Incorporating environmental aspects in an inventory routing problem. A case study from the petrochemical industry

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Abstract Carbon emissions from transport activities in a supply chain are extensively contributing to global warming. However, the focus of literature in the field of sustainable supply chain management is mainly on production processes or network design decisions, considering transportation as a "necessary evil". Consequently, transport activities are often accounted for in a rather simplified way in the analyses and are rarely analyzed on a high level of detail. Thereby the actual impacts transport processes have on the economic and environmental performance of a company are distorted. Our work focuses solely on the analysis of transport processes and shows the economic and environmental effects of routing decisions in a supply chain with vertical collaboration, for instance through vendor-managed inventory. We propose an Inventory Routing Model and apply it to a case study from the petrochemical industry. The outcome from this detailed transport analysis is then compared with results from former studies, where the main focus was on facility location decisions rather than on transportation decisions. The results point out the importance of detailed transport process analyses in order to get accurate results and suggest a potential for achieving pareto-improvements by reducing at the same time both costs and carbon emissions in a supply chain with vertical collaboration.

Keywords Sustainability · Collaboration · Inventory routing · Carbon emissions · Case study

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1 Introduction

The topic of environmental sustainability in business processes has attracted a great deal of attention in recent years. A lot of academic as well as scientific research has already been published concerning the effects of certain operations on the environmental performance of a company (see for example Seuring and Mueller 2008). Currently, the main focus of interest is on assessing and reducing the amount of greenhouse gas emissions of operations in order to decelerate further global warming. Priority is given to a detailed investigation of production processes because they usually offer a huge potential for energy and emission reduction and are, thus, enforced by environmental regulations of national and international organizations, for instance the European Union (EEA 2009). Distribution activities are currently not yet subject to strict environmental regulations with respect to greenhouse gas emissions, but it is nevertheless advisable to consider their environmental effects in decision making.

The distribution stage comprises all processes that are necessary to move and store products on their way from the production stage to the customer, hence consisting of transportation and warehousing activities (Chopra and Meindl 2010). Whereas there are already several authors dealing with the environmental performance of different distribution network designs (Diabat and Simchi-Levi 2009; Wang et al. 2011), transport processes are often considered as a "necessary evil" and are, therefore, not analyzed explicitly. In a recent work, Treitl and Jammernegg (2011) show the conflicting nature of optimizing costs and carbon emissions in facility location decisions. Since the main focus of that paper lies on strategic decisions, transport flows are incorporated in a highly simplified way and are assumed to be carried out unidirectionally and with almost full truckload. However, by starting to study transportation processes more closely, companies may be able to find further ways to improve their economic and environmental performance. This is of special relevance in regional distribution activities, because most of the transport is carried out via carbon intensive transport modes (i.e. trucks) over relatively short distances. Since it is expected that additional environmental regulations concerning emissions from truck transportation will come into force in the years to come (see, for example, European Commission 2011), an assessment and possible ways of improving these emissions should be studied more carefully.

One possibility to reduce emissions from transportation activities is increasing transport efficiency which can be measured through a vehicle's average load factor and the amount of empty trips. The improvement of these two measures is very attractive for companies, since it is assumed that both economic and environmental performance can be enhanced at the same time (McKinnon and Edwards 2010). Increased efficiency can be achieved through cooperation and collaboration in a supply chain e.g. by switching from a retailer-managed inventory (RMI) policy to a vendor-managed inventory (VMI) replenishment policy. Whereas in an RMI the retailer is responsible for replenishment decisions, the supplier decides the timing and quantity of shipments to the retailer in a VMI system (Cachon and Terwiesch 2009; Mishra and Raghunathan 2004). A collaboration concept like this is well adapted in certain industries, especially in, but not limited to, the grocery industry.

In order to show the applicability and the benefits of a VMI policy on both costs and carbon emissions from truck transportation, we analyze a special variation of the well-known Vehicle Routing Problem (VRP) and extend it to include environmental aspects. This so-called Inventory Routing Problem (IRP) features the same characteristics as VMI and allows an assessment of the economic and environmental performance based on a mathematical model.

We extend the model to also include environmental considerations and apply it to a real-world case study from the petrochemical industry in order to show its relevance in real-life applications. The formulation of a petrochemical distribution network as IRP is particularly suitable, since retailers and suppliers often belong to the same company, thus favoring collaboration activities. Furthermore, petrochemical companies consider logistics as quite a significant source of costs in their supply chain and, therefore, focus their efforts for cost reduction on logistics (McKinnon 2005). We base our work on the results of Treitl and Jammernegg (2011), who focus on strategic decisions and, thus, put no emphasis on a detailed analysis of transport processes. In this work, however, the transport processes are the center of attention and we seek to provide pareto-improvements compared to a situation where collaboration does not exist. When considering economic and environmental aspects we are, therefore, one of the first to show the importance of collaboration in supply chains and the significance of detailed transport analyses. By applying the IRP to this particular case study and by analyzing the results obtained from this work, we are able to respond to the following questions:

– Given a rather simplified analysis of transport processes, is it possible to gain more precise results concerning costs and emissions when incorporating routing decisions in a model?
– Does collaboration through VMI together with a detailed analysis of transport processes lead to substantial improvements in costs and emissions compared to RMI and an aggregated analysis of transport processes?
– Is there still a trade-off between costs and carbon emissions as soon as transport processes are analyzed in detail?

The remainder of this paper is organized as follows. Section 2 takes a look at the impact of transport activities on the environment in general. Section 3 provides a thorough analysis of literature concerning VRPs with environmental considerations and presents the basic concepts of an IRP. The model used for the economic and environmental analysis is introduced in Sect. 4, while Sect. 5 presents the application of the model to the case study and points out the results and interpretations of the calculations. Section 6 concludes this paper by pointing out limitations of the model and suggesting further research opportunities.

2 Emissions from transport activities

Economic growth and the development of transportation are closely related. Although transport has long been considered as a simple necessity, it soon started to gain importance and to be an integral way of achieving competitiveness (Golicic

et al. 2010). In the European Union, freight transport activities in terms of tonne-km increased steadily from 1995 to 2005, on average 2.8 % each year. By comparison, the current transport activities in the EU27 would equate to moving one ton of goods over 23 km per day per inhabitant. This drastic rise in transport activities can largely be attributed to increases in road transportation (on average 3.5 % per year), which is still the predominant transport mode in Europe. Currently, 47 % of freight transport activities are carried out via this mode (Mahieu 2009).

The reasons for increased transport activities are, for example, the ongoing integration of the market and the liberalization of the transport market itself in combination with relatively low costs of freight transport. Furthermore, current business strategies and operations favor increased transport activity in many cases. As mentioned by Aronsson and Huge-Brodin (2006) as well as Golicic et al. (2010), practices like global sourcing or just-in-time deliveries accelerate the recent growth in the transport sector, resulting in larger distances between resource extraction, manufacturing, and distribution facilities (McKinnon 2006). A significant reduction in transport activity is not likely to take place in the years to come. On the contrary, studies conducted by Piecyk and McKinnon (2010) show for the UK that current best practices like centralization of production and inventory as well as the relocation of production capacity to other countries are expected to proceed until 2020 and beyond. These strategies together with operational best practices like the increased use of online retailing, global sourcing and product-returns have considerable effects on a company's transport activities.

The combustion of fossil fuels releases greenhouse gases into the atmosphere contributing to further global warming. In accordance with the Kyoto Protocol, six different gases are subsumed under the term greenhouse gases with carbon dioxide (CO_2) accounting for 84 % of greenhouse gas emissions in the European Union in 2005. Other greenhouse gases like methane (CH_4) and nitrous oxide (N_2O) account for only a minor share of approximately 7 % respectively (EEA 2009). In 2006, the transport sector was responsible for almost 20 % of greenhouse gases emitted in the EU27, which makes it the second biggest polluter after the energy industries and the only sector that was not able to reduce its emissions compared to recent years. Almost 93 % of greenhouse gas emissions from transport activities stem from transportation on road, making it the predominant mode not only in terms of tonne-km but also in terms of greenhouse gas emissions (Mahieu 2009).

