; remanufacturing: re-use, product and material recovery) and waste management (source reduction; pollution prevention; disposal). We purposely do not consider literature and practices related to green logistics, as we feel that the issues are more operational than strategic in nature and may not be significant in the supply chain design *per se*. We also do not focus in detail on empirical studies on GrSCM and literature on green purchasing, industrial ecology and industrial ecosystems, as it is delimited by our research design. We focus more on RL as the establishment of efficient and effective RL networks is a prerequisite for efficient and profitable recycling and remanufacturing. We also focus more on mathematical modelling aspects. Both of these have received less attention in the GrSCM literature so far.

The classification is for the purpose of easier understanding of different problem contexts of GrSCM – their interactions and relationships – in order to present a well-defined and clear picture for further study and research. It is not rigid, and there may be many overlaps (for example, *reduce* gets attention not only in *green manufacturing and remanufacturing*, but also elsewhere as in *reverse logistics* and *waste management*; *green design*, too, emphasizes reduced use of virgin material and other resources. Similarly, *green design* should take into account the whole product life-cycle cost, including those during *manufacturing and remanufacturing*, *reverse logistics* and *disposal*. The figure does not take account of all these complex relationships and interactions but presents a simplistic view. Further, we do not show some other relevant aspects and areas such as green purchasing, industrial ecology and industrial ecosystems, as they are delimited by our research design.

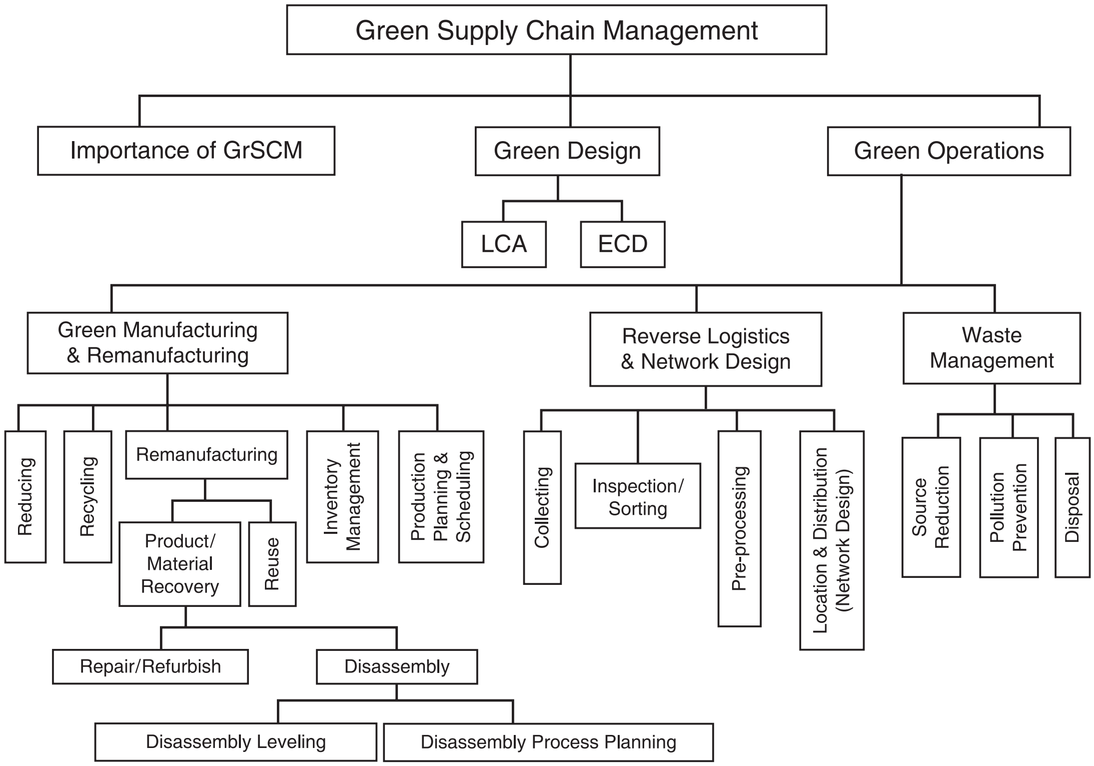


**Figure 1.** Classification based on problem context in supply chain design.

*Importance of GrSCM*

As in any emerging research area, the early literature focuses on the necessity and importance of GrSCM, defines the meaning and scope of various terms and suggests approaches to explore the area further. Fundamentals of greening as a competitive initiative are explained by Porter and van der Linde (1995a,b). Their basic reasoning is that investments in greening can be resource saving, waste eliminating and productivity improving. Three approaches in GrSCM, namely reactive, proactive and value-seeking, are suggested (Kopicki *et al*. 1993; van Hoek 1999). In the reactive approach, companies commit minimal resources to environmental management, start labelling products that are recyclable and use ‘end of pipeline’ initiatives to lower the environmental impact of production. In the proactive approach, they start to pre-empt new environmental laws by realizing a modest resource commitment to initiate the recycling of products and designing green products. In the value-seeking approach, companies integrate environmental activities such as green purchasing and ISO implementation as strategic initiatives into their business strategy.

The perspective then changes from greening as a burden to greening as a potential source of competitive advantage (van Hoek 1999). Owen (1993) and Sarkis (1995) discuss environmentally conscious manufacturing. Friedman (1992), Guide and Wassenhove (2002) and Gupta (1996) discuss the changing role of the environmental manager. Interactions among various stakeholders on integrated GrSCM and advantages that may accrue to them have been described by Gungor and Gupta (1999). At the end of the 1990s, integrating these issues into the mainstream was identified as the future research agenda (Angell and Klassen 1999). In a study linking GrSCM elements and performance measurement, Beamon (1999) advocates for the establishment and implementation of new performance measurement systems. He suggests that the traditional performance measurement structure of the supply chain must be extended to include mechanisms for product recovery (RL).

