Chapter 6: A Service network design model for multimodal Municipal solid waste transport

Abstract

A modal shift from road transport towards inland water or rail transport could reduce the total Green House Gas emissions and societal impact associated with Municipal Solid Waste management. However, this shift will take place only if demonstrated to be at least cost-neutral for the decision makers. In this paper we examine the feasibility of using multimodal truck and inland water transport, instead of truck transport, for shipping separated household waste in bulk from collection centres to waste treatment facilities. We present a dynamic tactical planning model that minimizes the sum of transportation costs, external environmental and societal costs. The Municipal Solid Waste Service Network Design Problem allocates Municipal Solid Waste volumes to transport modes and determines transportation frequencies over a planning horizon. This generic model is applied to a real-life case in Flanders, the northern region of Belgium. Computational results show that multimodal truck and inland water transportation can compete with truck transport by avoiding or reducing transhipments and using barge convoys.

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1. Introduction

Green House Gas (GHG) emissions associated with the transport of Municipal Solid Waste (MSW) in the European Union (EU) have been increasing over the last decades. Barring interventions, this evolution is expected to continue (EEA, 2011a). The European Environment Agency (EEA) recognizes the growing importance of the transport component in the total net GHG emissions associated with MSW management: “The collection and transport of waste, closely linked to waste volumes, is estimated to account for less than 5% of the direct greenhouse gas emissions of the waste sector, primarily due to the short distances over which municipal waste is usually transported. However, this figure represents 40% of the net emissions in 2020” (EEA, 2008).

MSW is defined as the waste collected by or on behalf of municipalities. In reality, it also includes waste that is identical or similar in nature but collected directly by the private sector (business or private non-profit institutions) (Eurostat, 2012). MSW can be recycled, incinerated with or without energy recuperation, or landfilled by Waste Treatment Facilities (WTF). The transport of MSW can be organised by a carrier or shipper. A carrier is a person or organisation that offers transportation services and a shipper is either the supplier or the owner of the cargo to be shipped (Agarwal and Ergun, 2008).

The increase in GHG emissions associated with MSW transport follows the same unfavourable evolution as the fast growth in EU GHG emissions associated with transport modes in general over recent decades. To mitigate this trend several technology or behaviour-based solutions have been developed (Waisman et al., 2013). On the technological side, carbon intensity can be lowered through the introduction of bio fuels and alternative energy carriers (electricity and hydrogen). Additionally, developing more energy-efficient vehicles can lower the energy intensity of transport and mobility. On the behavioural side, transport GHG emissions can be reduced through policy choices that cause decision makers to choose transportation options that will lower GHG emissions. On the one hand, the modal structure of mobility can be shifted from carbon-intensive options (air, passenger cars and trucks) to less carbon intensive ones (public transport and non-motorized modes for passengers, rail, and shipping; and inland waterways for freight). On the other hand, the volume of transport can be decreased by a more efficient spatial distribution of transport movements (Waisman et al., 2013).

These same strategies are formulated in a European Commission white paper to establish a competitive and resource-efficient transport system (EC, 2011). In addition to the development and deployment of new and sustainable fuels and propulsion systems, the European Commission advocates the increased use of more energy-efficient modes. Its goal is to shift 30% of road freight over 300 km to other modes (such as rail or waterborne transport) by 2030, and to shift more than 50% by 2050. In principle, moving a portion of the MSW currently transported by truck to other transport modes could contribute to lowering the growth in GHG emissions and congestion (EC, 2011). In practice, however, such a modal shift will take place only if it is at least cost neutral compared to truck transport. The main
issue that arises when considering such a move is that a modal shift is generally more expensive for long-haul distances shorter than 100 km. The break-even distances for a modal shift from truck transport to Inland Water Transport (IWT) differ across studies. Van Duin and Van Ham (1998) report break-even distances of 100-250 km for IWT and 200-400 km for railway transport. Pekin (2010) states that IWT can be cheaper than road transport above 99 km. The MIRA (2010) reports a break-even distance of 250 km for continental container transport with IWT or truck. The break-even distance for intermodal rail is longer than for intermodal barge transport (Macharis et al., 2012).

In consideration of the options presented by Waisman et al. (2013) to reduce GHG emissions for transport in general, we aim to examine whether a modal shift from truck to IWT for long-haul transport can be beneficial, given that transport distances shorter than 100 km are typical for MSW transport (see e.g. Sweden: Sonesson, 2000). We will not address the technological evolution towards more environment-friendly fuels and engines. For the impact of alternative, greener fuels in freight transport we refer to Erdogan and Miller-Hooks (2012) and Bektas and Eglese (2014).