The determination of greenhouse gas emissions from transport processes on the road is very complex. Especially CH_4 and N_2O emissions are difficult to assess, since they depend on lots of different aspects of combustion dynamics, for example the type of emission control system used in the vehicle, ambient temperature or air-to-fuel ratio (Lipman and Delucci 2002). CO_2 emissions, however, are directly proportional to the fuel consumption of a vehicle and are, thus, of particular interest for the environmental analysis of transport processes. Although it is often assumed that CO_2 emissions increase linearly with the distance driven, van Woensel et al. (2001) already indicated this to be wrong more than ten years ago. That is why not only the distance traveled but also the load of the vehicle and many other factors must be taken into consideration in order to determine the actual fuel usage accurately. Using average loads and average emission factors suffices only for the

determination of carbon emissions of rudimentary transportation tasks (unidirectional or pendulum routes) like it is done in carbon calculators on the Internet (see, for instance, EcoTransIT World 2008; NTM Road 2008). But an analysis like this leads to insufficient and inaccurate results as soon as the transport tasks become more complex. Treitl et al. (2010) conclude that different driving habits, the current weather situation, congestion and stop-and-go traffic influence the actual emissions of transport to a large extent. Furthermore, Palmer (2007) and Barth and Boriboonsomsin (2009) identify some additional influential elements like, amongst others, the size of the vehicle, average speed, the size of the engine, the type of fuel used, road geometry as well as the tires' rolling resistance and air density. Only if all these criteria are considered, an accurate measure of fuel usage and, consequently, transport emissions is possible.

The precise determination of emissions becomes increasingly important for companies today. According to Simchi-Levi (2010) three main reasons for this development can be identified. First, today's consumers are more aware of the products they buy, considering also issues like "Fair Trade" or minimal environmental damage. Consequently, consumers are increasingly demanding "green products". Second, companies usually associate high emissions with inefficiencies in their operations. Through the reduction of inefficiencies it is often assumed that environmental impacts are reduced as a positive side effect. The third reason mentioned by Simchi-Levi (2010) as well as Wu and Dunn (1995) is the need to comply with environmental regulations from governments and organizations. National as well as international governments (especially the EU) have already introduced different environmental regulations in order to reduce emissions or to protect the environment in general. Examples of regulations in this respect are manifold and include, for instance, vehicle emission standards, recycling requirements, or the EU Emission Trading Scheme (ETS). The EU ETS aims at reducing carbon emissions from manufacturing activities in certain energy intensive industries and aviation. However, activities associated with the (surface) distribution of products, i.e. transportation and warehousing activities, are not part of the EU ETS or other strict environmental regulations with respect to greenhouse gas emissions. However, this situation is expected to change in the near future (see, for example, European Commission 2009, 2011). There are several ways of imposing environmental regulations on distribution activities, but currently the main focus lies on regulating greenhouse gas emissions from transportation. One possibility is to set a carbon cap which is equivalent to an upper limit on the absolute amount of carbon emissions. But the most widely discussed topic in this respect is increased costs per unit of emissions, for example by imposing a tax on transport emissions (Aronsson and Huge-Brodin 2006; Piecyk and McKinnon 2007). Such regulations directly influence the economic result of a company, which makes it possible for companies to gain a competitive advantage if they assess the impact of their transport activities on the environment early enough.

One topic that is often mentioned when it comes to transport emission reduction opportunities, is increasing the load factor of vehicles and reducing empty driven km (empty trips). The weight-based load factor is determined by the ratio between the actual tonne-km a vehicle travels and the maximum tonne-km achievable if the

vehicle was loaded to its full capacity. Empty trips are excluded from this calculation and represent the amount of vehicle-km a truck runs empty compared to the total vehicle-km (Department for Transport 2011). To give an estimation, the average load factor in the petrochemical industry is 77 % with 20 % of empty running (McKinnon and Piecyk 2010). According to McKinnon and Edwards (2010), empty running is considered a consequence of unidirectional movement and, among others, a lack of cooperation across the supply chain. Consequently, an improvement of empty trips and load factors, meaning the enforcement of almost full truckload deliveries and reducing the length of trips gone empty, can be achieved through an efficient routing of vehicles together with appropriate measures of collaboration. By doing so, both the economic and environmental performance of transport processes can be enhanced.

3 Related literature

Distribution activities in general have recently started to be an integral part in sustainable supply chain literature. Decisions in this context must be taken on the long-, mid- and short-term level and some authors have already investigated the impacts different decisions can have on the environmental performance. Literature is, for example, available on facility location decisions (Wang et al. 2011; Treitl and Jammernegg 2011), lot sizing decisions (Benjafaar et al. 2010), inventory decisions (Hua et al. 2011; Bonney and Jaber 2010) or transport mode choice (Hoen et al. 2010). However, detailed analyses of transport activities and in particular vehicle routing decisions have long been ignored by research in the field of sustainable supply chains. Only recently transport processes have been given attention to in this field of research. There are already several authors dealing with the combination of sustainability issues and vehicle routing, which will be described in the following section. However, to the best of our knowledge, there is no contribution that incorporates environmental issues into an Inventory Routing Problem. Hence, only the basic concepts of IRPs are described in the subsequent section.

3.1 Vehicle routing problems and sustainability

Usually the objective of VRPs is the minimization of total transport costs or distance. Environmental issues have long been disregarded, since it is argued that optimizing routes and reducing total distance by itself results in less fuel consumption and, thus, less environmental damage (Sbihi and Eglese 2007). This, however, needs to be investigated in more detail, since fuel consumption is not only dependent on the distance traveled, but also on other factors like speed, load and type of the vehicle as well as driving patterns. Especially when environmental regulations with respect to greenhouse gas emissions from transportation come into force, the assessment of actual vehicle emissions and possible improvements, for example through collaboration, is of great importance.

   One of the first to consider this topic are Ericsson et al. (2006). They develop a framework for a driver support tool (navigation system) that determines optimal

routes not based on costs or time but based on the lowest total fuel consumption. In contrast to the majority of work concerning VRP, the authors use empirical data for their analyses. More than 200 cars in Lund (Sweden) have been equipped with a measuring unit over three years in order to register the driving behavior and pattern of the operator. Furthermore, different characteristics of roads are determined that have an influence on fuel consumption, among them are, for example, the street type (rural or city street), speed limits and traffic density. Their analyses show that through the choice of fuel-optimized routes, in contrast to a cost- or time-minimized route, a reduction in fuel consumption of more than 8 % can be achieved.

Kara et al. (2007) propose a mathematical model called "Energy Minimizing VRP". Arguing that the real costs of a vehicle traveling on a route are composed of different variables that are not directly related to distance measures, they add the actual load of a vehicle to the objective function. In some illustrative examples the authors show the differences between the "classic" distance minimizing VRP and their newly developed model. The routes that are selected differ significantly between the two models, indicating a trade-off between energy minimization and total cost minimization. Figliozzi (2010) takes a similar approach by introducing the "Emission Minimization VRP". The author formulates a multi-objective model taking into account vehicle costs, distance traveled, route duration and emissions. Emissions in this respect are dependent on the speed of the vehicle, thereby also considering congestions and stop-and-go traffic. The problem is then solved with a specific algorithm which shows that it is possible to reduce emissions with only negligible increases in routing costs by taking others than the cost-optimal routes.

