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ORIGINAL PAPER

Estimating the effect of changing retailing structures on the greenhouse gas performance of FMCG distribution networks

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Abstract The assessment of greenhouse gas (GHG) emissions of supply chain activities is performed to create transparency across the supply chain and to identify emission-cutting opportunities. Literature provides several generic and case study approaches to estimate GHG emissions. But research often focuses on products. This paper sheds light on how the greenhouse performance of a fast-moving consumer goods (FMCG) distribution network depends on several (FMCG specific) variables to set up a "CO_2 network footprint". Within a quantitative computational study, the distribution network footprint of an existing FMCG manufacturer is analyzed. Three options being fundamentally able to reduce total GHG emissions are identified: number of distribution centers, performance of the engaged logistics service provider and shipment structure. First, transportation processes for the investigated FMCG manufacturer are analyzed to derive GHG emissions caused by different distribution shipments. Second, initial data are manipulated to simulate variable changes, that is, different logistics structures. Third, results are reported and analyzed to show up how different changes in logistics structures may reduce GHG, without technological propulsion or use of regenerative energy.

Keywords Fast-moving consumer goods (FMCG) · Distribution network analysis · GHG/CO_2 network analysis · Carbon network footprint · Carbon performance

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1 Introduction

Consumer attitudes to products change over time. In the case of fast-moving consumer goods (FMCG), recent trends focus on environmental friendliness. Packages are recyclable, the system of returnable bottles was extended, and the carbon footprint (CFP) was introduced to measure the total greenhouse gas (GHG) emissions caused by an organization, event, product or person.[1] Logistics has been the missing link providing green products and services to the consumer. Greener logistics activities contribute to greener products [56]. Halldórsson et al. [16] identify several drivers for companies to improve sustainability. Besides international regulations like life-cycle assessments, the increased concerns of consumers about the carbon footprint of products, especially food products have an impact. Mainly, the CFPs of products have been investigated. The Platform for Climate Compatible Consumption in Germany (http://www.pcf-projekt.de) investigated the product CFP for some FMCG like strawberries, coffee, eggs or noodles. Different methods for calculating environmental impact were used. Kohn [21] used carbon dioxide emissions per ton-km, Hugo and Pistikopoulos [18] worked with a life-cycle assessment model, and Quariguasi et al. [42] used a life-cycle analysis to design a logistic network balancing profit and the environment. But no research has been undertaken yet to estimate the GHG emissions of a complete distribution network in the

[1] The abbreviations used in the analysis are GHG, greenhouse gas; CFP, carbon footprint; FMCG, fast-moving consumer goods; MDC, manufacturer distribution center; RDC, retailer distribution center; TSP, transshipment point; LSP, logistics service provider; DSD, direct store delivery; FTL, full truck loads; LTL, less than truck load; DS, delivery shipment.

German FMCG industry. Therefore, our analysis answers the following research question (RQ):

RQ: To which extend do transportation related changes affect the GHG performance of a FMCG distribution network?

Not only the emissions of a distribution network are assessed but also different key variables that may impact GHG emissions are manipulated during a case study with Dryco, an existing but disguised German FMCG manufacturer. This approach contains real data, for example, for plants, distribution center and customer locations, shipment sizes and shipment structure. While manipulating decisive variables, the intent is to unfold potential CO_2 reductions that companies hence can use. We identify the following variables: number of manufacturer distribution centers (MDC) and transshipment points (TSP), the concentration of clients of the logistics service provider (LSP), shipment sizes and the share of Direct Store Delivery (DSD). Simulation shows to which degree single changes in the structure influence the CO_2 performance of a typical FMCG distribution network. Particularly, the impact of the number of TSPs, the share of DSD and the concentration of clients of an assigned LSP to the GHG performance of a German FMCG distribution network are not compared in literature yet. Results can be used for a more precise estimation of a CFP, for life-cycle assessments where transport is part of the product system [7]. Three options for companies, which aim to reduce GHG emissions besides alternative propulsion technology and regenerative energy, are identified: changing the number of distribution centers, engaging a logistics service provider with a better performance and adjusting the shipment structure. The first option may require changes in the number of MDCs, the second is represented by the number of TSPs and the concentration of clients, and the third by the DSD share and the shipment sizes (Fig. 1).

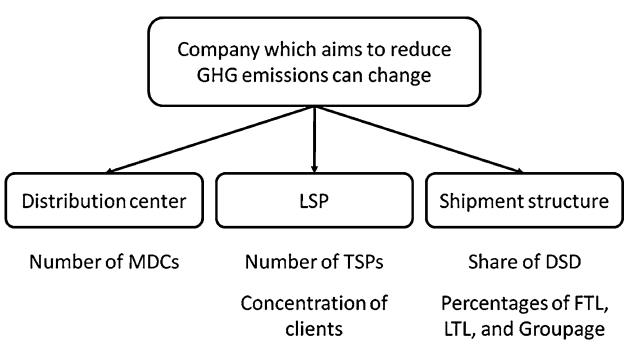

Fig. 1 Options for companies to change GHG emissions

2 Literature review of GHG emission in road freight transportation

2.1 Assessment of GHG emissions

A lot of initiatives for environmental indicators started in the late 1990s. They represent the interests of a diversity of company stakeholders in many combinations. Olsthoorn et al. [37] present an extensive overview of such indicators. As GHG emission assessment has become more important, there is an increasing number of protocols and initiatives to guide companies for sustainable reporting, including:

- World Resources Institute (WRI) Report [10]
- Sustainability Reporting Guidelines from the Global Reporting Initiative [15]
- GHG Protocol Initiative [53]
- ISO 14040, 14044 and 14064 [7–9]
- PAS 2050:2008 [4]

An overview is also given by [30] and [13]. While a convergence toward a unified and consistent approach to assessing emissions can be observed [28], currently no globally accepted standard for reporting transport and logistics related emissions exist. As a consequence, studies on GHG emission are hardly comparable [46]. The existing regulations are not unanimous and highlight various allocation factors and rules to allocate GHG emissions generated by road freight transportation to single products or shipments. Currently, the European Committee on Normalization is developing and agreeing standards for the measurement of GHG emissions from transport. Transportation accounts for about 25% of global CO_2 emissions [36]. In Germany, 81% of the CO_2 and 76% of the NOx emissions were generated by road traffic in 2008 [20].