During the present decade, related and emergent issues such as consideration of stages of the product life cycle during material selection (Kaiser *et al*. 2001), impact of green purchasing on a firm's supplier selection (Zhu and Geng 2001), waste management (Theyel 2001), packaging and regulatory compliance (Min and Galle 2001), greener manufacturing and operations (Sarkis 2001), study of the environmental management system (EMS) implementation practices (Hui *et al*. 2001), selection of environmental performance indicators (Scherpereel *et al*. 2001), relationship between environmental and economic performance of firms (Wagner *et al*. 2001), focus on third-party logistics providers (Krumwiede and Sheu 2002; Meade and Sarkis 2002), overview of management challenges and environmental consequences in reverse manufacturing (White *et al*. 2003) and extended producer responsibility (Spicer and Johnson 2004), including OEM, pooled and third-party take-back, have been taken up by researchers.

Zhu and Sarkis (2004) describe empirical findings on relationships between operational practices and performance among early adopters of green supply-chain management, while Bowen *et al*. (2001) seek to resolve the apparent paradox between the desirability and the actual slow implementation of GrSCM in practice. Chouinard *et al*. (2005) deal with problems related to the integration of RL activities within a supply chain information system. Nagurney and Toyasaki (2005) develop a multi-tiered network equilibrium framework for e-cycling, while Sheu *et al*. (2005) present an optimization-based integrated logistics operational model for GrSCM. Ravi *et al*. (2005) analyse alternatives in RL, Mukhopadhyay and Setoputro (2005) derive a number of managerial guidelines for return policies of build-to-order products, while Srivastava and Srivastava (2006) suggest ways to manage end-of-life product returns. Kainuma and Tawara (2006) extend the range of supply chain to include re-use and recycling throughout the life cycle of product and services and propose a 'lean and green' multiple utility theory approach to evaluate green supply chain performance from an environmental performance point of view.

### *Green Design*

The literature emphasizes both environmentally conscious design (ECD) and life-cycle assessment/analysis (LCA) of the product. The aim is to develop an understanding of how design decisions affect a product's environmental compatibility (Glantschnig 1994; Navin-Chandra 1991). Madu *et al*. (2002) present a very useful hierarchic framework for environmentally conscious design.

Sufficient literature exists on design for material and product recovery (Barros *et al*. 1998; Ferrer 1997a,b, 2001; Gatenby and Foo 1990; Guide and van Wassenhove 2001; Krikke *et al*. 1999a,b; Louwers *et al*. 1999; Melissen and de Ron 1999; Seliger *et al*. 1994). Boothroyd and Alting (1992), Krikke *et al*. (1999a,b, 2003), Kroll *et al*. (1996), Laperiere and ElMaraghy (1992), Lee *et al*. (1995), Moore *et al*. (1998, 2001), Scheuring *et al*. (1994), Seliger *et al*. (1994) and Taleb and Gupta (1997) discuss design for disassembly, whereas Gupta and Sharma (1995), He *et al*. (2004), Jahre (1995), Jayaraman *et al*. (1999), Johnson (1998) and Sarkis and Cordeiro (2001) deal with design for waste minimization.

A common approach is to replace a potentially hazardous material or process by one that appears less problematic. This seemingly reasonable action can sometimes be undesirable if it results in the rapid depletion of a potentially scarce resource or increased extraction of other environmentally problematic materials. Several examples of such equivocal proposals are presented by Graedel (2002).

Azzone and Noci (1996) suggest an integrated approach for measuring the environmental performance of new products, while Arena *et al*. (2003) assess the environmental performance of alternative solid waste management options that could be used. Design under legislation and regulations have been considered by Barros *et al*. (1998), Bellmann and Khare (1999, 2000), Fleischmann *et al*. (2001) and Das (2002), while Bras and McIntosh (1999), Guide and Srivastava (1997a, 1997b, 1998), Guide *et al*. (1999a, 2000a), Inderfurth *et al*. (2001) and Ishii *et al*. (1995) deal with design for remanufacturing. Bellmann and Khare (2000) and Henshaw (1994) take up design for recycling issues, while Krikke *et al*. (1999a) consider better choices of material.

Life-cycle assessment/analysis is described as a process for assessing and evaluating the environmental, occupational health and resource-related consequences of a product through all phases of its life, i.e. extracting and processing raw materials, production, transportation and distribution, use, remanufacturing, recycling and final disposal (Gungor and Gupta 1999). The scope of LCA involves tracking all material and energy flows of a product from the retrieval of its raw materials out of the environment to the disposal of the product back into the environment (Arena *et al*. 2003; Miettinen and Hämäläinen 1997; Tibben-Lembke 2002). Attempts have also been made to develop operational models to help companies understand, monitor and assess life-cycle management (Sanchez *et al*. 2004).

### *Green Operations*

Some of the key challenges of GrSCM such as integrating remanufacturing with internal operations (Ferrer and Whybark 2001), understanding the effects of competition among remanufacturers (Majumder and Groenevelt 2001), integrating product design, product take-back and supply chain incentives (Guide and van Wassenhove 2001, 2002), integrating remanufacturing and RL with supply chain design (Chouinard *et al*. 2005; Fleischmann *et al*. 2001; Goggin and Browne 2000; Savaskan *et al*. 2004) are posed in this area.

*Green manufacturing and remanufacturing*. This is a very important area within green operations. The techniques for minimum energy and resource consumption for flow systems in order to reduce the use of virgin materials are based on three fields of study: pinch analysis (Linnhoff 1993), industrial energy (Boustead 1979) and energy and life-cycle analysis (Lee *et al*. 1995).

Recycling, mainly driven by economic and regulatory factors, is performed to retrieve the material content of used and non-functioning products. Logistics represent up to 95% of total costs (Stock 1998) in recycling. Economically driven recycling finds its application in automobiles (Bellmann and Khare 1999) and the consumer electronics industry (de Fazio *et al*. 1997; Johnson 1998). Regulatory electronics recycling is also practised (Krikke *et al*. 1999a,b; Nagel and Meyer 1999; Pohlen and Farris 1992).

Hoshino *et al*. (1995) define remanufacturing as recycling-integrated manufacturing. Industries that apply remanufacturing typically include automobiles, electronics and tyres. Product recovery refers to the broad set of activities designed to reclaim value from a product at the end of its useful life. Pugh (1993) uses mathematical models in evaluating resource recovery options. Various authors categorize and classify the recovery process differently. Johnson and Wang (1995) define it as a combination of remanufacture, re-use and recycle, whereas Thierry *et al*. (1995) divide recovery into repair, refurbish, remanufacture, cannibalize and recycle. Melissen and de Ron (1999) define recovery practices and provide relevant definitions and terminology. A model for evaluating recovery strategies for the product without violating the physical and economical feasibility constraints is proposed by Krikke *et al*. (1998), which has been further modified and updated (Fleischmann *et al.* 2001, 2002; Goldsby and Closs 2000; Inderfurth *et al.* 2001; Krikke *et al.* 2003).