To support strategic decision making towards a modal shift in MSW transport it is crucial to evaluate the conditions that influence the feasibility of multimodal MSW transport. By demonstrating the feasibility of multimodal MSW truck/barge transport based on real life cases research could support strategic decision makers to consider this option. To this end, we formulate a tactical planning problem that minimizes the transportation costs for a given waste handling and processing infrastructure composed of multiple collection centres and multiple WTFs. Solving this problem enables decision makers to choose services and associated transportation modes (truck and/or barge), allocate volumes to orders while taking available capacities into account, and plan shipping itineraries. This tactical planning problem will be modelled as a Service Network Design Problem (SNDP) applied to a practical case of MSW transport in Europe. This approach is in line with a majority of research conducted at the tactical planning level that addresses specific real-world problems using algorithms designed for those problems (SteadieSeifi et al., 2014).

Generally speaking, multimodal transport has increased significantly due to the use of standardized containers that enable both faster loading/unloading at intermodal terminals and transportation of multiple commodities on the same mode (Ayar and Yaman, 2012). However, in the case of MSW, using dedicated containers for hygienic reasons leads to both empty backhaul and additional handling costs. For transport over distances shorter than 100 km, transportation costs can be significantly higher compared to truck transport, according to logistic experts that were interviewed. Therefore, in this paper we will examine the transport of MSW in bulk only. To the best of our knowledge, this is the first feasibility study of multimodal barge-truck bulk transport on distances shorter than 100 km.

The remainder of this paper is organized as follows. The literature on multimodal waste transport is discussed in the next section. The research objectives are formulated in Section 3. The methods for addressing the issue as a tactical planning problem, as well as the model, are
presented in Section 4; and the application to a practical case study is presented in Section 5. Finally, results are discussed in Section 6.

2. Literature review

In this section we begin by highlighting how MSW management optimization models have evolved in recent decades and which transport-related aspects have been taken into account. Next, in order to better position our choice to formulate a possible modal shift for MSW as a tactical planning problem, we will provide an overview of how modal-shift problems typically have been modelled. Finally we review recent articles addressing way to incorporate environmental concerns into (operational) planning models.

2.1. MSW modelling

Morrissey and Browne (2004) present an overview of the evolution of MSW modelling over recent decades. In their view, changes in MSW modelling reflect an evolution in the societal debate on MSW. Initial MSW models were developed in the 1960s and dealt with the optimisation of specific topics within MSW, such as e.g. waste collection problems. The major shortcoming of these models was their simplicity and lack of consideration for recyclability aspects. In the 1980s, MSW models adopted a systems approach and began taking into account relationships among various MSW management factors. These models were focussed mainly on minimizing the cost of waste management, although a few of them also encompassed some environmental and societal aspects. Models developed in the 1990s addressed waste minimization and prevention and, in the early 2000s, they began to reflect a shift from a narrower focus on landfills towards a wider range of waste management processing techniques based on the principles of Integrated Solid Waste Management (ISWM). ISWM considers the full range of waste streams to be managed and views available waste management practices as a menu from which to select a preferred option based on site-specific environmental and economic considerations. More recent MSW models consider the environmental impact of MSW management options over their entire life cycle. For examples of recent MSW models we refer to Reich (2005), Eriksson et al. (2005), Minciardi et al. (2008), Tavares et al. (2009) and Ghiani et al. (2014).

As regards transport, recently developed MSW models are focussed on lowering waste collection and haulage costs by means of scheduling strategies. However these models fail to address the influence of transport mode or its associated environmental and societal impact. Johansson (2006) acknowledges that collection and haulage of transport in modern MSW management systems are accountable for the greater part of total costs associated with MSW management. To manage these costs he presents a model that optimizes MSW collection and haulage by means of dynamic scheduling and routing allocation. McLeod and Cherrett (2008) model the effect of three different options for MSW collection to reduce vehicle mileage. Tavares et al. (2009) discuss a model for choosing optimal waste collection and haulage to lower the transport cost associated with the collection and haulage of MSW. The cost
associated with MSW transport accounts for the majority of total MSW management costs in the discussed case studies.

The MSW models using Life Cycle Assessment (LCA) to minimise environmental impact over the entire life cycle of MSW have the same shortcoming as the models discussed in the previous paragraph: they do not take into account the role of transport mode. Reich (2005) includes transport in Life Cycle Costing (LCC) as part of an LCA optimization model, but only for a single transport mode. Hung et al. (2007) take the three pillars of sustainability (People-Planet-Profit) into account in their life cycle modelling of MSW but do not address the role of transport or transport mode.