2.2 Estimating CO_2 emissions in road freight transportation

CO_2 emissions may be considered along the complete supply chain, covering inbound, intra and outbound logistics and return processes. Hence, to reduce total CO_2 emissions, it may be environmentally beneficial to increase CO_2 emissions from freight transportation on the one hand but achieve greater CO_2 savings with other supply chain processes on the other hand [33]. For example, Saunders et al. [45] analyzed the energy and emission performance of New Zealand's agricultural products sold in the UK compared with British agricultural products. In the case of dairy, Saunders and Barber [45] enlarged this research by including GHG emissions from methane and nitrous oxide. For apples, Rizet et al. [43] observed that the best performing GHG emission supply chains are for domestic fruits sold in the Paris region. Despite very short distances, also some supply chains with domestic products emit comparatively high amounts of GHG when small local producers transport very small quantities. These findings contradict the food miles concept (e.g. Smith et al. [47]) where the impact on the environment is only measured by the distance food travels and hence food should always be sourced locally.

In this paper we focus on transportation and do not make any statements on environmental impacts of production. The aim of our research was to assess the GHG emissions within a distribution network. The results allow for more precise CFP values, especially (but not only) in the German FMCG industry. McKinnon [33] estimates the CO_2-intensity of freight transportation modes in g CO_2 per ton-km for air transport, inland waterway, sea, road and rail. An analytical framework for assessing the potential for cutting CO_2 emissions at a macro level (in the UK) is presented by the same author [29]. The weight of the goods is related to CO_2 emissions from freight operations. The critical key ratios that affect the overall CO_2 intensity of the freight sector are handling factor, average length of haul, modal split, average load on laden trips, average percentage empty running, fuel efficiency and CO_2 intensity of energy source (fuel-specific). The connections between freight transportation and the economic activities that the framework serves are also presented. Olsthoorn [36] builds up four scenarios for global transport and investigates fuel consumption, energy efficiencies in transport, occupancy rates of transport means and size of cars on the market.

A method to calculate the carbon footprint of international supply chains to the UK, France and Belgium is presented by Leonardi and Browne [24]. However, they focused on the maritime sector. McKinnon and Piecyk [34] estimate CO_2 emissions from road freight transport at a macro level in the UK. They identify distance travelled and fuel efficiency as key variables. A FMCG supply chain for fresh food products like apples, tomatoes and yogurt in different retails systems in Europe from farms to consumers' homes with a focus on the last mile was investigated by Rizet et al. [43]. Besides GHG emissions for transport, they also considered GHG emissions in buildings like warehouses, stores and shops. And Liimatainen and Pöllänen [26] present a framework for energy efficiency in road freight transportation for Finland. Fuel consumption functions for all Euro-class vehicles and road types are estimated.

By investigating the influence of FMCG distribution network parameters on the GHG performance, this paper contributes to estimate CO_2 emissions of road freight transportation. Second, opportunities to reduce CO_2 are identified which companies can use to become greener.

2.2.1 Scoping: focus on direct emissions

GHG emissions occur in a vehicle running directly and indirectly [51, 53]. Direct GHG emissions (Scope 1) are generated from sources that are owned or controlled by the reporting company itself. Indirect GHG emissions arise as a consequence of the activities of a company but occur at sources owned or controlled by another company. They are sub-dived into emissions from imports of electricity, heat or steam (Scope 2) and other indirect GHG emissions (Scope 3). This paper will focus on direct emissions.

2.2.2 Estimating the conversion of fuel into GHG

Almost all GHG emissions from freight transport are energy-related. To calculate these emissions, the most accurate way is to record energy consumption and employ standard emission factors to convert energy values into GHG [31].

Literature recommends estimating the volume of GHG produced by transportation processes according to the following formula [1, 5, 19]:

$$\mathrm{GHG_{TO}} = (\mathrm{EC_{ve}} + (\mathrm{EC_{vf}} - \mathrm{EC_{ve}}) * \mathrm{VehicleLoad/Cap_v}) \\ /100\,\mathrm{km} * \mathrm{distance} * \mathrm{EF}$$

with GHG_{TO}: GHG emissions resulting from transportation operation TO, in kg CO_2(e); EC_{ve}: emission consumption of vehicle v when empty, in liters per 100 km; EC_{vf}: emission consumption of vehicle v when completely loaded, in liters per 100 km; vehicle load: actual vehicle load, in tons; Cap_v: maximum payload capacity of vehicle v, in tons; distance: trip length of the considered transportation operation, in km; EF: energy conversion factor, in kg CO_2(e) per liter.

GHG emissions for a transport operation (GHG_{TO}) are calculated by multiplying the vehicle's energy consumption (measured in liters of fuel) with an energy conversion factor (EF). The vehicle's energy/fuel consumption depends (a) on the vehicle's v specific consumption patterns (energy consumption EC_{ve} and EC_{vf}, measured in liters fuel per 100 km), (b) on the weight-based vehicle capacity utilization and (c) on distance travelled. EC_{ve} indicates vehicle's v energy consumption (measured in liters fuel per 100 km) if empty, and EC_{vf} if completely loaded. If specific vehicle consumption patterns are not known, default values as proposed by Kranke [22] can be utilized. The energy conversion factor EF indicates the amount of GHG, respectively CO_2 equivalents (CO_2e), produced during the combustion of a certain amount of fuel. DEFRA [5] recommends an energy conversion factor of 2.6413 kg CO_2 for the combustion of one liter diesel. This means direct emissions neglecting indirect emissions associated with the extraction and production of primary fuel [54]. This energy conversion factor is used during the whole paper. Referring to the formula, we assume the effect of vehicle loading on fuel consumption (and CO_2 emissions) being linear. Note that EC_{ve} and EC_{vf} represent vehicle specific consumption patterns capturing all factors influencing fuel consumption per 100 km (except weight capacity utilization), like vehicle design, driver behavior, average road gradients, congestion situations, share of urban/inter-urban tours and European emission standards.