Automobile, electronic and paper recycling are the most common examples of product recovery (Ashayeri *et al.* 1996; Barthorpe 1995; Ferrer 1997a; Fleischmann *et al.* 1997; Isaacs and Gupta 1997; Jayaraman *et al.* 1999; Krikke *et al.* 1998, 1999a,b; Lenox *et al.* 2000; Linton and Johnson 2000; Nasr 1997; Shrivastava 1995; Tan *et al.* 2002).

The purpose of repair is to return used products to 'working order'. The quality of repaired products is generally lower than the quality of new products. The purpose of refurbishing is to bring used products up to a specified quality. Analysis of remanufacturing facilities for household appliances and automotive parts by Sundin and Bras (2005) reveals that cleaning and repairing are the most critical steps in the remanufacturing process. Amini *et al.* (2005) find that RL operations and the supply chains they support are significantly more complex than traditional manufacturing supply chains. They present a case study of a major international medical diagnostics manufacturer to illustrate how a RL operation for a repair service supply chain was designed for both effectiveness and profitability by achieving a rapid cycle time goal for repair service, while minimizing total capital and operational costs. Most remanufacturing literature also deals with repair/refurbish (Ashayeri *et al.* 1996; Ayres *et al.* 1997; Craig Smith *et al.* 1996; de Ron and Penev 1995; Dowlatshahi 2000; Ferrer 1997a,b, 2001; Guide and Srivastava 1997c; Guide *et al.* 2000b; Gupta 1993; Linton and Johnson 2000; Thierry *et al.* 1995).

Disassembly is a systematic method of separating a product into its constituent parts, components, subassemblies or other groupings (Taleb and Gupta 1997). It may involve dismantling and/or demolition and/or reprocessing. Tani and Güner (1997) compare assembly and disassembly and describe the identifiers of the disassembly process. An important aspect of disassembly is to find efficient disassembly process scheduling (Dowie 1994; Gungor and Gupta 1998; Gupta and Taleb 1994).

Re-use of products and materials is not a new phenomenon. Thierry *et al.* (1995) describe four forms of re-use – direct re-use, repair, recycling, and remanufacturing. Re-use may be in the form of assemblies (Ayres *et al.* 1997; Dekker *et al.* 2004; Ferrer 1997a, 2001; Krikke *et al.* 1999a; Kriwet *et al.* 1995) or subassemblies and components (Ayres *et al.* 1997; Ferrer 1997a, 2001; Krikke *et al.* 1999a; Kriwet *et al.* 1995). It may also be re-use of materials (Ferrer 1997a, 2001; Fleischmann *et al.* 2001; Krikke *et al.* 1999a; Louwers *et al.* 1999). Linton and Johnson (2000) describe a decision support system for re-use and remanufacturing.

Traditional production planning and scheduling methods have limited applicability to remanufacturing systems. Guide and Srivastava (1997c) list the factors which induce complexity in such systems. Guide *et al.* (1999a) carry out a survey and evaluate research in various decision-making areas of production planning and control for remanufacturing. Fleischmann *et al.* (1997) give an excellent review of the re-use of products and materials from an operations research (OR) perspective, whereas Guide *et al.* (2003) discuss building contingency plans in such scenarios. Guide and Pentico (2003) develop a hierarchical decision model for remanufacturing and re-use, while Guide *et al.* (2005) analyse the performance of static priority rules for a remanufacturing shop that handles two remanufacturable products.

Most inventory models consider three types of stocked items: non-serviceable items, i.e. returned items that are not yet remanufactured, remanufactured items and manufactured items. Deterministic models, where the return and demand rates are known a priori also exist (Richter 1996; Richter and Dobos 1999; Richter and Sombrutzki 2000; Richter and Weber 2001). However, stochastic models, where the return and demand rates are probabilistic, provide better understanding of the inventory system (van der Laan *et al.* 1999b).

Both periodic and continuous review models have been developed. Examples of periodic review models include: a model in which returned products can be re-used directly (Ferrer 1997a); a model with a holding cost (Teunter *et al.* 2000); a model with variable set-up numbers (Richter 1996); and models considering the effects of non-zero lead-times (Inderfurth and van der Laan 2001; Kiesmüller and Scherer 2003; van der Laan and Salomon 1997). Among continuous review models, Heyman (1977) finds an optimal balance between inventory holding cost and production cost. Muckstadt and Isaac (1981) develop a model for a remanufacturing system with non-zero lead times and a control policy with the traditional ($s$, $Q$) rule, while van der Laan *et al.* (1996b) present a different approximation method. van der Laan *et al.* (1999a) also develop push and pull strategies for joint production and inventory for a system using both new and recovered parts. Minner (2003) discusses RL inventory models in detail.

*Reverse logistics and network design.* Reverse logistics activities differ from those of traditional logistics (Carter and Ellram 1998). Reverse logistics networks have some generic characteristics related to the coordination requirement of two markets, supply uncertainty, returns disposition decisions, postponement and speculation (Blumberg 1999; Fleischmann *et al.* 2000; Hess and Meyhew 1997; Jahre 1995; Krikke *et al.* 1999a, 1999b; Lambert and Stock 1993; Yalabik *et al.* 2005). As a result, they affect network design to a considerable extent.

Collection is the first stage in the recovery process in which product types are selected and products are located, collected and transported to facilities for remanufacturing. Used products originate from multiple sources and are brought to the product recovery facility in a converging process (Krikke *et al.* 1998).

Inspection/sorting illustrates the need for skill in the sorting of used products (Ferrer and Whybark 2000). This may be carried out either at the point/time of collection itself or afterwards (at collection points or at remanufacturing facilities). Cairncross (1992) suggests that collection schemes can be classified according to whether materials are separated by the consumer (i.e. separation at source) or centralized (i.e. mixed waste processed).