A recent publication in this respect is Bektas and Laporte (2011). They create a VRP model that also takes emissions from transportation activities into consideration. The calculation of emissions is based on several different aspects, however the most predominant parameters are the type of truck used, the load factor and the speed of the vehicle. Greenhouse gas emissions are then converted into costs and included in the objective function. Four different problems with different objectives are tackled in this work. First, the authors consider a "classical" distance minimizing VRP with constant speed as well as a problem with a weighted load minimizing objective function with constant speed. Furthermore, they present an energy minimizing problem where speed is a decision variable. Finally, a model is presented that optimizes total costs, consisting of costs for emissions, drivers and fuel. The results of an illustrative example show, among others, that the cost optimal route is not the one that minimizes energy demand.

All these publications show possible ways to incorporate sustainability issues into VRPs. However, in the general case of a VRP, the route a vehicle takes is optimized subject to several constraints. Whereas some parameters can be determined by the supplier, a few cannot and are determined by other entities, for example the retailer. Especially the quantity of the retailer's order as well as the demanded delivery time might counteract better results that could be achieved in a collaborative situation where retailer and supplier are working together, e.g. by using VMI. In order to assess the benefits of this type of collaboration, VRPs are not sufficient and must be extended to consider inventory decisions at the same time.

3.2 Inventory routing problems

IRPs are a variation of the classical VRP. As one of the first authors to do so, Federgruen and Zipkin (1984) show the positive economic effects the coordination of distribution and inventory decisions can have. In general, IRPs deal with the (repeated) distribution of products from a single facility to a certain number of customers (or retailers) over a given time horizon (Bertazzi et al. 2008). In contrast to classical VRPs, customer orders are not relevant in this particular class of problems. Instead, the quantity delivered to a customer is determined by the supplier (Moin and Salhi 2007). Therefore, decisions must be made concerning when to serve a customer, how much to deliver and which route to take, making the IRP a mid-term problem instead of a short-term problem as the VRP. Since they feature the same characteristics, IRPs are very suitable for VMI environments and have been addressed in different industries, for example the automotive industry, apparel industry and grocery (see Campbell and Savelsbergh 2004, and the references therein).

Due to its complexity, the ways to model IRPs are manifold. Models in this respect differ for instance according to the planning horizon which can be finite or infinite. Furthermore, the production and consumption rates can either be modeled in a deterministic or a stochastic way and they can be stationary or non-stationary. In addition to that, inventory holding costs can be incorporated at the supplier or at the customer, apply to both actors or to none. Even more, capacity constraints at the supplier and the customer as well as the type of fleet used for transportation can be different (Bertazzi et al. 2008). This means that, although the models share the same basic characteristics, it is rather unusual that different authors define the problem in the same way (Coelho et al. 2012).

IRPs are NP-hard and so far the only exact algorithm to solve small instances of this problem is presented by Archetti et al (2007). In many cases the authors apply certain heuristics to obtain almost-optimal solutions within reasonable time. Coelho et al. (2012), for example, use an adaptive large neighborhood search heuristic to solve their problem, whereas Archetti et al. (2012) use a hybrid approach, making use of tabu search as well as exact solution methods for small subproblems. For a better overview of different solution approaches see Moin and Salhi (2007) and Moin et al. (2011).

In this work we will present an IRP with a fixed number of available vehicles, capacity constraints at the customer as well as stationary and deterministic demand over a finite planning horizon. Inventory costs are not included in the model for reasons elaborated in the following section. Whereas classical IRPs aim at optimizing economic indicators, like costs or distance, there is currently no work available that combines economic and environmental aspects in IRPs. Hence, we extend the model to also include environmental aspects and present the results of a case study from the petrochemical industry. Because of its focus on the application, this work will not elaborate on the modeling of the IRP and on defining new solving methods for (near) optimal solution obtaining. Rather this paper aims at the managerial consequences for a company that switches from a retailer-managed inventory to a vendor-managed inventory and the corresponding economic and

environmental implications. Thus, we are not interested in solving the model exactly but we apply a given solution method to the model and stop the calculation after a predefined time limit, even if optimality is not granted. By doing so we provide means for pareto-improvements or win-win situations to the company under consideration, since we can show that at least one considered aspect is improved while another aspect is (at least) not deteriorated. Hence, we are able to show the positive effects of collaboration, in particular VMI, on the economic and on the environmental performance of a company based on a mathematical model, which has not been done yet to the best of our knowledge.

4 Problem and model description

4.1 A motivating case study

We illustrate our approach by presenting the results of a case study from the petrochemical industry. Being aware of the constant market pressure from international competitors, one of the leading petrochemical companies in South-eastern Europe aims at reducing its costs of distribution. Figure 1 depicts the distribution network of the company. Crude oil is either exploited from domestic oil fields or offshore oil rigs or it is imported from other oil producing countries. Afterwards, the crude oil is directly transported to a single refinery by pipeline or train for further processing. In the refinery the crude oil is transformed into several final products. In the course of this paper, the analysis concentrates on fuel, meaning gasoline and diesel products alike. For simplification purposes we make no differentiation between these two products. After processing, the fuel is transported to 21 storage locations (depots) spread across the region in accordance with the demand in the surrounding area. Inbound transportation to the storage locations (primary transport) is carried out by rail; there is only one storage location that possesses a direct connection to the refinery via pipeline. From the storage locations the fuel is further transported by truck to the company's own filling stations (secondary transport). The filling stations are responsible for replenishing their local
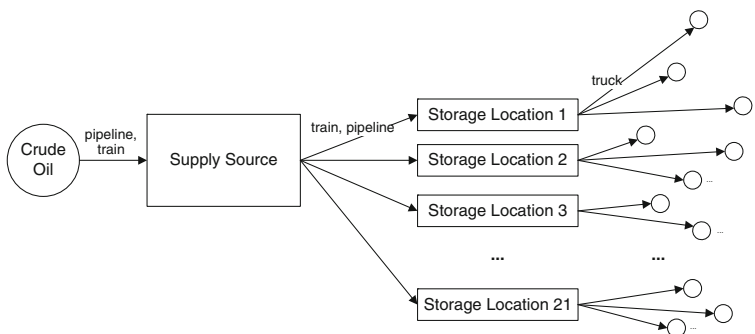

Fig. 1 Distribution network overview

inventories themselves. Consequently, they order almost full truckload quantities from their assigned depot whenever necessary.

In a former study, Treitl and Jammernegg (2011) determined the optimal number of storage locations and the corresponding allocation of demand points to these storage locations by solving a p-median problem. The cost-optimal network design under retailer-managed inventory turned out to consist of six strategically located operating storage locations. For that study, primary and secondary transport costs as well as fixed and variable storage costs were considered. It could be shown that reducing the number of storage locations leads to reductions in operational costs due to reductions in fixed costs, but also to increases in secondary transport activities (by truck) due to the storage locations being farther away from their assigned filling stations. Interestingly, total costs increased as soon as a certain degree of centralization was reached and decreases in fixed costs were compensated through increases in secondary transport costs. From an environmental perspective, the performance was determined by direct carbon emissions from truck transportation and indirect emissions from transportation via rail. Because of its higher carbon intensity (compared to rail transportation) the overall amount of emissions was to a large extent dependent on the amount of truck transportation in the network. Hence, by reducing the number of storage locations, the amount of truck transportation and, thus, overall emissions increased drastically. A trade-off between economic and environmental measures could be shown, indicating that improvements in costs result in a deterioration of environmental performance.