2.3 Key variables to estimate GHG emissions in the German FMCG distribution network

The VTL 'CargoFamily' as a leading general freight partnership (with over 120 SME freight operators) and provider of pan-European logistics solutions with its headquarters in Fulda calculated GHG emissions (CO_2e) of shipments during the whole general freight distribution network. As a result of this study, an average shipment emits about 37 kg CO_2e. About 90% result from transportation. Storage, handling and administration are insignificant [50]. Also, Romilly [44] discovers that CO_2 emissions are mainly determined by fuel consumption. To assess the GHG emissions for our research, we omit emissions from storage, handling, pick and pack, administration, etc. We identified five key variables to assess the German FMCG distribution network: number of MDCs and TSPs, concentration of clients in on-carriage areas, shipment size and DSD share. MDCs are warehouses operated by the manufacturer and used for the distribution. In contrast, retailer distribution centers (RDCs) are operated by retailers but fulfill similar functions for distribution. In this context, TSPs are the hubs of the LSP and used to break the consolidated shipments of the main legs down to delivery trips within the area a TSP serves. The processes within the TSPs are out of consideration. Proximate literature—mainly in the context of cost analysis/optimization—shows the selected variables being most important in the context of FMCG distribution networks.

2.3.1 Number of MDCs

The first variable that may influence the GHG emissions of a distribution network is based on the number of MDCs. In their paper, Wouda et al. [55] present a mixed-integer linear programming model to identify the optimal supply network for a Hungarian FMCG manufacturer. Levén and Segerstedt [25] present a capacity analysis model applied to a FMCG manufacturer. As a result of the case study, the authors propose the location of additional storage capacities in the vicinity of existing production facilities and to concentrate production capacities. For food distribution, the case study of Tüshaus and Wittmann [49] investigates facility locations for a simple plant. To estimate network sensitivities, Bottani and Montanari [3] present a simulation model to quantitatively assess the effects of different supply configurations on the resulting total supply chain costs of a FMCG supply chain. Furthermore, Lalwani et al. [23] assess the optimum configuration for a network being most at risk because of the uncertainties associated with stock-holding costs and delivery frequencies rather than customer demand volume changes and transport tariffs. Manzini and Gebennini [27] present other mixed-integer linear models applied to the dynamic facility location-allocation problem and the fit of the proposed models to a case study.

Although these papers often focus on logistics costs, the results need to be adopted. Up to now, companies attempt to minimize costs not GHG emissions. The optimal number of MDCs can be seen as external parameter, which may not be changed easily due to savings of GHG emissions.

2.3.2 Number of TSPs

The length of delivery trips during the on-carriage of shipments is basically defined by the number of TSPs of the LSP. The more the TSPs, the shorter is a delivery trip. On the other hand means a higher density of locations for example raising fixed costs. Harris et al. [17] assess in a case study from the European automotive industry the impact of traditional cost optimization approaches to strategic modeling on overall logistics costs and CO_2 emissions by taking into account the number of depots. Their environmental model regards CO_2 emissions from depots but also transportation. The levels of emissions relate directly to factors like distances travelled, the load of the engine over the distance and the speed of the vehicle. The distance travelled mainly depends on the number of depots. Also McKinnon and Woodburn [32] state the direct effect of physical infrastructure of a network, such as numbers, locations and capacities of depots, on freight transportation operations and hence on CO_2 emissions.

2.3.3 Concentration of clients of the LSP in the on-carriage areas

The number of clients inside the on-carriage areas impacts different variables like capacity utilization, length of delivery trips and number of stops. There is a lack of literature discussing the effects of customer concentration in given delivery areas on GHG emissions, whereas tools for estimating tour lengths exist [2, 14]. Research on investigating the last mile effect for products mainly focuses on the distances customers travel to stores and shows the major influence on the GHG emissions [11, 32]. Whereas the delivery of small units within round tours has comparative effects on the total emissions, these processes are less investigated. This indicator describes the number of clients the LSP serves in a certain TSP area. Thus, we observe the effect when the number of retailer locations in each TSP area is raised by a given factor. A factor of two indicates that the LSP serves all of the retailers and additionally within the same TSP area another time the same number of destinations of other clients. In that situation, the amount of GHG emissions is expected to be reduced as the delivery trips will be shortened with retailers lying closer to each other.

2.3.4 Shipment size

German FMCG companies focus on shipment size as key variable for future development. The close future of distribution in the German FMCG industry shows four main strategies: lowering inventory, fasten replenishment, maximizing bundling and breathing with the consumer [38]. Especially the first two result in increasing numbers of shipments with smaller sizes. This leads to higher CO_2 emissions of distribution networks due to increased number of delivery trips.

2.3.5 DSD share

The last variable whose sensitivity we analyze is the share of DSD. DSD represents the share of the total distributed tonnage that is directly transported from MDCs to the outlets, bypassing RDCs. DSD may bypass one or more TSPs (Fig. 2).

The DSD share affects the network structure due to smaller shipment sizes to customers than to RDCs. Due to multiple reasons, Dryco is interested in shipping DSD directly to retailing stores and bypassing RDCs. Yet over the last years, DSD has lost importance. According to Thonemann [48], the share of DSD deliveries (not volume!) reached 81% in 1985 and dropped to 17% in 2010. Otto and Shariatmadari [39], Müller and Klaus [35] and Otto et al. [40] give more insights into the concept of DSD and its implication for retailing logistics in the German FMCG industry.

3 Assessing the GHG performance of a FMCG distribution network

3.1 Dryco's network structure and shipment data

Dryco is an existing but disguised FMCG manufacturer. It operates a network of six plants that are all located in Germany and produce 500.000 tons of dry, that is, non-

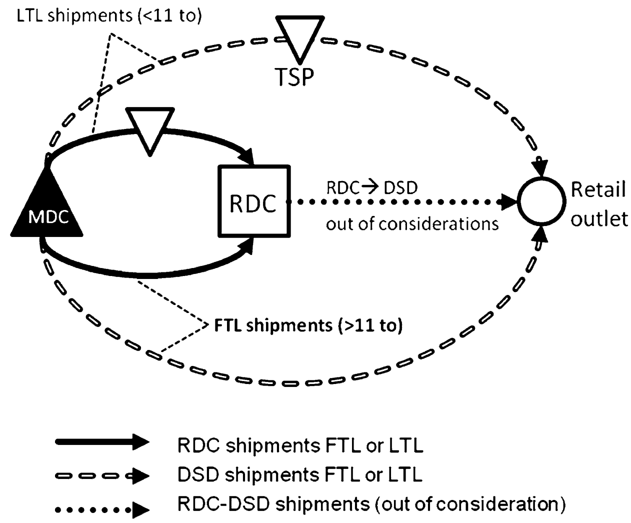

Fig. 2 DSD and RDC shipments from the MDC

perishable and non-refrigerated FMCG per year for the German market, split up into 1.200 stock keeping units (SKUs). Dryco supplies all major retailers in Germany both via RDC (10% ship-to locations) and DSD (90% ship-to locations) out of one MDC, which hence carries the full SKU range. Shipments from the plants to the MDC (production flows, PF) are always done in full truck loads (FTL), shipments from the MDC to the retailers (delivery shipments, DS) via FTL (above 11 tons), LTL (less than truck loads, 2–11 tons) and Groupage (below 2 tons). The physical logistic operation has been completely outsourced (warehousing, pick and pack, transportation) to several logistic service providers.