The need for environmentally responsible logistics systems is highlighted by Wu and Dunn (1995). The importance of RL programmes and the process of their development and implementation have also been described in the literature (Poist 2000; Stock *et al.* 2002). Redesigning logistics networks to accommodate product returns and remanufacturing and re-use of such parts and components can often be profitable and is assuming greater importance in business as well as in research (Tibben-Lembke 2002). The physical location of facilities and transportation links need to be chosen to convey used products from their former users to a producer and to future markets again (Fleischmann *et al.* 2001).

Companies need to realize the hidden value in RL and start to focus in this area (Mollenkopf and Closs 2005). They need to understand the financial impact of RL strategies. Srivastava and Srivastava (2005) develop a hierarchical decision-making framework to find the feasibility of profit-driven RL networks. They find RL activities profitable for their select category of products. Nowadays, information and communication technologies (ICT) are likely to play a key role in the co-ordination and integration of GrSCM activities (Dekker *et al.* 2004). Problems related to the integration of RL activities within an organization have been dealt by Chouinard *et al.* (2005), while Daugherty *et al.* (2005) find that resource commitment to information technology leads to superior RL performance.

For traditional ‘forward logistics’ environments, quantitative approaches such as mixed integer linear programming (MILP) models (Mirchandani and Francis 1989) are readily available; however, a standard set of models is yet to be established for reverse networks. A survey by Fleischmann *et al.* (2000) compares nine case studies on recovery networks in different industries. These include carpet recycling (Louwers *et al.* 1999), electronics remanufacturing (Jayaraman *et al.* 1999; Krikke *et al.* 1998), reusable packages (Kroon and Vrijens 1995), sand recycling from demolition waste (Barros *et al.* 1998) and recycling of by-products from steel production (Spengler *et al.* 1997). They discuss the applicability of traditional forward approaches and examine the resulting network structure in different contexts.

In recent years, a lot of work related to quantitative approaches in RL has been published. Shih (2001) discusses in detail the RL system planning for recycling electrical appliances and computers in Taiwan. Hu *et al.* (2002) present a cost-minimization model for a multi-time-step, multi-type hazardous-waste RL system. They present application cases to demonstrate the feasibility of their proposed approach. Nagurney and Toyasaki (2005) develop an integrated framework for modelling the electronic waste RL network which includes recycling, while the framework of Srivastava and Srivastava (2005) incorporates three types of rework facilities. Ravi *et al.* (2005) use analytical network process (ANP) and balanced score card for analysing RL alternatives for end-of-life computers. Listes and Dekker (2005) present a stochastic programming-based approach by which a deterministic location model for product recovery network design may be extended to account explicitly for uncertainties. They apply it to a representative real case study on recycling sand from demolition waste in the Netherlands. Their interpretation of the results gives useful insights into decision-making under uncertainty in a RL context. Mostard and Teunter (2006) carry out a case study to derive a simple closed-form equation. They determine the optimal order quantity given the demand distribution, the probability that a sold product is returned and all relevant revenues and costs for a single period model. Min *et al.* (2006) determine the number and location of centralized return centres using a non-linear mixed-integer programming model and a genetic algorithm that solves the RL problem involving product returns.

*Waste management.* Caruso *et al.* (1993) model a solid waste management system (including collection, transportation, incineration, composting, recycling and disposal) using a multi-objective location-allocation model supported by planning heuristics. A decision support system, for urban waste management in a regional area, for evaluating general policies for collection and for identifying areas suitable for locating waste treatment and disposal plants is presented by Haastrup *et al.* (1998). Giannikos (1998) uses a multi-objective model for locating disposal or treatment facilities and transporting waste along the links of a transportation network. Bloemhof-Ruwaard *et al.* (1996a,b), Richter (1996) and Richter and Dobos (1999) use other mathematical modelling techniques for waste management. Mourao and Amado (2005) describe a heuristics for a refuse collection application.

The source-reduction/pollution-prevention (SR/P2) strategy focuses on ‘preventing’ pollution at the source (in products as well as manufacturing processes) rather than ‘removing’ it after it has been created. It is the concept of preventing the creation of waste rather than managing it after it is generated (Gupta and Sharma 1995). The term ‘pollution prevention’ was coined in 1976 by the 3M Company. Dunn and El-Halwagi (1993) develop a methodology for the optimal design of recycle/re-use process networks to minimize the emission of hydrogen sulphide from pulp and paper plants. Zhang *et al.* (1997) list four preferences in their ‘waste management hierarchy’. An example of pollution prevention with growing public visibility and product design in the case of internal combustion engines is presented by Hanna and Newman (1995).

Disposal has always been a compelling problem and has led to green consciousness. In the case of GrSCM, efforts to minimize disposal have been the focus. Bellman and Khare (1999) suggest reducing the economic and environment-related costs of automobile shredding residue (ASR). Various waste management and inventory models take disposal costs into account. Richter and Dobos (1999) analyse economic order quantity (EOQ) repair along with waste disposal with integer set-up numbers. Louwers *et al*. (1999) include transport costs and waste disposal in their model. Richter and Weber (2001) extend the reverse Wagner/Whitin model to the case with additional variable manufacturing and remanufacturing cost. Teunter and Vlachos (2002) focus on the necessity of a disposal option for remanufacturable items.

Recent work in the area is related mainly to the study of EMS implementation practices (Hui *et al*. 2001), total product system concept (Warren *et al*. 2001), life-cycle assessment and management (Arena *et al*. 2003; Sanchez *et al*. 2004), management challenges and environmental consequences in reverse manufacturing for the computer industry (White *et al*. 2003), a generic functional model for modelling the material and flow of waste from both a physical and cumulative cost perspective (Hicks *et al*. 2004), revaluing the hierarchy of paper waste management policies in a dynamic general equilibrium model (Samakovlis 2004), policy evaluations under environmental constraints using a computable general equilibrium model (Masui 2005) and a case study on waste management in a large complex health care organization in UK (Woolridge *et al*. 2005).