Figure 1: GHG emissions from MSW management in the EU (EAA, 2011). GHG emissions after 2008 are projected as ‘business as usual’.

Macharis et al. (2012) found that, on average, barge transport has a lower CO$_2$-eq emission than truck and rail transport. Hence, a modal shift of MSW transport could help to reduce the share of transport in total GHG emission related to MSW management. This is a topic that recently has gained attention in the EU as a result of the successful shift in focus away from landfills towards prevention and recycling of MSW, since the early 2000s. The shift has resulted in a decline of the total GHG emissions linked to MSW treatment in the EU (see Figure 1) and it has highlighted the importance of transport—and in the total GHG emissions linked to it—as an opportunity to further reduce MSW GHG emissions in the near future (EAA, 2011). This importance is depicted by the Net MSW transport versus the Net MSW GHG emissions line in Figure 1, which indicates that in 2015 the transport of MSW will contribute 40% of the net MSW GHG emissions associated with MSW Management.
2.2. Modelling approaches to modal shift

In this section we discuss how modal choice/shift has been studied since 2000 for freight transport to set the scene for the formulation of our research objectives in Section 3 and the development of the MSW model in Section 4. At the most basic level, a distinction can be made between papers modelling modal shift policy and multimodal freight transportation planning. The first type of papers is focused on evaluating modal shift transport policy measures with the aim of creating awareness and consideration of modal shift as a transport policy option. The second type of papers mostly analyses practical case studies that deal with the implementation of multimodal transport at the strategic, tactical or operational level in order to assess the feasibility of a modal shift.

2.2.1. Modal shift policy

Papers on modal choice in the EU mainly consist of case studies comparing different transport modes. An evaluation of the best transport mode choice is made based on the associated minimal Total Logistics Cost (TLC), or by using Multi-Criteria Decision Modelling (MCDM) reflecting the preferences of decision makers (DM) on criteria linked to several transport modes under investigation. MCDM for modal shift assessment can be split into two types: (i) Cost function based modelling that is primarily focused on minimizing the TLC and (ii) Utility function based modelling that is based on Multi-Attribute Utility Theory (MAUT), an approach largely developed by Keeney and Raiffa (1976). Underlying this theory is the idea that the DM wants to satisfy simultaneously a number of different attributes (transport cost, transit time, CO$_2$ emission, etc.). In the case of a modal shift, the DM wants to minimize all the aforementioned attributes.

Despite infrastructure improvements made in the EU since 1995 and despite policy measures taken to promote alternative modes for road and air transport, the modal shift from truck to IWT, or train inland freight transport, has not been successful. In 1995, the relative share of inland freight transport by truck in the EU-27 was 67.4%. Moreover, this share grew continuously to 72.7% by 2010 (EC, 2012). Differences can be noted in the modal split per country in the EU-27, depending on geographic and infrastructural situations. Over the last decade, several authors have discussed the underlying problems related to effectively establishing a modal shift (e.g. Blauwens et al., 2006 and Liedtke, 2012).

Blauwens et al. (2006) evaluate three types of transport mode used for containers being moved between a seaport and its hinterland: direct road, combined rail/road and combined barge/road. A TLC reflecting the following logistics characteristics characterizes each transport mode: transport costs, cycle stock costs (related to loading capacity), inventory-in-transit costs (related to average lead-time) and safety stock costs (related to the average and variance in lead-time, as well as average and variance in demand for a given service level). Based on TLC calculation, researchers evaluated the effectiveness of three policy measures.
aimed at obtaining a modal shift for freight transport in the European Union for a hypothetical case. They found that an increase in transport tax costs for road transport (reflecting congestion cost) or a decrease in rail transport costs (due to the forthcoming deregulation of the European rail freight transport market) would be beneficial for the shift to rail/road transport. Additionally, they found that decreasing combined road/rail and barge/road transport lead times by removing current obstacles would be beneficial for a modal shift to both multimodal transport modes.

Liedtke (2012) evaluate the LOGOTAKT project in Germany aimed at achieving a modal shift from transport that is smaller than truckload (i.e. pallet transport) to rail transport using curtain side containers. The use of curtain side containers lowers train transport costs on long hauls (typically a core single wagon is used) while offering a solution for the transhipment of the pre- and post-haulage of a single pallet. Intermodal transhipment of an entire curtain side container by a traditional crane also remains possible. The research outcomes show that logistics costs are reduced by LOGOTAKT because of increased delivery frequency, which leads to savings in warehouse (inventory) cost and slightly reduced transport cost. The LOGOTAKT concept demonstrates that train transport could be integrated into a multimodal transportation system offering high frequency transport services over long distances for smaller shipments.