As Dryco's data did not allow tracking the physical routes of shipments from origins to destinations, the following assumptions are made.

In the GHG network analysis, we suppose that all FTL shipments—both production flows and delivery shipments—are transported directly from origin to destination with no hub/transshipment point (TSP) in between. FTL shipments from the plants to the MDC have a payload of 17 tons, corresponding to the average quantity of all productions flows. LTL and Groupage shipments are first transported from MDC to a TSP to be forwarded to the final destination within delivery tours (Fig. 3). The retailer is supplied via DSD if it is an outlet or via RDC shipment if it is a distribution center.

The TSP locations correspond to an existing structure of a major German logistic service provider. Customers are assigned to exactly one TSP as a function of the minimum distance from TSP to RDC or DSD location, describing delivery areas (dotted circles). For all shipments, vehicle utilization depends on capacity utilization when transporting goods and empty running [33]. For the average load on laden trips, the loading factor is determined as ratio of

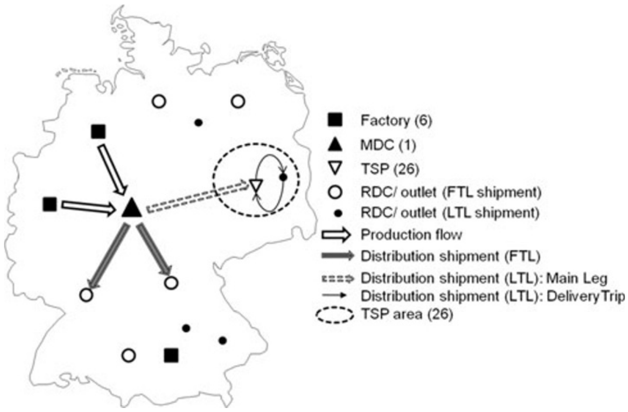

Fig. 3 Flow of goods in Dryco's distribution network

the ton-km that a vehicle actually carries to the ton-km it could have carried if running at its maximum gross weight. For Great Britain, the lading factor in 2009 is 57% and expected to rise until 2020. On the other hand, empty running is assumed to decline from 27% in 2009 to 18% in an optimistic and 26% in a pessimistic approximation [41]. Harris et al. [17] use three different freight vehicle utilization ratios of 90, 75 and 60% in the simulation model. The calculated capacity utilization (in % of weight) for Dryco's distribution network is about 70%. The number of shipments from the MDC to the single TSPs corresponds to the total amount of goods demanded within the delivery areas for LTL and Groupage shipments divided by the number of tons being transported by a heavy goods vehicle with this capacity utilization. For all distribution flows and every RDC or DSD destination, we use location-specific shipment sizes corresponding to the average shipment size in each shipment class, that is, FTL, LTL and Groupage.

3.2 Limits of the system of observation

The analysis investigates the GHG emissions of a FMCG distribution network across all products. During the complete product life-cycle, the analysis starts when finished FMCGs leave the plants. It ends at RDCs (or outlets when shipped DSD). All GHG emissions caused by upstream processes like sourcing, manufacturing or transportation of raw material are not considered. Since this research contributes to CO_2 emissions of road freight transportation, we do not account for loading, pick and pack, administration and warehousing, which are insignificant anyway [50]. However, we include and calculate empty legs of 40 km for every vehicle to reach the plants. As the number of vehicles going to and leaving the MDC and RDCs is about 50 per day, we assume that the same vehicles that serve the MDC later the day serve the RDCs or outlets. No more empty legs occur here. Empty legs when leaving the observed system, that is, after the retailers are supplied, are not considered. Consequently, all GHG emissions from RDC-DSD deliveries are out of consideration, too. For the analysis ending at RDCs or outlets, last mile processes from the stores to the consumers are also not regarded, as well as other subordinated or downstream processes like:

- Transport activities during handling in TSPs
- Non-freight transport activities of the transport provider (estate energy, administration, travel of employees)
- Construction and maintenance of transport infrastructure
- Activities linked with vehicle purchases like construction, repair or recycling
- Upstream emissions from fuel production, transport and refineries processes

For all observations we only regard Scope 1.

3.3 Evaluating sub-processes of the distribution network

Three types of transportation processes are considered: production flows (from the plants to the MDC(s)), distribution shipments FTL (from the MDC(s) to the retailers; transported tonnage >11 tons) and distribution shipments LTL (from the MDC(s) to the retailers; transported tonnage <11 tons).

3.3.1 Estimating GHG(PF)

GHG emissions from production flows (GHG(PF)) arise for the transportation processes from the factories to the MDC. We suppose that for each shipment an empty leg of 40 km is necessary to reach the factory.

$$\mathrm{GHG(PF)} = \sum_{\mathrm{fj}} \mathrm{GHG_{fj}}, \tag{2}$$

where

$$\begin{aligned}\mathrm{GHG_{fj}} = {} & ((\mathrm{EC_{ve}} + (\mathrm{EC_{vf}} - \mathrm{EC_{ve}}) * 17\mathrm{tons}/\mathrm{Cap_v})/100\,\mathrm{km} \\ & * d_{\mathrm{fj}} + \mathrm{EC_{ve}}/100\,\mathrm{km} * 40\,\mathrm{km}) * \mathrm{EF} * \mathrm{NbSh_{fj}},\end{aligned} \tag{3}$$

with

$$\mathrm{NbSh_{fj}} = q_{\mathrm{fj}}/17\,\mathrm{tons} \tag{4}$$

and

$$q_{\mathrm{fj}} = \sum_{\mathrm{i}} q_{\mathrm{ij}} * \mathrm{fq_{fi}}, \quad \text{for all f, j} \tag{5}$$

with GHG(PF): GHG emissions resulting from all production flows, in kg CO_2(e); $\mathrm{GHG_{fj}}$: GHG emissions resulting from all production flows between factory f and MDC j in kg CO_2(e); d_{fj}: distance between factory f and MDC j, in km; $\mathrm{NbSh_{fj}}$: total number of shipments/transportation operations taking place between factory f and

MDC j; q_{fj}: total tonnage to be shipped from factory f to MDC j, in tons; q_{ij}: total tonnage to be shipped from MDC j to costumer i, in tons; fq_{fi}: factory quota: factory f's contribution to satisfy costumer i's demand (in tons), in percent.