## Classification Based on Methodology/ Approach

The literature on GrSCM may also be classified on the basis of methodology and approach used into: thought papers and perspectives; frameworks and approaches; empirical studies; mathematical modelling approaches; and reviews. This helps us to understand GrSCM from a different perspective from the problem context described earlier. Thought papers and perspectives as well as frameworks- and approaches-related articles have been sufficiently covered in ‘Importance of GrSCM’. Similarly, review papers have been covered in the Introduction, and are not covered further. Therefore, empirical studies and mathematical modelling approaches are covered here.

### *Empirical Studies*

Empirical research studies include case research, field surveys and interviews, field experiments, mail surveys, laboratory experiments and game simulations. Several empirical studies in the area of GrSCM have been published. They consist mainly of case studies and surveys. Most case studies deal with green design (product and logistics) and green operations (remanufacturing, recycling, RL, etc.). The IBM product recovery management programme is covered by Roy and Whelan (1992) and Thierry *et al*. (1995). The product recovery management system of a photocopier manufacturer for its used products is discussed by Thierry *et al*. (1995). They look at the specific characteristics of repair, cannibalization, recycling and remanufacturing operations. Johnson (1998) presents six caselets on purchasing practices while discussing managing value in RL systems. Lenox *et al*. (2000) carry out an assessment of design-for-environment practices in leading US electronics firms, including AT&T, Xerox, IBM and DEC.

Goldsby and Closs (2000) describe the case study of a Michigan beverage distributor and retailer who collects empty beverage containers for recycling purposes. They discuss the re-engineering of supply chain-wide processes using activity-based costing (ABC). Duhaime *et al*. (2000) describe value analysis and optimization of reusable containers at Canada Post. Ritchie *et al*. (2000) discuss the RL supply chain of a UK pharmacy. Warren *et al*. (2001) describe a total product system concept for a highly customized build-to-order product system. Scherpereel *et al*. (2001) use a case study to establish the relevance of selecting environmental performance indicators, while Khoo *et al*. (2001) present a case study of a supply chain concerned with the distribution of aluminium. They use simulation to create a green supply chain. Tan *et al.* (2002) take on a computer company in the Asia-Pacific region. De Koster *et al.* (2002) carry out an exploratory study with nine retailer warehouses regarding returns handling. Review of a number of case studies in RL is provided by de Brito *et al.* (2003). Flapper *et al.* (2005) address a number of case studies on closed-loop supply chains covering pharmaceuticals, electronics, breweries, containers, mail orders, tyres, photocopiers, cars, computers, cosmetics and consumer durables.

A large number of articles using survey-based empirical methods have also been published in the area of GrSCM. We mention a few important ones here. Lund (1984) carried out a detailed survey of remanufacturing practices in the US, while Guide and Srivastava (1998) carried out a simulation in US navy depots. Blumberg (1999) conducted in-depth surveys of logistics and purchasing executives in more than 400 firms, while Guide (2000) carried out surveys on production planning and control in remanufacturing; Zhu and Sarkis (2004) carried out a survey of 186 respondents in Chinese manufacturing enterprises, while recently, Daugherty *et al.* (2005) conducted a survey in automobile aftermarket.

### *Mathematical Modelling*

A variety of tools and techniques have been used for problem formulation. Linear programming (Barros *et al.* 1998; Bloemhof-Ruwaard *et al.* 1996a,b; Crainic *et al.* 1993; Fleischmann *et al.* 2001; Haas and Murphy 2002; Hu *et al.* 2002; Kroon and Vrijens 1995; Jayaraman and Srivastava 1995; Jayaraman *et al.* 1998, 1999; Louwers *et al.* 1999; Marin and Pelegrin 1998; Ritchie *et al.* 2000, Srivastava and Srivastava 2005) is the most common technique used for problem formulation, followed by dynamic programming (Inderfurth and van der Laan 2001; Inderfurth *et al.* 2001; Kelle and Silver 1989; Kiesmüller and Scherer 2003; Klausner and Hendrickson 2000; Krikke *et al.* 1998, 1999a; Richter 1996; Richter and Sombrutzki 2000; Richter and Weber 2001). Non-linear programming (Jayaraman *et al.* 1998; Richter and Dobos 1999; Sarkis and Cordeiro 2001) has also been used. Nagurney and Toyasaki (2005) use a network equilibrium model to establish variational inequality formulation. Mostard and Teunter (2006) derive a simple closed-form equation that determines the optimal order quantity, given the demand distribution, the probability that a sold product is returned and all relevant revenues and costs. Even pure algebraic equations (Ashayeri *et al.* 1996; Mukhopadhayay and Setoputro 2005; Richter 1996; Richter and Dobos 1999) are used in many papers.

Markov chains (Fleischmann *et al.* 2002; Gupta 1993; Kiesmüller and van der Laan 2001; van der Laan *et al.* 1996a,b, 1999a,b; van der Laan and Salomon 1997) have been used in inventory-related problem formulations. Guide *et al.* (2005) and van der Laan *et al.* (1996b) use queuing. Moore *et al.* (1998, 2001) use PetriNets. Ferrer and Ayres (2000) use an input–output model, whereas Majumder and Groenevelt (2001) use game theory to formulate their problem. Marx-Gomez *et al.* (2002) use fuzzy and neuro-fuzzy to forecast scrapped products returns. Analytical network process is used by Sarkis (1998, 1999) and Ravi *et al.* (2005), while analytical hierarchy process (AHP) is used by Madu *et al.* (2002).

Computer programs are often used for data input. Louwers *et al.* (1999) use Fortran, Johnson and Wang (1995) use C++, while Spender *et al.* (1997) use TuboPascal and dBase. Barros *et al.* (1998), Krikke *et al.* (1998) and Louwers *et al.* (1999) use spreadsheets. Minner (2001) formulates a combinatorial optimization problem, while Ferrer (1997a), Haas and Murphy (2002) and Sarkis and Cordeiro (2001) formulate regression equations.

For solving LP formulations, LP solvers such as LINDO (Spengler *et al.* 1997) and GAMS (Barros *et al.* 1998; Jayaraman *et al.* 1998, 1999; Srivastava and Srivastava 2005) have been used. Heuristics (Barros *et al.* 1998; Bloemhof-Ruwaard *et al.* 1996a; Gupta 1993; Jayaraman *et al.* 2003; Marin and Pelegrin 1998; Mourao and Amado 2005; Richter and

 

Sombrutzki 2000; Richter and Weber 2001) are widely used to solve complex problems. Ferrer and Ayres (2000) use an input–output model, whereas Marx-Gomez *et al*. (2002) use fuzzy and neuro-fuzzy methods for solution. PetriNets are used by Moore *et al*. (1998, 2001).