Papers using utility function based modelling in the EU are presented by Pérez-Mesa et al. (2012) and Truschkin and Elbert (2013). A utility function is used to assess modal shift options for situations where a modal shift from road transport is not yet in place. Pérez-Mesa et al. (2012) assess the possible modal shift for fruit and vegetable transport from southeast Spain to the rest of Europe. Combined Short Sea Shipping (SSS) and road transport is compared to current road transport. Increasing road transport costs, future drawbacks from the introduction of environmental taxes, and traffic limitations all make it attractive to pursue an alternative transport mode by means of intermodal transport using combined SSS and road transport. Because empirical data was unavailable, the weighting factors for transport cost and transition time in the objective utility function are estimated using Analytic Hierarchy Process (AHP) (For AHP see e.g. Saaty, 2008). The outcome of the model shows that the cost of intermodal transport using combined SSS and road transport can be 14% lower than current road transport but total transit time can double, which is not favourable for the shelf life of fruits and vegetables.

The above papers demonstrate the feasibility of a modal shift from truck transport to rail or waterborne transport in order to make policy makers consider such a modal shift. The next section will focus on examining the feasibility of the implementation of this modal shift on a tactical and operational level.

2.2.2. Multimodal freight transportation planning

The planning of multimodal freight transport is an interesting area in Operations Research. Most authors split up the related planning problems based on their decision horizon leading to
strategic, tactical and operational planning models (e.g., SteadieSeifi et al., 2014, Crainic and Laporte, 1992). SteadieSeifi et al. (2014) describe the three planning levels (as follows). Strategic planning problems relate to investment decisions on present infrastructure (networks). Typical problems addressed at this level are the consolidation of cargo in order to maximize the utilization of multimodal transportation and the location of hubs in order to minimize total transportation costs. Tactical planning problems are aimed at optimizing the utility of existing infrastructure through the selection of services and associated transportation modes, the allocation of their capacities to orders, and the planning of their itineraries and frequency. Finally, operational planning problems relate to making the best choices with regard to services and associated transportation modes, itineraries, and allocation of resources to demand. Operational planning deals with variability and stochasticity that are not explicitly addressed at strategic and tactical levels. For a detailed literature review of these models, the reader is referred to SteadieSeifi et al. (2014).

Figure 2 outlines the key decisions that need to be made at different levels of the planning horizon in multimodal road-waterborne transport (Agarwal and Ergun, 2008). In the strategic planning stage, the optimal number and mix of ships (or barges) in a fleet is determined as input for the tactical planning stage. During that stage, the service network is designed by creating the ship routes, i.e. the sequence of port visits by a given fleet and the assignment of ships to such routes. Finally, in the operational stage, a carrier makes decisions on which cargo to accept or reject for servicing and which path(s) to use to ship the selected cargo. Decisions made at one planning level affect the decision making at other levels. General policies and guidelines are defined in the upper level; while feedback with respect to revenue and cost information is generated in the underlying levels and assists decision-making at the higher level.

In addition to economic aspects leading to a decrease in transportation related costs and an increase in efficiency (such as, e.g., cooperation and utilizing resources more efficiently), environmental concerns are high on the agenda. The latter are driven by new regulations and taxes that encourage companies to shift to more sustainable solutions (SteadieSeifi et al., 2014).
2.2.3. Green operational planning modelling

Environmental concerns have been addressed mainly in operational rather than tactical planning models.

CO$_2$ vehicle emissions are related directly to fuel consumption (Bektas and Laporte, 2011). For trucks, CO$_2$ emissions are determined mainly by distance driven and total weight of the vehicle (Gaur et al. 2013). CO$_2$ emissions from road freight transport can vary by as much as 30% depending on the definition of trucking activity, the geographical scope of the calculation, and the degree of reliance on survey, vehicle test-cycle or traffic count data (McKinnon and Piecyk, 2009). Several authors have made extensions to the classic Vehicle Routing Problem (VRP) to determine routes with the lowest CO$_2$ emissions. Laporte (1992) defines the VRP as the problem of designing optimal delivery or collection routes from one or several depots to a number of geographically scattered cities or customers, subject to side constraints. Several exact and approximate algorithms have been developed for the VRP but research on environmental factors is rather recent (Bektas and Eglese, 2014).