The total amount of GHG emissions from production flows corresponds to the sum of GHG emitted for all the flows from the factories to the MDC. GHG that are associated with the flow of goods from factory f to MDC j are calculated by using a given vehicle's specific fuel consumption pattern, EC_{ve} (energy consumption if empty, measured in liters fuel per 100 km) and EC_{vf} (energy consumption if completely loaded), its maximum payload capacity Cap_v (measured in tons), the distance between factory f and MDC j (d_{fj}) and the emission conversion factor of 2.6413 kg CO_2 per liter fuel. $NbSh_{fj}$ indicates the total number of shipments, that is, transportation processes between factory f and MDC j. q_{fj} corresponds to the tonnage that MDC j demands from factory f. It is calculated by summing up the demands of all retailers i that are assigned to MDC j (q_{ij}) respecting the retailer factory-specific quotas (factory quota, fq_{fi}) as the single factories f contribute to different degrees to satisfy the demands of the single retailers i. We use distances proposed by EWS ("Entfernungswerk Straße") that serves as basis of computation for tariffs in German truck freight traffic. For closer insight into calculations of GHG, see also Department for Transport and Harris et al. [6, 17].

3.3.2 Estimating GHG(DS-FTL)

Delivery shipments that have a payload above 11 tons are assumed to be transported directly to the final destination (RDC or DSD) with no transshipment operations in between. GHG emissions that arise from the transportation processes FTL from MDC j to retailer i (GHG_{ji}^{FTL}) are calculated as follows:

$$GHG_{ji}^{FTL} = \left(EC_{ve} + (EC_{vf} - EC_{ve}) * to_i^{FTL}/Cap_v\right)/100\,km * d_{ji} * EF * NbSh_i^{FTL} \quad (6)$$

with GHG_{ji}^{FTL}: GHG emissions from all transportation operations from MDC j to customer i in shipment class "FTL", in kg CO_2(e); to_i^{FTL}: average tonnage of shipments of costumer i in shipment class "FTL", in tons; d_{ji}: distance between MDC j and costumer i, in km; $NbSh_i^{FTL}$: total number of shipments to be shipped to customer i in shipment class "FTL".

to_i^{FTL} corresponds to the average tonnage that retailer i demands for FTL shipments, d_{ji} is the distance between MDC j and retailer i and $NbSh_i^{FTL}$ captures the number of shipments that retailer i demands for shipments of this shipment class.

We assume that distribution shipments do (generally) not require the integration of an additional empty leg for the vehicles to reach the MDC as, for most time, vehicles that ship goods from the factories to the MDC are instantly reused for subsequent delivery shipments.

3.3.3 Estimating GHG(DS-LTL)

Delivery shipments with a payload below 11 tons are collected at the MDC, transported within FTL shipments to a TSP (main leg) to be finally delivered to the retailers within delivery tours (delivery trip).

3.3.3.1 Estimating GHG(DS-LTL): main leg GHG from the transportation of goods from MDC j to TSP t (GHG_{jt}) are calculated as follows:

$$GHG_{jt} = (EC_{ve} + (EC_{vf} - EC_{ve}) * avgCapUt/Cap_v)/100\,km * d_{jt} * EF * NbSh_{jt} \quad (7)$$

$$NbSh_{jt} = \sum_i q_{it}^{LTL}/avgCapUt, \quad \text{for all} \quad j, t \quad (8)$$

with GHG_{jt}: GHG emissions resulting from all main leg transportation operations between MDC j and TSP t, in kg CO_2(e); avgCapUt: average weight-based capacity utilization on the main legs, in tons; d_{jt}: distance between MDC j and TSP t, in km; $NbSh_{jt}$: total number of shipments to be shipped from MDC j to TSP t; q_{it}^{LTL}: demand of costumer i that is assigned to TSP t for goods to be shipped in shipment class "LTL", in tons.

avgCapUt corresponds to Dryco's average vehicle capacity utilization, d_{jt} is the distance between MDC j and TSP t. $NbSh_{jt}$ is the total number of shipments from MDC j to TSP t that equals the total demand, shipment class LTL, of all retailers i that are assigned to TSP t divided by avgCapUt.

3.3.3.2 Estimating GHG(DS-LTL): delivery trip Dryco's shipments that are below 11 tons are usually delivered within delivery trips by a LSP. To estimate the GHG volume from the delivery trips, three steps are performed: (1) estimate the physically performed delivery trips and (2) derive GHG emissions, (3) allocate emissions to Dryco's shipments.

The tour lengths of the delivery trips are estimated using Fleischmann's ring model to know the number of tour stops (cf. [14] and [52]). The first and last legs to reach the delivery areas correspond to that from TSP t to retailer i. The distances between the tour stops (d_t^{RR}), that is, between the retailers, vary for each TSP area t, taking into account the surface of the TSP area $A(r_t^{max})$ and the number of retailers within this area $n(r_t^{max})$ and are estimated as following (cf. [2] and [12]):

$$d_t^{RR} = 0.79 * \mathrm{sqr}\left(A\left(r_t^{max}\right)/n\left(r_t^{max}\right)\right), \quad \text{for all} \quad t \tag{9}$$

with d_t^{RR}: distance between two costumers/retailers in TSP area t; $A(r_t^{max})$: surface of (the ring-like) TSP area t in km^2, being approximated using the distance between the TSP and the farthest away costumer for the radius r_t^{max} in km; $n(r_t^{max})$: estimated total number of costumers in delivery area t.

For this analysis with 26 TSP areas, the radius r_t^{max} of the ring-like delivery areas (A) is the distance from the farthest customer within this area to the TSP. n is the number of shipment locations within the considered delivery area. The distances between two tour drops vary for each area and range for the initial situation between 8 and 17 km.