Haas and Murphy (2002), Sarkis (1999) and Sarkis and Cordeiro (2001) use data envelopment analysis (DEA) for problem formulation, solution and analysis. Spengler *et al*. (1997) use branch-and-bound as well as modified Bender's decomposition for solution, while Listes and Dekker (2005) assign priority orders to integer variables for branching. Lagrange decomposition is used by Bloemhof-Ruwaard *et al*. (1996a,b) and Marin and Pelegrin (1998). Grid-search is used by Inderfurth *et al*. (2001). Various meta-heuristics such as genetic algorithm, tabu search and simulated annealing are used by Minner (2001). Recently, Min *et al*. (2006) use a genetic algorithm approach to develop a multi-echelon RL network for product returns. Simple enumeration techniques (Inderfurth *et al*. 2001; van der Laan and Salomón 1997; van der Laan *et al*. 1996a, 1999b) are sometimes used for solution. Software tools such as EDS R-Log (Nagel and Meyer 1999), EDIT (Johnson and Wang 1995) and MATLAB (Guide *et al*. 2005) have also been used.

Simulation (Ashayeri *et al*. 1996; Guide and Srivastava 1997a,b, 1998; Guide *et al*. 1996, 1997a,b,c, 1999b, 2000b; Haas and Murphy 2002; Hirsch *et al*. 1998; Khoo *et al*. 2001; Linton and Johnson 2000; Marx-Gomez *et al*. 2002; Vlachos and Tagaras 2001) is commonly used for scenario generation and analysis. Srivastava and Srivastava (2006) use system dynamics simulation for estimating end-of-the-life returns. Fleischmann *et al*. (2001) and Swenseth and Godfrey (2002) carry out parametric analysis. Scenario analysis is carried out by Linton and Johnson (2000), while Klausner and Hendrickson (2000) and van der Laan *et al*. (1999a,b) carry out sensitivity analysis. Majumder and Groenevelt (2001) use game theory for analysis and interpretation, while Haas and Murphy (2002), Sarkis and Cordeiro (2001) and Zhu and Sarkis (2004) carry out regression analysis.

Chinander (2001), Guide *et al*. (1996, 1997a), Haas and Murphy (2002) and Sarkis and Cordeiro (2001) use descriptive statistics. Chinander (2001), Guide (1997), Guide and Srivastava (1997a,b), Guide *et al*. (1997a,b,c, 2000a) and Swenseth and Godfrey (2002) carry out ANOVA extensively.

A variety of the above tools and techniques have been used for problem formulation, solution and analysis in papers published in edited books such as Dekker *et al*. (2004), Dyckhoff *et al*. (2003), Fleishmann and Klose (2005) and Klose *et al*. (2002).

### *Mapping of Tools/Techniques Used* vis-à-vis *the Contexts of GrSCM*

We map various mathematical tools/techniques *vis-à-vis* the contexts of GrSCM. This depends much on the methodology used and also helps us to gauge their applicability/suitability. This is shown in Table 1. The cited reference numbers correspond to the serial numbers in the Reference list. It is worth noting that the particular tool/technique used depends on a host of factors, such as the nature of the problem, the nature and availability of data, familiarity with the technique, compatibility between the analysis and solution tools/techniques envisaged, previous related works and the wish to use new emergent tools/techniques in operations research/decision science (OR/DS).

Very few models have been used for integrated GrSCM. AHP/ANP, Regression, DEA and descriptive statistics (based on surveys/interviews) have been tried. Linear programming, non-linear programming (NLP) and MILP have also been suggested in books but have not been used to a great extent. Green design has seen very little application in terms of mathematical tools, techniques and methodologies. Lately, LP, MILP formulations and software packages and spreadsheets for solution have been used.

Green manufacturing and remanufacturing have used mathematical models, tools and

**Table 1.** Mapping of mathematical tools/techniques used *vis-à-vis* the contexts of GrSCM[a]

| | Context of GrSCM | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Green Design | | Green operations | | | | |
| | | | | Green manufacturing & remanufacturing | | | Reverse logistics | Waste management |
| Mathematical tools/techniques | Importance of GrSCM | LCA | ECD | Reducing/ recycling/ remfg | Inventory management | PP&S | | |
| Algebraic | | | | | 5, 54, 66, 68, 94, 109, 116, 118, 160, 173, 174, 202, 206, 207 | 44, 66, 72, 73, 74, 78 | 158, 174 | 161, 173, 211 |
| AHP/ANP | 184 | | | 139 | | | 172 | |
| Computer programs | | | | 18, 121, 156, 157, 195 | 65, 68, 84, 101, 106, 115, 162, 174 | 52, 63, 65, 66, 71, 72, 74, 76, 78, 101, 106 | 105, 107, 137, 162, 195 | |
| Descriptive statistics/ANOVA | 25, 184 | | | 25, 42, 53 | 65, 68, 202, 207 | 63, 65, 66, 71, 72, 73, 78 | 40, 53, 88 | 186 |
| DEA | 184, 186 | | | | | | 88 | 186 |
| Dynamic programming | | | | 100, 115, 121 | 100, 101, 113, 115, 173, 175 | 101, 175, 176 | 100, 113 | 173 |
| Fuzzy/neuro-fuzzy | | | | 143 | | | | |
| Game theory | | | | | | | 140 | |
| Heuristics | | 16 | 16 | 16, 150, 157, 195 | 66, 84, 100, 115, 157, 213 | 44, 175, 176 | 8, 108, 142, 195 | 15 |
| I/O Model | 45 | | | | | | | |
| LP and MILP | 186 | 16 | 122, 127 | 53, 122, 195 | 113 | | 8, 28, 35, 53, 105, 107, 108, 113, 137 | 15, 16, 24, 58, 186 |
| Markov chain/queuing | | | | | 54, 84, 100, 116, 211, 212, 213, 215 | 211 | | |
| Metaheuristics | | | | | 100, 152, 206, 215 | | 151 | |
| Non-linear programming | 186 | | | | 66, 106, 174 | 106 | | 186 |
| Petrinet | | | | | | | 156, 157 | |
| Regression | 117, 186, 227 | | | 42, 117 | | | 88 | 186 |