Bektas and Laporte (2011) developed the Pollution Routing Problem (PRP) by extending the objective function of the VRP to include the cost of minimizing GHG emissions. The overall objective of the PRP is to minimize total costs composed of cost of emissions, cost of operations and cost of drivers.
Erdogan and Miller-Hooks (2012) developed the Green Vehicle Routing Problem (GVRP) that accounts for the additional challenges associated with operating a fleet of vehicles using alternative cleaner fuels, denoted as Alternative Fuel Vehicles (AFVs). AFVs are fuelled by biodiesel, electricity, hydrogen, methanol, natural gas (liquid-LNG or compressed-CNG), and propane, amongst others. AFVs require Alternative Fuelling Service stations (AFSs) for replenishment. The GVRP takes into account a vehicle’s fuel tank capacity limitation and chooses the optimal placement of AFS visits within the tour.

These green operational planning modelling examples show the importance of integrating the cost or effect of GHG emissions, associated with the selected transportation mode, in the transportation planning models.

3. Research objectives

Bontekoning and Priemus (2004) indicate that the main growth potential for a modal shift to barge transport can be found in the market for freight flows on shorter distances. They find the following to be helpful for lowering the break-even distance with truck transport: (i) increasing the volume to be shipped over the long haul distance, thereby reducing the costs per tonkm; (ii) eliminating or reducing the need for pre or post haulage; and (iii) reducing transhipment costs.

The literature review in Section 2 found no study that had evaluated a modal shift of MSW road freight transport to a combination of road and waterborne transport. As explained in the introduction, we do not consider intermodal train transport as it is more expensive than waterborne transport on the short distances over which MSW is commonly transported. Moreover, the role of IWT, also called barge transport, is less examined in the literature on modal shift transport. The aim of this paper is to close this gap by evaluating a modal shift for MSW from road transport to a combination of road and waterborne barge transport. Practitioners will consider a modal shift if they can be convinced, using real life data, that such a shift is economically and technologically feasible. To support strategic decision making towards a modal shift in MSW transport it is crucial to evaluate the conditions that influence the feasibility of multimodal MSW transport. To this end we formulate a tactical planning optimization model that minimizes the operational, environmental and societal transportation and transhipment costs, and that is similar to the objective function of Bektas and Laporte (2011) at an operational planning level. The generic model discussed in this paper is capable of optimizing MSW transport in a wide variety of settings and will be used to provide insight into the following research questions by examining a real-life case study for the transport of MSW in bulk in Belgium:

(i) Can a modal shift towards combined road and waterborne barge transport for MSW be beneficial compared to current road freight transport of MSW?

(ii) What is the effect of internalising the external costs related to road freight transport for MSW on a shift to combined road and waterborne barge transport for MSW?
4. Problem description and modelling

The problem under consideration consists of determining the most sustainable mode of transport for MSW. This means identifying the mode with optimal trade-off between transport cost, GHG emission and societal impact; and it means determining the associated transport itineraries and frequencies for each selected transport mode, subject to the following constraints: (i) the MSW must be transported within a certain time window because of limited space in the collection centres and the risk of self-combustion; (ii) only a single type of MSW may be transported each time since mixing up waste types is prohibited by law; and (iii) the waste bunkers used to store MSW at the Waste Treatment Facility (WTF) have a finite capacity to be operated within a certain volume range. Because no goods may be transported in a vehicle that has transported waste, empty backhauling will occur.