The company in consideration has implemented the suggested cost-optimal network structure in the considered region, but faces inefficiencies in its transport processes. This is mainly due to the filling stations operating based on an RMI replenishment policy and, thus, ordering fuel from the depot whenever they need to be refilled. Usually, the order quantities are chosen in order to be delivered by a full truck. Between the different filling stations there is currently no collaboration or communication and so the only information for the depot is the amount ordered by the individual filling stations. Therefore, the company must deliver almost full truckload quantities to the filling stations and the trucks return back to the depot empty, thus performing a pendulum route. This results in a high amount of empty driven kilometers which negatively effects the economic as well as environmental performance of transport activities. In order to improve this situation, the company plans to implement a VMI replenishment policy, where the replenishment of the filling stations is coordinated centrally by the depot and no longer by the filling stations themselves. Generally, it is assumed that VMI helps to abate the bullwhip effect through information sharing, reducing order synchronization effects and reducing order-batching (Cachon and Terwiesch 2009). The latter is achieved through the shipment of smaller batches than would be usually ordered. This fact, however, does neither counteract nor favor the increased use of less-than-truckload deliveries, but enables the combination of deliveries to different customers. In this particular case, this means that the depot decides when and how much to deliver to the filling stations, allowing a truck to visit several filling stations on its route and replenishing them with smaller quantities. This kind of collaboration is possible and very suitable since the depot and the filling stations belong to the same company.

However, the determination of optimal delivery schedules and the assessment of economic and environmental performance measures requires a more detailed analysis of transport processes than, for instance, facility location decisions.

For a better overview, the characteristics of the replenishment operations analyzed in this work are briefly summarized in Table 1. Whereas the transport processes based on the p-median problem are determined by orders from the filling stations (RMI), the depot decides about replenishment in the IRP. Consequently, only pendulum routes are considered under the RMI replenishment policy, whereas all kinds of round trips are allowed under the VMI replenishment policy. By analyzing and comparing the transport processes in these two different settings, we can derive the benefits a VMI replenishment policy has on transport efficiency compared to a RMI replenishment policy.

4.2 Model definition

By analyzing and comparing the transport processes in the two different models, we can derive the benefits a VMI replenishment policy has on transport efficiency in this particular case study compared to a RMI replenishment policy. Therefore, we solve the basic IRP without considering inventory costs and extend it to integrate environmental aspects. Since in this case the retailers (filling stations) as well as the supplier (depot) belong to the same company, the costs for holding inventory can be neglected (see Bertazzi et al. 2008). Moreover, because of the high turnover at the filling stations, inventory holding costs are not relevant in this case study.

We focus on one particular depot that is responsible for replenishing filling stations with fuel, assuming stationary and deterministic demand at the filling stations. Whereas the filling stations have only limited storage capacities, the supplying depot has an infinite supply of fuel available and no capacity constraints. Each truck can leave the depot only once per period, but more than one truck can visit a filling station in each period, as long as product availability is granted at all times. Backorders are not allowed in the model. Costs incur in the transportation process itself and consist of a variable part that is dependent on the distance traveled and of a fixed part that occurs every time a truck leaves the depot. Each tour starts and ends at the depot. In addition to this classical definition of an IRP, direct CO_2 emissions from truck transportation and indirect CO_2 emissions from energy purchasing in the filling stations are determined during the calculation and added to the objective function using a carbon price. The IRP is then solved with the objective of minimizing total costs.

Table 1 Characteristics of replenishment operations

Deliveries based on	p-Median	IRP
Replenishment policy	RMI	VMI
Order/delivery decision made by	Filling station	Depot
Route type requirement	Only pendulum route	Round trip

Let $G = (V, A)$ be a complete graph and $\{1, \ldots, T\}$ a set of time periods. $V = \{0, 1, \ldots, n\}$ is the vertex set and A is the arc set. Vertex 0 stands for the depot, where K homogeneous trucks, each with capacity Q are located. Vertices $i = 1, \ldots, n$ represent the filling stations that were assigned by solving the p-median problem. The length of arc $(i, j) \in A$ is given by l_{ij}, whereas the travel cost on arc $(i, j) \in A$ is denoted c_{ij}; the travel cost matrix satisfies the triangle inequality. When a vehicle leaves the depot, fixed costs of c_f are charged. The demand that occurs at filling station i at time period t is represented by d_i^t. The initial inventory level at filling station i is I_i^0. The maximal inventory level at filling station i is limited by C_i.

P_{ij}^{tk} represents the amount of energy (in Joule) that is necessary for vehicle k to traverse the arc from vertex i to j in period t. The calculation of energy is rather complex and requires the vehicle speed v, the length of the arc l_{ij} and the vehicle weight w as well as other specific parameters ($a, g, \theta, C_r, C_d, A, \rho$) which are explained in Table 3. The result can be different for every vehicle and can directly be translated into CO_2 emissions using the conversion factor cf_v. The electricity that is needed at filling station i to pump fuel in and out of its local inventory is denoted by h_i. En_i is the total amount of energy required at filling station i which can be translated into CO_2 emissions using conversion factor cf_w. Emissions are associated with a carbon price per ton c_e and the total amount of emissions E_{tot} must not exceed a certain upper limit (carbon cap, E_{cap}).

The following decision variables are introduced. Flow variable x_{ij}^{tk} is a binary variable set to 1 if filling station j is visited immediately after filling station i in time period t by vehicle k, 0 otherwise. The volume of fuel that is delivered to filling station i by vehicle k in time period t is denoted s_i^{tk}. Variables I_i^t are introduced to compute the inventory level at filling station i before demand occurs at time period t. The load of vehicle k on the arc (i, j) in time period t is described by q_{ij}^{tk}.

Table 2 summarizes the general notation. Using this notation, the Inventory Routing Model can be formulated as follows:

$$min : \sum_{i=0}^{n}\sum_{j=0}^{n}\sum_{t=1}^{T}\sum_{k=1}^{K} c_{ij}\, x_{ij}^{tk} + \sum_{j=1}^{n}\sum_{k=1}^{K}\sum_{t=1}^{T} c_f\, x_{0j}^{tk} + c_e\, E_{tot} \tag{1}$$

$$\sum_{i=0,i\neq p}^{n} x_{ip}^{tk} = \sum_{j=0,j\neq p}^{n} x_{pj}^{tk} \quad p=0,\ldots,n, t=1,\ldots,T, k=1,\ldots,K \tag{2}$$

$$q_{ij}^{tk} - s_j^{tk} + \left(1 - x_{ij}^{tk}\right) M \geq q_{jy}^{tk} \quad i=0,\ldots,n, j=1,\ldots,n, y=0,\ldots,n, k=1,\ldots,K, t=1,\ldots,T \tag{3}$$

$$M \sum_{i=0}^{n} x_{ij}^{tk} \geq s_j^{tk} \quad j=1,\ldots,n, k=1,\ldots,K, t=1,\ldots,T \tag{4}$$

$$q_{ij}^{tk} \leq Q \quad i=0,\ldots,n, j=0,\ldots,n, k=1,\ldots,K, t=1,\ldots,T \tag{5}$$

$$\sum_{j=0}^{n} q_{0j}^{tk} = \sum_{j=0}^{n} s_j^{tk} \quad t=1,\ldots,T, k=1,\ldots,K \tag{6}$$