According to the ring model, we suppose that for a given delivery trip, all retailers are delivered the equal tonnage. The tonnage used to compute GHG from the delivery trip corresponds to half of the tonnage totally delivered.

GHG caused by Dryco's shipment from TSP t to retailer i (GHG_{ti}) follows from

$$\begin{aligned} GHG_{ti} = & \left(EC_{ve} + (EC_{vf} - EC_{ve}) * NbSt_i * to_i^{LTL}/2/Cap_v\right) \\ & /100\,km * EF * NbSh_i^{LTL} \\ & * \left(2d_{ti} + (NbSt_i - 1) * d_t^{RR}\right)/NbSt_i \end{aligned} \tag{10}$$

with GHG_{ti}: GHG emissions resulting from all transportation operations to deliver costumer's i goods out from TSP t, in kg CO_2(e); $NbSt_i$: estimated total number of stops for delivery trips in that costumer i takes part; to_i^{LTL}: average tonnage of shipments of costumer i in shipment class "LTL", in tons; $NbSh_i^{LTL}$: total number of shipments to be shipped to customer i in shipment class "LTL"; d_{ti}: distance between TSP t and costumer i, in km.

$NbSt_i^{LTL}$ is the estimated number of stops within the trips to deliver retailer i. Note that the share of GHG from the delivery trips are allocated equally to the destinations.

3.4 GHG footprint of Dryco's distribution network

The variables of Dryco's distribution network which are manipulated later on are in the initial situation:

- Number of MDC: 1
- Number of TSPs: 26
- Concentration of clients: 3
- DSD share: 35%
- Shipment size (percentage of tonnage): 61% FTL, 33% LTL, 6% Groupage

Table 1 gives more insights into the shipment structure.

The resulting GHG footprint of Dryco's distribution network is presented in Table 2. Production flows from the factories to the MDC emit 2,723 tons CO_2, which means 5.7 kg per ton. Together with GHG emissions of the distribution shipments caused by DS-FTL (3,944 tons CO_2), main leg (2,642) and delivery trip (1,813), a sum of 11,122 tons of CO_2 is emitted by the given distribution network design. Least GHG emissions of 5.7 kg per ton arise during the production flows due to the shortest distances between the six plants and the MDC. 13.5 kg per ton occur for transportation FTL shipments from MDC directly to the customer, and 23.8 kg per ton are generated by shipments to TSPs and further during delivery trips to the customers. Altogether for the whole distribution chain, the average is 23.2 kg per ton. Relating to the emission per ton-km, the DS-FTL shows the lowest value with 40.6 kg and the delivery trip the highest with 65.3 kg.

Table 1 Relative importance of FTL, LTL and Groupage shipments in the initial situation

Shipment class	Delivered tonnage	Number of shipments	Avg. tonnage per shipment
FTL shipments	61%	11%	18.7
LTL shipments	33%	37%	2.9
Groupage shipments	6%	52%	0.4
Sum	500,000 tons	145,000 shipments	3.3

4 Analyzing GHG network sensitivities by single variable changes

4.1 Number of MDCs

To understand the effect of an increasing number of MDCs on the GHG performance of the distribution network, we suppose to select the geographical locations of the warehouses only with respect to cost optimization. Therefore, distribution costs have been analyzed. The distribution costs for Dryco consist of transportation costs, inventory holding costs and handling costs. To analyze the effect of an increasing number of MDCs on the GHG performance of the network, GHG emissions are calculated for one up to five MDCs. When adding MDCs, we suppose that locations are selected to minimize total transportation costs. Using a p-median linear problem formulation and Dryco's shipment data, we identify cost optimal MDC configurations. Transportation costs are modeled with respect to shipment sizes, distance and supposing distinct cost functions for each shipment class (FTL, LTL and Groupage). The emitted GHG volume for one MDC can be seen in Table 2. The principal findings for network configurations are reported from two up to five MDCs. The effect is considered ceteris paribus.

Table 2 GHG performance: current network

Transportation process	Vehicle data[a]	Tons of CO_2 emitted	Kg CO_2 per ton
Production flows	$EC_{ve} = 21.2$ l/100 km	2,723	5.7
	$EC_{vf} = 31.3$ l/100 km		
	$Cap_V = 25$ tons		
GHG(DS-FTL)	$EC_{ve} = 21.2$ l/100 km	3,944	13.5
	$EC_{vf} = 31.3$ l/100 km		
	$Cap_V = 25$ tons		
GHG(DS-LTL): main leg	$EC_{ve} = 21.2$ l/100 km	2,642	23.8
	$EC_{vf} = 31.3$ l/100 km		
	$Cap_V = 25$ tons		
GHG(DS-LTL): delivery trip	$EC_{ve} = 19.2$ l/100 km	1,813	
	$EC_{vf} = 29.6$ l/100 km		
	$Cap_V = 17$ tons		
Total		11,123	23.2

[a] Values according to [22] averaged for vehicles with European Emission standards 3 and 4. Results based on an energy conversion factor of 2.6413 kg CO_2 for the combustion of one liter diesel for Scope 1 as proposed by [5]

An additional (second) MDC is located to minimize total transportation cost. Compared to a distribution network with only one MDC, the production flows emit 3,625 tons of CO_2 instead of 2,723 tons (+33.2%). This results from longer distances from the plants to the MDCs. On the other hand, the distances for FTL shipments from MDCs to the customers decrease by 18.7% from 3,944 to 3,206 tons. At the same time, the distances for the main legs are also reduced because the 26 TSPs are supplied out of two geographically separated MDCs. GHG emissions fall by 20.6% from 2,642 to 2,098 tons. Due to the same number of TSPs, the emissions of the delivery trips remain unchanged. The total emitted CO_2 per ton drops by 3.4% from 23.2 to 22.4 kg, concerning the changed tonnage of CO_2 emitted (Table 3).

The cost optimized distribution structure emits a total of 11,122 tons of CO_2. Two MDCs reduce the emissions to 10,742 tons, three to 10,578, four to 10,453 and five to 10,341 tons. From the initial situation to five MDCs, the GHG reduction would be 7.0%. The amount of CO_2 per ton decreases thereby from 23.2 to 21.6 kg per ton (Table 4). If more MDCs were added, the GHG emissions are expected to fall.