**Table 1.** *Continued*

| | Context of GrSCM | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Green Design | | Green operations | | | | |
| | | | | Green manufacturing & remanufacturing | | | Reverse logistics | Waste management |
| Mathematical tools/techniques | Importance of GrSCM | LCA | ECD | Reducing/ recycling/ remfg | Inventory management | PP&S | | |
| Scenario/sensitivity analysis | | | | 118, 134 | 211, 215 | 211 | 107, 118 | |
| Simulation | | | | 134, 143 | 5, 65, 68, 206, 207, 217 | 63, 65, 66, 67, 71, 72, 74 | 88, 96, 198 | 206 |
| Software and spreadsheets | 162 | | 122 | 109, 122, 156, 157 | 40, 54, 65, 66, 68, 100, 101, 106, 207, 211, 213, 215 | 44, 63, 65, 66, 72, 73, 74, 76, 78, 80, 87, 101 | 8, 50, 88, 105, 107, 119, 137, 162, 195 | 211 |

[a]Numbers correspond to cited references.

techniques to a much larger extent. MILP, simulation, computer programming, software packages, spreadsheets and dynamic programming have been used extensively. Other traditional tools and techniques such as simulation, Markov chains, algebraic equations, ANOVA, heuristics, meta-heuristics and regression have also been used. Fuzzy reasoning, neuro-fuzzy and game theory too have been tried.

In production planning and control, the dominant approach is to formulate problems using priority rules followed by simulation for generating descriptive statistics for analysis. Computer programming and software packages have been used for input, interface and computations. Dynamic programming is used when inventory control, waste disposal and cost considerations are taken into account. In inventory management, EOQ-type algebraic formulae are dominant.

Reverse logistics models concentrate on network design problems and borrow heavily from traditional location and layout models. Computer programming and software tools are being increasingly used. The problems are generally formulated as LP, NLP and MILP. Dynamic programming has been used in RL and remanufacturing systems. The models for waste management are generally traditional models incorporating disposal options.

## Conclusion

GrSCM can reduce the ecological impact of industrial activity without sacrificing quality, cost, reliability, performance or energy utilization efficiency. It involves a paradigm shift, going from end-of-pipe control to meet environmental regulations to the situation of not only minimizing ecological damage, but also leading to overall economic profit. The area throws various challenges to practitioners, academicians and researchers.

We present a state-of-the-art literature review of GrSCM integrating the whole gamut of activities in the area. Our literature review highlights the ongoing integration process in GrSCM. We find that the depth of research in various categories has been different. Many specific empirical studies have been carried out, and categories such as remanufacturing have been studied to a great depth. Even, within remanufacturing *disassembly* has been studied to a very detailed level. Of late, other categories such as RL have started getting more attention. We focus more on relatively unexplored categories, as they offer potential for further exploration and research.

Our classifications will help academicians, practitioners and researchers to understand integrated GrSCM from a wider perspective. Based on our problem context classification and scope for future practice and research, an evolutionary timeline has been prepared taking into account all the relevant and seminal papers published in the area of GrSCM. The same is depicted in Figure 2. Our classifications along with timeline and cited references may be used as a broad frame of reference to develop concepts and models that facilitate managers and other stakeholders trying to integrate environmentally sound choices into supply-chain management. Practitioners can also gain good insight into real-life problems and how some companies have tried to address them by referring to the empirical studies. This can serve as a platform for them to adapt and develop their own initiatives and practices.

Research in GrSCM to date may be considered compartmentalized into content areas drawn from operations strategy. The primary areas of emphasis have been quality, operations strategy, supply-chain management, product and process technologies, which are collectively beginning to contribute to a more systematic knowledge base. It is reasonable to expect that these research areas will continue to hold the greatest promise for advance in the short term. However, more integrative contributions are needed in the longer term, including intra- and inter-firm diffusion of best practices, green technology transfer and environmental performance measurement.

One of the biggest challenges facing the field of GrSCM is extending the historical

 