The above problem can be formulated as a service network design problem. The problem we study explicitly considers modal shift opportunities and incorporates choice of services (transport mode and frequencies). Other approaches to solve this problem are multiobjective programming by minimizing transportation costs and minimizing environmental and societal impact, or the lexicographic goal programming approach (Morissey and Browne, 2004; Sun et al., 2015). Service network design generally covers a wide variety of applications in which all or some of the links in the network are optional and may be used, provided that a corresponding fixed cost is paid. Through the network a set of known demands must be routed between specific origin-destination pairs at given unit flow costs. The aim of designing a network is realized by selecting links in the network that will be used to satisfy demand. This is done by determining flow distribution at minimum cost, which is computed as the total cost of the selected links and the total cost of the flow distribution (Chouman and Crainic, 2010). The model is defined over a given planning horizon (typically one week), divided into time periods (typically one day for a single type of waste). Analysing five days is sufficient to obtain relevant measures of the sustainability of a modal shift, as no transport occurs over the weekend and no waste is shifted to the next week. The result is that weekly schedules are independent. Furthermore seasonal variation in the flows of MSW is limited so one “average” week is representative for an entire year. For every time period a variable amount of MSW is added to the stock of MSW collection centres. The demand by the WTF for MSW per time period can vary. The MSW is transported through the network either by truck transport or by multimodal truck- barge transport. In case of multimodal truck- barge transport, transhipment at origin and destination may take place. The time needed to collect a sufficient amount of waste at the collection centres and to transport the shipment to the WTF destination will differ for the two transport modes, truck and barge, because they differ in carrying capacity and transportation lead-time. We assume that the MSW is transported to the WTF within one time period for both transport modes. The storage capacity at the WTF is sufficiently large to accommodate the multimodal shipments; therefore, we can assume an infinite buffer capacity at the WTF. Moreover, we assume that all waste is transported in bulk.
In the next sections we present the network and time-space representation required to address the scheduling aspect of the MSW SDNP, following the stepwise description of Andersen et al. (2009). The MSW Service Network Design Problem (SNDP) developed in section 4.4 is an extension of the static SNDP formulated by Crainic and Laporte (1992). Alternative formulations of the static SNDP can be found in e.g. Crainic and Kim (2007).

4.1. Notations

The MSW network discussed in this paper consists of nodes representing collection centres at the terminals of origin, a transhipment point for each terminal of origin, a transhipment point for each WTF and a number of WFTs at the terminals of destination. Arcs between adjacent nodes in the network represent the services between these nodes. MSW is to be transported from the collection centres to the WTF by means of truck or truck-barge. The following sets are defined:

\[ N = \text{set of all network nodes} \]
\[ N_o = \text{set of nodes representing the waste collection centres at the terminals of origin} \]
\[ N_g = \text{set of transhipment nodes at the terminals of origin} \]
\[ N_f = \text{set of transhipment nodes at the terminal of destination} \]
\[ N_e = \text{set of destination nodes} \]

\[ N = N_o \cup N_g \cup N_f \cup N_e \]

The arcs between the nodes represent different transport options or services. The following sets are defined:

\[ A = \text{arcs } (i, j) \text{ between two adjacent nodes } i, j \in N \]
\[ A_t = \text{arcs connecting nodes } i \in N_o \text{ with the nodes } j \in N_e \text{ carried out by truck} \]
\[ A_v = \text{arcs connecting nodes } i \in N_o \text{ with the nodes } j \in N_e \text{ representing the service of pre-haulage carried out by truck} \]
\[ A_w = \text{arcs connecting nodes } i \in N_g \text{ with the nodes } j \in N_f \text{ carried out by barge} \]
\[ A_p = \text{arc connecting nodes } i \in N_f \text{ with the nodes } j \in N_e \text{ representing the service of post-haulage carried out by truck} \]

\[ A = A_t \cup A_v \cup A_w \cup A_p \]

All arcs represent connections between physical entities.

\[ A_t, A_v, A_w, A_p \text{ and } A_p \text{ represent the time-indexed version of the respective arc set (see the next section for details).} \]
4.2. Time-space network

![Time-space network diagram]

Figure 3: MSW time space network and an example of a feasible service plan

The network is represented by a directed graph $G= (N^T, A_t)$ in which $N^T$ represents the state of the nodes in set $N$ at a certain time period $T= \{1, 2, \ldots, T_{Max}\}$ for a given planning horizon $T_{Max}$. The set $A_t$ represents the state of the arcs at a certain time $t$, $A_t= \{(i_0, j_1), (i_2, j_2), \ldots, (i_o, j_i), \ldots\}$ where $i, j \in N^T$ and $A_t \subseteq N^T \times N^T$. Each node and each arc belonging to the sets $A_{rt}$, $A_{st}$, $A_{nt}$ and $A_{pt}$ are replicated once for each time period $t$ over the given planning horizon $T_{Max}$.

An example of the time-space network is depicted in Figure 3 for a planning horizon of five time periods $t= 0 \ldots 4$ and the simplest configuration of a network with a single collection centre and a single WTF. Each time period $t$, a new amount $s_{lt}$ of MSW is supplied to the collection centre $i$ represented by node $n_o = (0, t), t \in T$, since in this example we have only one collection centre at node 0. At time $t=0$, a supply $s_{00}$ is added to the initial stock $w_{00}$ at node $n_0$. Note that, generally, $w_{00}=0$. A volume $d_0$ represents the demand of the WTF to be satisfied by collection centre at time $t=0$. The volume is shipped by truck and/or by multimodal truck-barge transport. After shipping the volume $d_0$, the remaining stock level of the collection centre to be transferred to the next period $t=1$ is $w_{01}=w_{00}-d_0+s_{00}$. Such a process is iterated also in the following intervals. In general, each collection centre $i\in N_o$ has a maximum capacity $L_i$ that may not be exceeded. Note that because of this constraint the
quantity transported to the WTF in each period can be larger than $d_t$. If there is more than one collection centre or WTF, the specific production and demand values may be different for each of them.