Table 2 Notation of the model

Parameters	
n	Number of filling stations
T	Number of time periods
K	Number of trucks
d_i^t	Amount of fuel demanded at filling station i in period t
Q	Maximum capacity of a vehicle
I_i^0	Initial inventory at filling station i
c_{ij}	Cost for traveling from location i to location j
l_{ij}	Length of arc (i, j)
c_f	Fixed vehicle costs
c_e	Emission costs per ton of CO_2
C_i	Maximum storage capacity at filling station i
P_{ij}^{tk}	Energy requirements (in Joule) of vehicle k in period t on arc (i, j)
h_i	Energy required (in kWh) to handle one ton of fuel in filling station i
v_{ij}	Vehicle speed on arc (i, j)
w	Empty vehicle weight
En_i	Total energy requirements (in kWh) at filling station i
E_{tot}	Total amount of CO_2 emissions from transportation and warehousing
cf_v	Conversion factor for transport activities (Joule to kg CO_2)
cf_w	Conversion factor for warehousing activities (kWh to kg CO_2)
E_{cap}	Emission cap
Variables	
x_{ij}^{tk}	1 if vehicle k goes directly from location i to j in period t 0 otherwise
s_i^{tk}	Quantity delivered to location i in period t by vehicle k
q_{ij}^{tk}	Load of vehicle k on arc (i, j) in period t
I_i^t	Inventory at location i at the beginning of period t

$$I_i^t = I_i^0 - \sum_{f=0}^{t-1} d_i^f + \sum_{k=1}^{K} \sum_{f=0}^{t-1} s_i^{fk} \quad i=1,\ldots,n,\, t=1,\ldots,T \tag{7}$$

$$I_i^t + \sum_{k=1}^{K} s_i^{tk} \le C_i \quad i=1,\ldots,n,\, t=1,\ldots,T \tag{8}$$

$$P_{ij}^{tk} = \left(a + g\left(\sin\theta_{ij} + C_r \cos\theta_{ij}\right)\right)\left(w\, x_{ij}^{tk} + q_{ij}^{tk}\right) l_{ij} \\ + (0.5\, C_d\, A\, \rho) v_{ij}^2 l_{ij} \quad i=0,\ldots,n,\, j=0,\ldots,n,\, t=1,\ldots,T,\, k=1,\ldots,K \tag{9}$$

$$En_i = \sum_{t=1}^{T} h_i d_i^t + \sum_{t=1}^{T} \sum_{k=1}^{K} h_i s_i^{tk} \quad {}_{i=0,\dots,n} \tag{10}$$

$$E_{tot} = cf_v \sum_{i=0}^{n} \sum_{j=0}^{n} \sum_{t=1}^{T} \sum_{k=1}^{K} P_{ij}^{tk} + cf_w \sum_{i=1}^{n} En_i \tag{11}$$

$$E_{tot} \leq E_{cap} \tag{12}$$

$$I_i^t \geq 0 \quad {}_{i=0,\dots,n,\,t=1,\dots,T} \tag{13}$$

$$x_{ij}^{tk} \in \{0, 1\} \quad {}_{i=0,\dots,n,\,j=0,\dots,n,\,t=1,\dots,T,\,k=1,\dots,K} \tag{14}$$

$$q_{ij}^{tk} \geq 0 \quad {}_{i=0,\dots,n,\,j=0,\dots,n,\,t=1,\dots,T,\,k=1,\dots,K} \tag{15}$$

$$s_i^{tk} \geq 0 \quad {}_{i=0,\dots,n,\,t=1,\dots,T,\,k=1,\dots,K} \tag{16}$$

Equation (1) represents the objective function, minimizing total transport costs as well as costs for CO_2 emissions from transport activities and warehousing activities over the planning horizon. Constraints (2) make sure that vehicles that enter a filling station for replenishment also leave the filling station in the same time period. Constraints (3), in which M is a sufficiently large number, force the vehicle load to decrease after the visit of filling station j. It is determined by the vehicle load carried from i to j minus the quantity of fuel delivered to j. By these constraints subtours are eliminated as well. Constraints (4) represent demand satisfaction constraints, assuring that deliveries to j are only carried out when a vehicle travels to j. Constraints (5) determine the load of a vehicle as less or equal to the maximum capacity of a vehicle. Constraints (6) make sure the load of a truck leaving the depot is the same as the sum of deliveries to the filling stations in time period t. The inventory at filling station i in time period t follows Constraints (7). Inventory is measured at the beginning of each period. After the determination of the inventory level the deliveries of the current period arrive, followed by the realization of the current period's demand. As a consequence, the inventory level plus the deliveries in a certain period must not exceed the capacity at the filling stations. This is made sure of by Constraints (8). Equation (9) determine the energy (in Joule) that is required for a vehicle k to traverse arc (i, j) in period t. The calculations are explained in more detail in the following. Equation (10) determines the energy (electricity) in filling station i that is required to pump fuel in and out of the filling station. With the help of conversion factors cf_v and cf_w, Eq. (11) calculates the total amount of CO_2 emissions caused by transport and warehousing activities. Constraint (12) assures that the total amount of emissions does not exceed a certain emission cap. The remaining constraints determine the variables of the IRP.

We will now go into detail concerning Constraints (9), (10), (11) and (12). These constraints as well as the last term in the objective function are extensions of IRPs in the literature and determine the environmental component of this model. As already described in Sect. 2, CO_2 emissions from transport processes depend on many different aspects. Although there are several authors dealing with the topic of

Table 3 Parameters for emission calculation

Empty vehicle weight (w, in tons)	16.00
Acceleration of vehicle (a, in m/s^2)	0.00
Gravitational constant (g, in m/s^2)	9.81
Road angle (θ, in degrees)	0.00
Coefficient of rolling resistance (C_r)	0.01
Coefficient of drag (C_d)	0.77
Frontal surface (A, in m^2)	6.50
Air density at ground level at 20°C (ρ, in kg/m^3)	1.20
Energy required (in kWh) to handle one ton of fuel in filling station i (h_i)	0.55
Conversion factor for vehicle energy consumption (cf_v)	6.94×10^{-8}
Conversion factor for warehousing energy consumption (cf_w)	0.41

calculating emissions and fuel usage from transportation (see, in particular, Palmer 2007), we base our calculations on Barth and Boriboonsomsin (2009) and on a specific adaption of Bektas and Laporte (2011) for vehicle routing applications. This calculation procedure results in energy requirements in Joule (P_{ij}^{tk}) needed by vehicle k to traverse arc (i, j) with length l_{ij} (in meters) in period t. In this formulation the vehicle load on that particular arc (q_{ij}^{tk} in kg) as well as the average vehicle speed (v_{ij} in m/s) on a trip from i to j is included, which makes this method particularly suitable for vehicle routing problems in general. Besides the distance, the average speed and the load, many other aspects must be considered in order for the analysis to be accurate. Thus, Eq. (9) takes into account further vehicle related aspects as well as geographical aspects which are summarized in Table 3. These parameters remain unchanged during the calculation. Nevertheless, a detailed outcome of the calculations is warranted and guarantees a much more accurate result than just applying a conversion factor on the total amount of kilometers driven.

Since a homogeneous fleet of vehicles is used, the rolling resistance (C_r), the frontal surface of the vehicle (A) and the coefficient of drag (C_d) are the same for all trucks. We assume a perfectly horizontal road with no incline and no decline, thus resulting in a street angle (θ) of zero degrees. Additionally, air density (ρ) remains unchanged, assuming an altitude of ground level and a temperature of 20 degrees Celsius. For each trip on a tour we assume an average speed without acceleration and deceleration, resulting in an acceleration value (a) of zero m/s^2. This assumption is perfectly reasonable for overland transportation where a constant speed can be traveled, but this is not the case for inner-city transportation. Within cities usually acceleration- and brake applications alternate, which influences emissions drastically (although the distance traveled stays unchanged). In order to account for this fact, we introduced an "inner-city factor" that increases the energy requirement for inner-city transport by one third compared to motorway and rural transportation (see NTM Road 2008). Values for the coefficient of rolling resistance are taken from Gillespie (1992), while Akcelik and Besley (2003) provide estimates for the coefficient of drag as well as the frontal surface area of a medium to heavy truck. The energy in Joule is directly proportional to diesel energy which can finally be converted to CO$_2$ emissions using the conversion factor cf_v (Defra 2011).