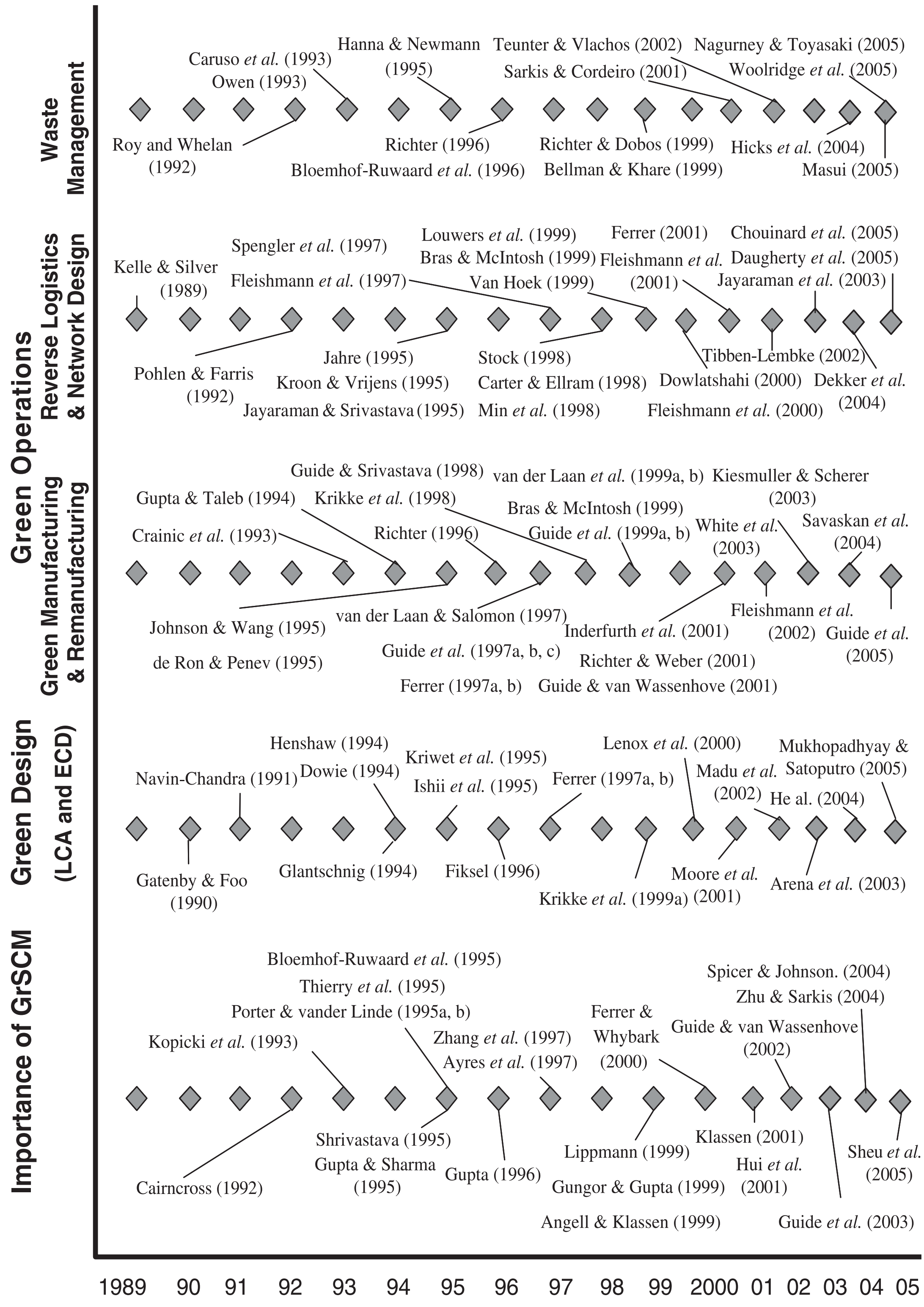


**Figure 2.** GrSCM's evolutionary timeline.

'common wisdom' about managing operations. Much research, management education and many practical applications have focused on buffering the operations function from external influences, including the natural environment, in order to improve efficiencies, reduce cost and increase quality. When the natural environment is considered, it is typically recognized or modelled as an external constraint, requiring operations to work within prescribed limits. Once this basic assumption is relaxed, a fundamental question arises about how to pursue research on green issues in operations: should this be considered a separate research stream with its own strategic framework or should green issues be integrated into existing operations management research frameworks and areas? While the complexity of green issues might favour the former approach, the greatest contributions can be achieved by pursuing opportunities within a more integrative framework.

The inherent complexity of environmental issues – their multiple stakeholders, uncertain implications for competitiveness and international importance – present significant challenges to researchers. Much research is needed to support the evolution in business practice towards greening along the entire supply chain. Effective approaches for data-sharing across the supply chain need to be developed. Researchers might take advantage of the emergent ICT for more effective collaboration and cooperation. Although research on intelligent GrSCM is still in its infancy, there is no doubt that this will be the hottest topic in the near future. Artificial intelligence techniques, including knowledge-based systems, fuzzy systems and neural networks, are expected to play a significant role in research and development.

Although many empirical studies (case studies, survey-based empirical methods, etc.) have been carried out, they have not dealt with each and every aspect of GrSCM. Detailed empirical case studies need to be carried out in such areas as organizational commitment to GrSCM at the firm level, selection of returns and rework facilities in alignment with competitive priorities, the influence of remanufacturing on the supply chain of a particular firm and how service quality and recovery strategies influence consumer behaviour and vice versa. Scope also exists to carry out empirical studies to find how the regulatory environment, economic considerations and level of commitment influence the volume of returns. Similarly, studies to find how various uncertainties influence channel relationships within GrSCM are also desired.

Disassembly is an important component of remanufacturing which is currently labour-intensive and expensive. Thus, it becomes very important to develop automated disassembly systems which may eliminate the drawbacks of manual disassembly, i.e. lengthy disassembly completion time, human exposure to possible hazardous materials and by-products, expensive labour use, etc. Products will have to be designed as technical systems based on a strictly modular master plan, with ease of maintenance and ease of out-of-sequence disassembly by workers or robots.

The product life cycle has been studied in great depth. However, more research is needed in understanding RL and its connection to the product life cycle. An important area for investigation would be to see how, in practice, RL activities do change over the life of a particular product. More information is needed about returns levels. At a basic level, there is little published information on product return levels by product type. More study of the impact of marketing on returns is needed. In general, theory and models need to be developed and consolidated to establish the relationship between new product sales and returns rates. Research is needed into how companies should process, store and dispose of returned goods. Much more research is needed in understanding secondary markets, and how companies should best sell unwanted products. In addition to traditional brokers, many firms are now selling this material through online and traditional auctions.

 

Although the current development in GrSCM research is encouraging, it is being conducted in clusters (mainly Europe and North America). It is, therefore, necessary that interactions between these research efforts be studied in order to develop interrelationships and determine the global effect of this field. Literature on integrated business strategy (comprising product and process design, manufacturing, marketing, RL and regulatory compliance) in the context of GrSCM is at the level of thought papers and frameworks only. More research is needed in determining how companies should best select products for each outlet to maximize returns, while still protecting brand integrity. Further, GrSCM deserves special attention in terms of resource commitment within a firm/ supply chain.

GrSCM seems a promising area for trying out new operations research techniques and for using traditional techniques for overall GrSCM Design. The problem is complex and challenging, as a very large number of parameters, decision variables and constraints are involved along with a large number of estimation requirements such as those of expected demands and returns and cost criteria associated with each decision. Perhaps, a combination of various tools and techniques (both traditional and new) may be combined for the purpose of formulation, approximation, analysis and solution of such complex problems.

Many changes in concepts, technologies and players can be expected in the years ahead. We can expect a steady growth in the area of recovery/re-use/remanufacture of items and a quantum leap in the area of RL. Moreover, the rules that govern the attractiveness of recovery/re-use of products, materials and components are undergoing changes at the local, state, national and global levels. Major producers of virgin items, many of whom have not been particularly active in various Rs, are likely to increase their activities in response to public, regulatory and market forces. In many cases, they will probably work in partnership or even joint ventures with entrepreneurial firms.

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