The arcs connecting the nodes represent services in the network. Services represented by the arcs $A_r$ (truck transport) and $A_v$, $A_w$, $A_p$ (multimodal truck-barge transport) can take place simultaneously. The same sequence as described for $t=0$ takes place each time period prior to $T_{\text{Max}}$. As previously mentioned, at $t=0$ no initial stock $w_{00}$ is present at the collection centre. At the end of the planning horizon $T_{\text{Max}}$ (represented by $t=4$ in Figure 3) all the MSW available at the collection centre terminal must be shipped. MSW planning cycles typically encompass a five-day work week and no transport occurs during the weekend: meaning, on Friday the remaining volumes collected at the collection centres must be shipped to the WTF. This ensures that sufficient storage capacity is available at the collection centres for the next workweek and that there is a sufficient stock at the WTF to continue incineration operations over the weekend. The storage capacity of the WTF can be assumed to be sufficiently large to accommodate all waste flows.

4.3. Services and vehicle fleets

Services $s$ are assumed to depart from and arrive at the nodes at the beginning of each time period. Each service is defined by its origin terminal $i$ and destination terminal $j$, where $i, j \in N$, and is performed by using vehicles (trucks, barges) deployed on the arc $(i, j) \in A$ with given capacity $V_T$ and $V_B$ respectively, as well as fixed and variable costs. The capacity of the service is defined as the maximum volume that a service can ship. We assume that loading, transhipment and unloading take place in the service time defined by the time period; therefore, service times are not explicitly modelled. After unloading, vehicles are available again for service.

4.4. The Municipal Solid Waste Service Network Design Problem Model

Following SteadieSeifi et al. (2014), the Municipal Solid Waste Service Network Design Problem (MSW SNDP) can be characterized as a dynamic SNDP with asset management and multiple-fleet coordination. The MSW SNDP is optimized by taking the fixed, variable and environmental transportation cost for the transportation modes (i.e. truck and barge) into account. In the model, described hereafter, constants and sets are denoted in capital letters while variables and indices are denoted in small caps.

The network described by the model at time $t \in T$ consists of $k$ collection centres represented by the nodes $o_{k,i} \in N_o$, $l$ transhipment terminals at origin represented by the nodes $so_{l,j} \in N_g$, $m$ transhipment terminals at destination represented by the nodes $se_{m,i} \in N_f$, and $n$ WTFs represented by the nodes $e_{n,j} \in N_e$ as depicted in Figure 4. MSW can be transported from the collection centres at origin to the WTFs by truck or by barge. Back-haulage transport is not
included since we assume that only MSW waste may be transported by the selected transportation modes.

Figure 4: network representation of the MSW SNDP with $k$ collection centres, $l$ transhipment terminals at origin, $m$ transhipment terminals at destination and $n$ WTFs.

For the truck and barge services the decision and network design variables are:

$x_{ijt} \geq 0$: Decision variable: total flow on arc $(i, j) \in A_t$ between two adjacent nodes $i$ and $j$ at time $t$ [ton]

$y_{ijt} = \{0, 1\}$: Network design variable: $y_{ijt} = 1$ in case the arc $(i, j) \in A_t$ is activated at time $t$, otherwise $y_{ijt} = 0$

$z_{ijt} \in \mathbb{Z}^+$: decision variable: number of vehicles on arc $(i, j) \in A_t$ between two adjacent nodes $i$ and $j$ at time $t$

Let:

$F_{ij}$: fixed cost for opening activity on arc $(i, j) [\€]$

$K_{ij}$: fixed cost per vehicle deployed on arc $(i, j) [\€]$  

$V_{ij}$: unit variable cost for shipping goods $x_{ij}$ on arc $(i, j) [\€/tonkm]$  

$E_{ij}$: unit external (environmental, societal) cost for shipping $x_{ij}$ on arc $(i, j) [\€/tonkm]$  

$D_{ij}$: distance for shipping $x_{ij}$ from node $i$ to $j$ [km]

$NT_t$: maximum number of trucks that can be used at time $t \in T$

$NB_t$: maximum number of barges that can be used at time $t \in T$

$V_T$: capacity of a truck [ton]