Note that an increased number of MDCs and TSPs mean more processing activities, more handling, storage and administration, and hence, more GHG emissions, resulting from these processes. These emissions are excluded from our analysis as literature shows that the share of GHG emissions resulting from these activities is very complex to quantify and relatively unimportant in distribution networks compared to emissions caused by transportation processes [43, 44, 50].

4.2 Number of TSPs

To estimate the effect of a changing number of TSPs, the number of TSPs is reduced from originally 26 TSPs for the German LSP to 12, 17 and 22. Thus, we are able to observe ecological consequences of selecting LSPs because different LSPs operate a different number of TSPs. The main effects that are expected to be exerted by a reduced number of TSPs: slightly varied main legs, longer delivery trips, greater TSP areas and changed retailer-TSP allocations. In the initial situation, 11,123 tons CO_2 are emitted with 23.2 kg per ton. A reduction in the number of TSPs leads to higher CO_2 emissions. While the emissions for production flows and GHG(DS-FTL) shipments remain unchanged, the main effects base on the delivery trips. The CO_2 emissions of the main legs have values between 2,640 and 2,653 tons for 17, 22 and 26 TSPs. Just the configuration with 12 TSPs only shows 2,587 tons for the main legs. The

Table 3 GHG performance with two MDCs

Transportation process	Tons of CO_2 emitted	Kg CO_2 per ton
Production flows	3,625	7.6
GHG(DS-FTL)	3,206	11.0
GHG(DS-LTL): main leg	2,098	20.9
GHG(DS-LTL): delivery trip	1,813	
Total	10,742	22.4

Table 4 GHG performance from one up to five MDCs

Number of MDCs	Tons of total CO_2 emitted	Kg CO_2 per ton
1 (initial situation)	11,123	23.2
2	10,742	22.4
3	10,578	21.4
4	10,453	21.8
5	10,341	21.6

Table 5 GHG performance depending on the number of TSPs

Number of TSPs	Tons of total CO_2 emitted	Tons of CO_2 main leg	Tons of CO_2 delivery trip	Kg CO_2 per ton
12	11,900	2,587	2,646	24.8
17	11,404	2,640	2,097	23.8
22	11,289	2,653	1,969	23.6
26 (initial situation)	11,123	2,642	1,813	23.2

majority of the GHG increase is caused by the delivery trips. For 26 TSPs, 1,813 tons are emitted. This amount rises from 1,969 tons for 22 TSPs and 2,097 tons for 17 TSPs to a peak of 2,646 tons for 12 TSPs. That means a plus of 45.9% compared to 26 TSPs (Table 5).

Another effect is a result of the fact that within greater TSP areas, the number of clients per trip might decrease if time restrictions (in our case 8 h maximum driving time per vehicle) are reached. For Dryco, this means on the one hand longer distances from the TSP to the first costumer in a trip, respectively, from the last one back to the TSP. On the other hand, fewer costumers in the faraway trips lead to shorter distances between first and last costumer and less tonnage shipped.

4.3 Concentration of clients of the LSP

Another indicator describing the infrastructure of a LSP is the number of clients it serves. Thus, we observe the effect when the number of retailer locations in each TSP area is raised by a given factor. A factor of 2 indicates twice the ship-to locations. Dryco's LSP serves all of Dryco's retailers and additionally within the same TSP area another time the same number of destinations of other clients. Within a delivery trip, half of the clients are served with Dryco's products. In that situation, the amount of GHG emissions is expected to be reduced as the delivery trips will be shortened with retailers lying closer to each other. Only the transportation process GHG(LTL) for delivery trips is affected. The transportation processes from the plants to the TSPs (PF and main leg) and the FTL shipments, which go directly to the outlets, are not affected. In the initial scenario, our concentration of clients is three due to the assumption that a LSP supplies more than one company with many different customers. The outcome of this design is 11,123 tons of emitted GHG. If the LSP only valets Dryco, this amount would rise to 11,740 ton (+5.6%) or 24.5 kg per ton. Twice the number of clients in a TSP area lowers CO_2 of delivery trips from 2,430 to 2,008 tons and total GHG emission by 3.6% to 11,318 tons. Implied a better or bigger LSP with a concentration of clients of 4 improves the sustainability of the distribution

Table 6 GHG performance according to the concentration of clients

Concentration of clients	Tons of total CO_2 emitted	Tons of CO_2 delivery trips	Kg CO_2 per ton
1	11,740	2,430	24.5
2	11,318	2,008	23.6
3 (initial situation)	11,123	1,813	23.2
4	11,010	1,701	23.0

network and reduces the total GHG emissions for delivery trips to 1,701 tons or total to 11,010 tons, which means 23.0 kg per ton (Table 6).

4.4 Shipment size

To simulate shipment size variations, we "transfer" client specific tonnages between the shipment classes FTL, LTL and Groupage. During the data manipulation process with moving tonnage from one shipment class to another, it is important to maintain the initial situation as far as possible in order to create realistic scenarios. At first, we observe a situation in which the tonnage of FTL shipments is reduced from 61 to 55%. Further the tonnage shipped LTL is 33% and 12% for Groupage. Production flows are not affected. Due to less FTL, the GHG emissions DS-FTL decrease from 3,944 to 3,563 tons (−8.9%). The direct distances of FTL shipments (DSD or RDC) are shorter than shipments via TSPs with main legs and delivery trips. Due to the reduced amount of FTL that is now transported LTL or Groupage through TSPs the GHG emissions of main legs and delivery trips together boost by 23.4% from 4,455 to 5,499 tons. This results in highly increased total emissions of 11,815 tons (+6.2%). In a second situation, the tonnage shipped FTL rises to 65%, LTL remains 32% and Groupage is reduced to 3%. A higher tonnage is now transported directly to RDCs or outlets, and the distances travelled for those shipments are optimized. The reduced number of shipments through the TSPs (and hence less main legs and delivery trips) results in slightly higher GHG(DS-FTL) of 4,225 tons compared to 3944 tons in the initial situation. However, lower LTL shipments save 634 tons (3,821 compared to 4,455 tons) and outnumber the risen FTL emissions. In all the results, there are lower total emissions of 10,769 tons (−3.2%). A summary is presented in Table 7.