The energy requirements of the filling stations consist mainly of the electricity that is used to pump fuel into the local storages (i.e. when deliveries are made) and out of local storages when demand occurs. This energy is directly proportional to the amount of fuel and amounts to h_i kWh per ton of delivery or demand. Since the company under consideration does not produce its own electricity it must purchase it and, consequently, also the emissions associated with it. Given the energy mix of the region where the company operates, the conversion factor cf_w can be applied in order to obtain the indirect CO_2 emissions that are caused by electricity use in the filling stations (ABB 2011).

4.3 Illustrative example

Before the case study from the petrochemical industry is analyzed, we present an illustrative example to show the aim of this work more clearly. Consider a discrete time setting with a planning horizon of six days where a depot is responsible for the replenishment of three retailers (filling stations). These retailers serve customers from a local storage, whereby the daily demand (d) and the maximum inventory capacity (C) as well as the distance between the retailers and the depot (in km) are given in Fig. 2. For the sake of simplicity assume that the traveling costs are linear and equal one Euro per km. At the beginning of the planning horizon the local storages at the retailers are filled to their maximum capacity. The retailers' storages are replenished using an RMI policy. Consequently, the retailers order goods from the depot whenever their inventory (at the end of the period) does not suffice to satisfy the demand in the next period. They receive the delivery on the next day before demand occurs, delivered by trucks with a capacity of 24 units. Fixed costs of 30 € occur whenever a truck leaves the depot. The order quantity is chosen to fill the local storages to their maximum capacity.

Analyzing this basic setting (with RMI) in detail concerning order quantities and timing of orders results in Table 4a, where the actual inventory is displayed in bold numbers and deliveries in italics. For the two retailers A and B, the inventory level in period 3 is too low to serve the demand in the next period. Consequently, an order is issued at the depot of 24 and 21 units, respectively, and delivered to the retailers at the beginning of period 4. The capacity of the vehicle is too small to serve both
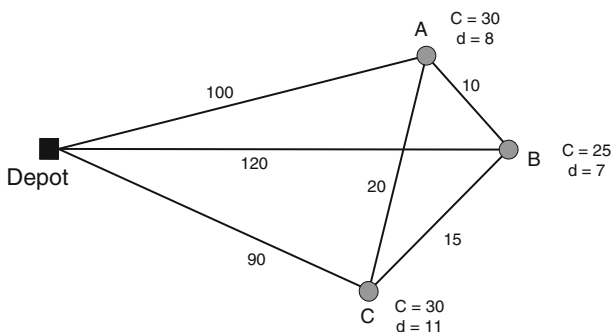

Fig. 2 Illustrative example

Table 4 Analysis of illustrative example

Time		A	B	C
(a) Basic setting				
0	Initial Inventory	**30**	**25**	**30**
	Delivery	*0*	*0*	*0*
1	Demand	−8	−7	−11
	Inventory	**22**	**18**	**19**
	Delivery	*0*	*0*	*0*
2	Demand	−8	−7	−11
	Inventory	**14**	**11**	**8**
	Delivery	*0*	*0*	*+22*
3	Demand	−8	−7	−11
	Inventory	**6**	**4**	**19**
	Delivery	*+24*	*+21*	*0*
4	Demand	−8	−7	−11
	Inventory	**22**	**18**	**8**
	Delivery	*0*	*0*	*+22*
5	Demand	−8	−7	−11
	Inventory	**14**	**11**	**19**
	Delivery	*0*	*0*	*0*
6	Demand	−8	−7	−11
	Inventory	**6**	**4**	**8**
(b) VMI setting				
0	Initial Inventory	**30**	**25**	**30**
	Delivery	*0*	*0*	*0*
1	Demand	−8	−7	−11
	Inventory	**22**	**18**	**19**
	Delivery	*+7*	*+7*	*+9*
2	Demand	−8	−7	−11
	Inventory	**21**	**18**	**17**
	Delivery	*0*	*0*	*0*
3	Demand	−8	−7	−11
	Inventory	**13**	**11**	**6**
	Delivery	*0*	*0*	*+24*
4	Demand	−8	−7	−11
	Inventory	**5**	**4**	**19**
	Delivery	*+11*	*+10*	*+3*
5	Demand	−8	−7	−11
	Inventory	**8**	**7**	**11**
	Delivery	*0*	*0*	*0*
6	Demand	−8	−7	−11
	Inventory	**0**	**0**	**0**

The actual inventory is displayed in bold numbers and deliveries in italics

Table 5 Results of illustrative example

(a) Basic setting	
Number of deliveries	4
Number of trucks	2
Fixed costs	120 €
Distance traveled	800 km
Total costs	920 €
Load factor	90.00 %
Empty trips	50.00 %
Transport CO_2 emissions	216.9 kg
Warehousing CO_2 emissions	54.9 kg
Total CO_2 emissions	271.8 kg
(b) VMI setting	
Number of deliveries	7
Number of trucks	1
Fixed costs	90 €
Distance traveled	610 km
Total costs	700 €
Load factor	93.94 %
Empty trips	45.90 %
Transport CO_2 emissions	147.9 kg
Warehousing CO_2 emissions	51.6 kg
CO_2 emissions	199.5 kg

customers at the same time, so at least two trucks are necessary for the delivery. Retailer C has a higher demand and, consequently, has to be replenished twice in the planning horizon. Since the orders from the retailers are done independently from each other, a coordination of replenishments is not possible. This means that the trucks go from the depot to the retailers with (almost) full truckload and return to the depot empty. Trucks leave the depot four times during the planning horizon, traveling 800 km and resulting in 120 € of fixed costs.

The amount of greenhouse gas emissions that are caused in this setting are determined by many different aspects, whereby the most important factors are the load of the trucks, the average speed of the trucks and the distance traveled both, loaded and empty. Obviously, the share of empty driven kilometers is 50 %. Since only pendulum routes are performed exactly half of the total distance is gone empty. Calculating the average weight-based load factor results in a value of 90 %. Assuming that the trucks can travel with a constant speed of 70 km/h, Eq. (9) is used for determining the required transport energy. In addition, using Eq. (10) determines the energy requirements of warehousing activities. Both values can be converted to CO_2 emissions by Eq. (11), which results in a total amount of 271.8 kg CO_2 that is emitted into the atmosphere, as indicated in Table 5a.

This situation is now compared to a situation where the depot replenishes the retailers using VMI. Since now the supplier is responsible for the coordination of shipments to the retailers, it is possible to deliver other than full truckload

quantities, combine retailers on tours and also determine the time of delivery. In order to show the benefits of VMI we solve this small illustrative example exactly with the proposed model assuming emission costs of zero and an infinite emission cap. Solving the problem towards minimal costs leads to the results depicted in Tables 4b and 5b, respectively. It is interesting to see that in the VMI setting only one truck is required instead of two in the basic situation. Furthermore, the retailers are not exclusively replenished in full truckload quantities any more, which results in the truck being able to serve more than one retailer on a tour. The truck makes, in total, seven deliveries but leaves the depot only three times, which reduces fixed costs to 90 € and also reduces the total distance that is necessary to 610 km. Consequently, the average weight-based load factor increases to 93.94 % and reduces the share of empty driven kilometers. Using again Eqs. (9), (10) and (11) total CO_2 emissions are calculated, amounting to 199.5 kg.

The results obtained by this illustrative example already indicate the outcome of the actual case study. By coordinating deliveries and shifting the decision making process from the filling stations to the depot, traveling costs as well as traveled kilometers can be reduced in a VMI environment. Total distance is reduced by 23.75 % compared to the RMI situation. It is obvious that a reduction of total kilometers driven is also accompanied by a reduction of CO_2 emissions but it is, however, interesting to see that the total emissions are not only dependent on the distance. Compared to total cost reduction, the reduction of emissions is much higher, namely almost 32 %. One reason for this emission reduction is increased efficiency, which is expressed through the higher load factor and the smaller share of empty driven kilometers in the VMI setting. This example shows that the load factor is of high importance for accurate emission calculation, especially since the load of a vehicle changes every time a filling station is visited. In a setting where only pendulum routes are considered, this fact is negligible. We also tested the robustness of this illustrative example concerning a longer planning horizon (12 days) and were able to observe the same implications. Thus, not only the route choice in the network but also the delivery quantities and the load of the vehicle need to be investigated in detail in order to properly assess the impact of VMI and the corresponding efficiency increases on the environmental performance of a company.

Although this setting is small enough to be solved exactly, the main focus of this work is not on obtaining (near) optimal solutions. Instead, the focus is on providing pareto-improvements or win-win situations which can be defined as improving one aspect of a problem without deteriorating another one or (ideally) improving all aspects of a problem. In this case we focus on two aspects, namely total costs and CO_2 emissions. We were able to show a pareto improvement in this illustrative example since costs as well as CO_2 emissions were improved at the same time. In the following, we seek pareto-improvements with respect to the RMI situation for the real-world case study.

5 Case study results

In this section, the results from the case study introduced in Sect. 4.1 are described. First, we analyze the transport processes in the p-median problem. Afterwards, we

apply the IRP to the case study and compare the results of the different models from an economic as well as environmental perspective. Additionally, we extend the analysis also for emission minimization and compare the results. The focus of the analysis is on one particular depot in the considered region that is responsible for replenishing seven provinces and a total of 45 filling stations in 27 cities.

5.1 Transport processes in the p-median model

In their work, Treitl and Jammernegg (2011) found out that the filling stations order almost full truckload quantities (on average 20.4 tons) from their assigned depot. Consequently, the company under consideration delivers fuel to its filling stations and returns back to the depot empty. This unidirectional delivery entails some economic as well as environmental drawbacks, since transportation is not done efficiently.

In a first step, we now take a closer look at the total transport costs and transport emissions caused in a situation where only pendulum routes occur. We refer to this as "basic situation". Assuming that deliveries can be made on seven days per week throughout the year, trucks with a capacity of 24 tons deliver on average 20.4 tons of fuel to the filling stations at each visit. This equates to a load factor of 85 % on the way to the filling station. After the delivery, the truck leaves the filling station to go back to the depot without any load, which means that 50 % of the total distance driven per year is gone empty. Given the annual demand and assuming stationary and deterministic sales, an average number of visits per year can be calculated. Consider, for instance, a filling station i that has an annual demand of 1,825 tons, equally distributed over the whole year. Assuming an average order quantity of 20.4 tons, a truck has to visit this filling station 1,825 / 20.4 $\approx$ 90 times per year. The distance from the depot to this filling station is 110 km, so a truck travels $90 * 110 = 9,900$ km per year with a load of 20.4 tons, resulting in 201,960 tonne-km to filling station i. However, the truck returns back to the depot empty, resulting in 9,900 empty driven kilometers. The total distance that has to be covered (in both directions) for all trucks supplying the filling stations in all provinces can be calculated this way. In total, vehicles drive 2,143,281 km in order to serve the 45 filling stations in the considered area each year. The vehicles consume an amount of 176,327 liter of Diesel and produce 461,979 kg of CO_2 emissions in the basic situation. Additionally, the warehousing operations consume 203,962 kWh of electricity which is equivalent to 83,216 kg of CO_2. Overall, a total amount of 545,195 kg CO_2 is emitted in the basic situation every year.

5.2 Transport processes in the IRP

We now show the advantages of VMI on this case study by applying the proposed IRP (we refer to this situation as "routing situation"). By allowing the depot to decide when and how much to deliver to the filling stations as well as determining the route the trucks are traveling on, a much more detailed analysis of transport processes concerning economic and environmental criteria is possible than in the p-median problem. Consequently, the results obtained are much more accurate and

are a good reference point for further studies and improvements. In a first step, we assume that costs for carbon emissions as well as a carbon cap do not exist, which is the case in reality today. The IRP is solved using a standard algorithm implemented in CPLEX 12.2 and concert technology. The calculations are carried out on a cloud system running Debian Linux 6 with up to 32 GB RAM and 8 parallel CPUs. For the calculation a time limit of one hour is imposed, independent of the gaps obtained. Since the focus of this work is not on finding the optimal solution of the problem but to provide the company with a win-win situation compared to the basic situation in reasonable time, this approach is justified.

For the case study we consider a time horizon of seven days. At the start of the planning period, initial inventory at the filling stations is at least 1.5 times the daily demand. In order to receive repeatable results, we assume that the demand of the eighth day must be satisfied from inventory. Furthermore, we assume a truck fleet of homogeneous vehicles with a capacity of 24 tons each. Since the size of the problem is still too large to be solved exactly with the proposed model in reasonable time, we use a decomposition approach and split the area into several small instances, denoted with letters A–G. These smaller instances correspond to the political provinces the depot is supplying and it is legitimate to assume that each province has its own dedicated truck team. By combining the solutions of the different instances, a results for the entire area can be derived. Depending on the size of the province, the truck teams consist of one to six trucks. These trucks are located at the depot and are solely responsible for the replenishment operations in their assigned area.

The details for the individual instances (number of trucks available and the number of filling stations supplied) as well as the computational statistics (gap and computational time) are depicted in Table 6. CPLEX uses a branch-and-cut algorithm for searching an optimal solution in mixed integer programs. It starts with an initial solution that satisfies all constraints. The solution space is explored systematically in order to find new best solutions and to eliminate infeasible solutions. For solutions that only violate the integrality constraints of the problem and that are smaller (for minimization problems) than the incumbent solution, the algorithm tries to improve them in order to become feasible. If all constraints are met, this solution becomes the new incumbent solution, otherwise it is removed from consideration. Thus, there is always a solution better than all the others but that does not suffice the integrality constraints. This so called best bound can be compared to the incumbent solution and the difference between the objective values as percentage of the incumbent solution can be interpreted as a measure of finding and proving optimality. As the search space is explored, the objective values of the best bound and the incumbent solution converge, thus a gap of 0 % means that the optimal solution is found. Consequently, a positive gap of, for instance, 5 % means that the optimal objective value for a minimization problem is at most 5 % lower than the objective value of the incumbent solution. The incumbent solution is, thus, an upper bound for the solution (IBM 2012).

The results obtained from the different instances all show similar results. In total, trucks leave the depot 137 times per week to replenish the filling stations. In most of the cases, approximately 80 %, the trucks visit exactly one filling station and return back to the depot empty. However, the main difference to the basic situation is that

Table 6 Computational statistics for the routing situation

Instance	Nr. of trucks	Nr. of FS[1]	Gap[2] (%)	Comp. time (s)
A	1	4	0.01	116.03
B	2	3	0.54	3,600
C	6	9	10.08	3,600
D	6	8	9.45	3,600
E	2	4	8.58	3,600
F	6	7	6.29	3,600
G	6	10	7.62	3,600

[1] FS = filling stations

[2] Gap = relative difference of the best lower bound to the incumbent solution

the decision on when to replenish is made by the depot, enabling better coordination. Almost 20 % of the time, trucks replenish at least two filling stations along their route. The average delivery quantity, thus, differs largely from the almost full truckload quantities that are delivered in the basic situation.