4.5 DSD share

Changing flows of goods from DSD destinations toward RDC and vice versa will change the average shipment size and the total number of shipments because DSD deliveries are smaller than RDC deliveries. The average delivered tonnage per DSD shipment in the initial situation is about

Table 7 GHG performance according to percentage of FTL shipments

Transportation process	Tons of CO_2 emitted with 55% FTL shipments	Tons of CO_2 emitted with 61% FTL shipments (initial situation)	Tons of CO_2 emitted with 65% FTL shipments
Production flows	2,723	2,723	2,723
GHG(DS-FTL)	3,563	3,944	4,225
GHG(DS-LTL): main leg	3,030	2,642	2,377
GHG(DS-LTL): delivery trip	2,470	1,813	1,444
Total	11,815	11,123	10,769

Table 8 Relative importance of RDC and DSD shipments in the initial situation

Initial situation	Delivered tonnage (%)	Number of shipments (%)	Avg. tonnage per shipment
DSD destinations	35	73	1.6
RDC destinations	65	27	8.1

Table 9 GHG emissions according to DSD share

Transportation process	Tons of CO_2 emitted with a DSD share of 25%	Tons of CO_2 emitted with a DSD share of 35% (initial situation)	Tons of CO_2 emitted with a DSD share of 45%
Production flows	2,723	2,723	2,723
GHG(DS-FTL)	4,337	3,944	3,579
GHG(DS-LTL): main leg	2,304	2,642	2,998
GHG(DS-LTL): delivery trip	1,517	1,813	2,163
Total	10,867	11,123	11,476

1.6 and 8.1 tons for RDC deliveries (see Table 8). When simulating DSD parameter changes, we consider individual customer demands as well as order sizes separately for each shipment class c.

A reduced DSD share of 25% results in increasing FTL shipments because RDCs are served with more shipments and RDC tonnages are higher than DSD ones. Thus, GHG emissions of FTL climb to 4,337 tons (+10.0%), whereas main legs drop from 2,642 to 2,304 tons and delivery trips from 1,813 to 1,517 tons. These changes lead to reduced total GHG emissions of 10,867 tons and the emissions per ton decrease by 2.3% to 22.7 kg. A higher DSD share of 45% means that more outlets are supplied directly. Their order volumes are smaller than RDC order volumes. So, the number of FTL shipments is reduced and LTL shipments increase. FTL shipments emit 3,579 tons compared to 3,944 tons in the case of 35% DSD. Main leg emissions rise by 356 to 2,998 tons and delivery trip emissions by 350 tons to 2,163 tons. The total GHG emissions ascend by 3.2% to 11,476 tons (Table 9).

5 Conclusion

An existing German FMCG manufacturer emits throughout its distribution network from finished goods leaving the plants to RDCs or outlets (when shipped DSD) a total of 11,123 tons of CO_2. This sum consists of four transportation processes: production flows emit 2,723 tons, FTL shipments to outlets 3,944 tons, LTL shipments for main legs 2,642 tons and for delivery trips 1,813 tons. Changing one or more identified key variables of the distribution network modifies the GHG performance. Not all variables affect the same transportation processes in the same manner. The emissions of the productions processes depend only on the number of MDCs because the PFs occur only from the plants to the MDCs. A higher number of MDCs reduces MDC-outlet distances and distances for main legs and hence GHG(DS-FTL) and GHG(DS-LTL) emissions. The emissions of the delivery trips remain unchanged since they are not affected by the number of MDCs. FTL shipments are not transported through TSPs, so PF and GHG(DS-FTL) remain while changing the number of TSPs. Due to the relatively high number of TSPs distributed equally in Germany, the main legs are also barely affected from 17 to 26 TSPs. Only when reducing to 12 TSPs the main legs emit a little less. Most effects occur during delivery trips where the emissions drop the more TSPs are installed. Regarding the variable concentration of clients, the transportation processes from the plants to the TSPs are not affected. The GHG emissions of the delivery trips fall when concentration increases. A concentration of

Table 10 Overview of GHG performance for single variable changes

Increasing of	Affects the emissions of				To a total extent of	Percentage of change
	Production flows	GHG (DS-FTL)	GHG (DS-LTL): main leg	GHG (DS-LTL): delivery trip		
Number of MDCs	↑	↓	↓	→	10,341 tons CO_2 with 5 MDCs to 11,123 with 1 MDC	−7.0
Number of TSPs	→	→	→ (↗)	↓	11,900 tons CO_2 with 12 TSPs to 11,123 with 26	−7.0
Concentration of clients	→	→	→	↓	11,740 tons CO_2 with concentration of 1 compared to 11,010 tons with concentration of 4	−6.2
Structure of shipment sizes (FTL↑; LTL/Groupage↓)	→	↑	↓	↓	11,123 tons CO_2 with 61% FTL to 10,769 tons with 65% FTL	−3.2
DSD share	→	↓	↑	↑	10,867 tons CO_2 with 25% DSD to 11,476 tons with 45% DSD	+5.6

1 causes 11,740 tons of CO_2, one of 4 only 11,010 tons. Modifications of the shipment sizes impact all distribution shipments. An increased percentage of FTL accordingly leads to higher FTL emissions but simultaneously to less LTL volume. Due to the analysis, the difference of less GHG of main legs and delivery trips outranges the increased FTL emissions. An increased number of FTL from 61 to 65% decrease the total GHG emissions by 3.2% to 10,769 tons. Increasing the DSD share takes an opposite effect: FTL emissions fall and LTL emissions go up. Table 10 integrates the single variable changes. Increasing the number of MDCs, TSPs and the concentration of clients and enlarging the shipment sizes lead to total reductions in GHG emissions. Otherwise a higher DSD share causes more GHG emissions.

Regarding the three options for companies to influence the GHG performance of a distribution structure (see Fig. 1), the analysis results as follows:

1. Increasing the number of MDCs lead to less GHG emissions. Since the initial situation with one MDC is cost optimized costs for additional MDCs have to be taken into account.
2. A higher number of TSPs and an improved concentration of clients result in a better GHG performance of the distribution system. The latter can be realized by selecting an appropriate LSP.
3. Reductions in the DSD share and bigger shipments (more FTL, less LTL and Groupage) also decrease the total GHG emissions.

The calculations demonstrate on a value basis of GHG emissions the impacts of changes in the distribution network in the field of logistics. This allows companies for improved decisions to become greener.

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