Comparing the results of the economic and environmental analysis in the basic situation and in the routing situation over one year results in Table 7. The amount of fuel that is demanded at the filling stations is equal in the basic situation and in the routing situation. In the routing situation, a total distance of approximately 1,712,520 km has to be traversed by trucks in one year in order to completely satisfy demand. This equals a total reduction of more than 20 % compared to the basic situation. In total, the routing situation reduces total transportation costs by more than 12 %. One reason for this improvement is the drastic increase of the load factor that can be achieved through better coordination of deliveries. It amounts to 96.24 % in the routing situation. The total kilometers driven empty decline by 21 %, but the relative share of empty trips remains almost unchanged, being 50 % in the basic situation and 49.06 % in the routing situation. Due to the reduction in kilometers driven but also, to a large extent, due to the increases in efficiency, the total amount of fuel usage can be reduced which positively impacts the economic performance of the company and improves the environmental performance at the same time. A reduction of CO_2 emissions from truck transportation by approximately 16 % per year can be achieved compared to the basic situation by implementing a VMI policy and analyzing transport processes in more detail. Yet, it is again interesting to see that the distance alone is not solely responsible for emission reductions but also the load and the route choice are important. This is per se an interesting and remarkable result, for this implies both an economic and environmental benefit. By switching the replenishment policy to a VMI policy both costs and CO_2 emissions in the distribution network can be reduced, resulting in a pareto-improvement and a win-win situation for the company.

5.3 Further analyses

Since companies usually aim at optimizing economic performance measures, the analysis and the conclusions drawn in the previous sections often suffice. In order to

Table 7 Comparison of basic situation and routing situation in one year

	Basic situation	Routing situation	Change
Total costs (%, basic = 100)	100	87.70	−12.29 %
Total distance driven (km)	2,143,281	1,712,520	−20.09 %
Empty driven distance (km)	1,071,640	840,211	−21.59 %
Share of empty trips	50.00 %	49.06 %	
Weight-based load factor	85.00 %	96.24 %	
Total diesel consumed (l)	176,327	148,168	−15.97 %
Vehicle CO_2 emissions (kg)	461,979	388,202	−15.97 %

prepare for possible future environmental regulations, however, we want to analyze the true potential of VMI with respect to CO_2 emission reduction. Therefore, we altered the objective function of the presented model and made Eq. (11) the only objective, minimizing total CO_2 emissions from truck transportation as well as warehousing activities.

The results obtained from this analysis (we refer to this situation as "environmental situation") are summarized in Table 8 and compared to the results of the routing situation. It turns out that albeit the already achievable reduction in emissions in the routing situation, a further improvement of the environmental performance is still possible. A total reduction of more than five tons of CO_2 can be achieved in one year by changing the objective towards emission minimization. This reduction in emission is attributable only to reductions in transport emissions, since the emissions from warehousing activities are not affected by the change in the objective function. In this situation, trucks leave the depot 138 times, thereby almost doubling the number of tours compared to the routing situation (from 26 to 45 times). Since the total kilometers driven are not the only criterion that determines emissions, the environmental situation leads to an increase in distance traveled (0.52 % or more than 9,000 km each year), which, consequently, leads to slight increases in total transport costs (0.55 %) compared to the routing situation. Nevertheless, emissions can be reduced because the trucks take alternative routes and also the vehicle loads are different in some instances. Because of this fact, the average load factor in the environmental situation as well as the share of total empty

Table 8 Comparison of environmental situation and routing situation

	Environmental situation	Routing situation	Change
Total costs (%, Basic = 100)	88.19	87.70	0.55 %
Total distance driven (km)	1,721,562	1,712,520	0.53 %
Empty driven distance (km)	829,504	840,211	−1.27 %
Share of empty trips	48.18 %	49.06 %	
Weight-based load factor	92.99 %	96.24 %	
Total diesel consumed (l)	146,170	148,168	−1.35 %
Vehicle CO_2 emissions (kg)	382,967	388,202	−1.35 %

driven kilometers is lower than in the routing situation, but still higher than in the basic situation without VMI.

Table 9 shows the computational statistics for the environmental situation. Since the objective function in this analysis is more complex and takes into account more aspects than in the cost minimizing approach, the gaps of the environmental situation are generally higher than in the routing situation. Furthermore, it can be assumed that the size of the gap increases with the size of the instance as well as with the filling stations being located quite close to each other, which is the case in instance C. However, with this model our aim of providing pareto-improvements compared to the basic situation is achieved, even if optimality is not granted.

From the environmental optimization in this case study we can draw interesting conclusions. It can be shown that an economic optimization leads to a different optimal solution than optimizing an environmental objective. Since companies usually aim at improving their economic performance, they will tend to implement the cost optimal solution. However, a small deviation from the cost optimal situation can result in notable improvements in environmental performance, as it is the case in our case study. Consequently, Inventory Routing Models where carbon emissions are implicitly or explicitly incorporated, so called "environmentally extended IRPs", will be of increasing importance in the future, especially when environmental regulations with respect to greenhouse gas emissions from transportation come into force. One possible regulation is a price on CO_2 emissions that is charged for every ton of CO_2 emitted. However, we incorporated the actual price of one ton of CO_2 that is charged in the EU ETS (7.32 € on 20.04.2012) as a reference into the optimization model but it turns out that this does not alter the results of the economic optimization. In order to have an influence on the results, the price of carbon emissions must be significantly higher in order for companies to be motivated to optimize their CO_2 emissions instead of their costs. Nevertheless, companies are well advised to consider the possible effects of certain operations and possible future regulations on the economic and environmental performance of their distribution processes. By considering the proposed IRP, the focal company has a suitable and detailed reference point to what the current or possible future situations looks like and is able to gain a competitive advantage over its competitors.

Table 9 Computational statistics for the environmental situation

Instance	Nr. of trucks	Nr. of FS[1]	Gap[2] (%)	Comp. time (s)
A	1	4	0.30	3,600
B	2	3	0.13	3,600
C	6	9	29.46	3,600
D	6	8	20.86	3,600
E	2	4	8.38	3,600
F	6	7	12.13	3,600
G	6	10	8.28	3,600

[1] FS = filling stations

[2] Gap = relative difference of the best lower bound to the incumbent solution

6 Conclusions and future research

The efficient routing of vehicles in a company's distribution network results in economic and, in most cases, in environmental benefits. Decisions to improve the efficiency of transport processes are made on a mid-term planning level, making detailed analyses of the underlying transport processes inevitable. Whereas the level of detail in transport process analysis can be smaller on the long-term planning level (as it is the case for instance in facility location decisions), a much higher level is required for mid- and short-term decisions, leading to more precise results. We show in this work the positive consequences of accurately investigated transport processes, by means of routing consideration, on the economic as well as on the environmental performance. Furthermore, by including inventory decisions into routing considerations, even better results can be achieved.

It can be shown that in this particular case study a situation where routing and collaboration are considered results in a reduction of total kilometers driven by 20 % compared to a simplified transport analysis. Empty driven kilometers can be reduced by nearly 22 % which equates to a reduction of the share of empty driven kilometers by 1.24 percentage points. In addition, the average load factor can be increased drastically. All these aspects positively influence transport efficiency, leading to improvements in economic as well as environmental performance. We also showed that the environmental performance can be further improved, however causing slightly negative impacts on the economic performance. Since the actual price for one ton of CO_2 (in the EU ETS) is currently very low, we could also show that costs for carbon emissions have, currently, no impact on the optimal solution.

Yet, one must keep in mind that the assumptions the proposed model is based on are quite strict. In order to reflect reality more accurately, improvements can be done, for example by including stochastic demand and safety stock considerations into the model. This would, obviously, increase the complexity of the model, making exact solutions almost impossible to obtain. Therefore, the use of different heuristic solution methods will be inevitable in order to provide good results. By using heuristics it is possible to expand the model and analyze a region the company under consideration is supplying without decomposition. In this way, a more realistic situation can be reflected through the model, thus enhancing its applicability in real life situations.

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