$V_B$: capacity of a barge [ton]

$L_i$: maximum storage capacity at node $i \in N_o$

$M_{ij}$: maximum flow on arc $(i, j)$
s_{it}: production of MSW supplied to collection centre \( i \in N_o \) at time \( t \in T \) [ton]
d_{it}: minimum demand of destination \( i \in N_e \) (WTF) at time \( t \in T \) [ton]
w_{0i}: initial stock level at collection centre \( i \in N_o \) at time \( t \in T \) [ton]

The model is then given by:

Minimize \[
\sum_{i \in T} \sum_{(i,j) \in A} (V_{ij} + E_{ij} \cdot D_{ij}) \cdot x_{ijt} + \sum_{i \in T} \sum_{(i,j) \in A} F_{ij} \cdot y_{ijt} + \sum_{i \in T} \sum_{(i,j) \in A} K_{ij} \cdot z_{ijt}
\] (4.1)

Subject to

\[
s_{it} + w_{it} - w_{it+1} - \sum_{(i,j) \in A} x_{ijt} = 0; \quad \forall i \in N_o, \forall t \in T
\] (4.2)

\[
\sum_{(i,j) \in A} x_{ijt} - \sum_{(i,j) \in A} x_{ijt} = 0; \quad \forall t \in N_g, \forall t \in T
\] (4.3)

\[
\sum_{(i,j) \in A} x_{ijt} - \sum_{(i,j) \in A} x_{ijt} = 0; \quad \forall i \in N_f, \forall t \in T
\] (4.4)

\[
\sum_{(i,j) \in A} x_{ijt} \geq d_{ij}; \quad \forall j \in N_e, \forall t \leq T_{Max}
\] (4.5)

\[
w_{i0} = 0; \quad \forall i \in N_o
\] (4.6)

\[
w_{it} \leq L_i; \quad \forall i \in N_o, \forall t \in [0, T_{Max}]
\] (4.7)

\[
w_{it+1} = 0, \quad \forall i \in N_o
\] (4.8)

\[
x_{ijt} \leq y_{ijt} \cdot M_{ij}, \quad \forall (i,j) \in A_t \cup A_{pt}, \forall t \in T
\] (4.9)

\[
x_{ijt} \leq z_{ijt} \cdot V_{r}, \quad \forall (i,j) \in A_t \cup A_{pt}, \forall t \in T
\] (4.10)

\[
x_{ijt} \leq z_{ijt} \cdot V_{s}, \quad \forall (i,j) \in A_w, \forall t \in T
\] (4.11)

\[
\sum_{(i,j) \in A_t \cup A_{pt}} z_{ijt} \leq NT_t, \quad \forall t \in T
\] (4.12)

\[
\sum_{(i,j) \in A_t \cup A_{pt}} z_{ijt} \leq NB_t, \quad \forall t \in T
\] (4.13)

\[
x_{ijt} \geq 0, \quad \forall i,j \in A_t, \forall t \in T
\] (4.14)

\[
w_{it} \geq 0, \quad \forall i \in N_o, \forall t \in [0, T_{Max}]
\] (4.15)

\[
y_{ijt} \in \{0,1\}, \quad \forall (i,j) \in A_t \cup A_{pt}, \forall t \in T
\] (4.16)

\[
z_{ijt} \in \mathbb{Z}^+, \quad \forall (i,j) \in A_t
\] (4.17)

The objective of the MSW SNDP (4.1) is to minimize the costs linked to the transport of MSW from origin to destination taking into account the fixed cost linked to the organisation.
of transport associated with the transportation mode selected, $F_{ij}$, the fixed cost associated with deploying a vehicle or vessel, $K_{ij}$, the variable cost per tonkm, $V_{ij}$, and the external costs representing the environmental and societal impact associated with the selected transportation mode, $E_{ij}$.

Constraints that have to be taken into account follow. The flow balance in the collection centres is expressed in (4.2). At time period $t \in T$ a new amount of MSW $s_{it}$ is supplied to the collection centre $i \in N_o$ and is added to the remaining amount of MSW $w_{it}$ that was present in the beginning of period $t$. An amount $x_{ijt}$ is allocated for the transport to the WTF at destination $j$ and a remaining amount $w_{it(t+1)}$ stays in the collection centre $i \in N_o$. The flow balance between the transhipments terminals is expressed in (4.3) and the flow balance at the destination transhipment terminals where the MSW is transported to the WTFs is expressed in (4.4). For all periods $t \in T$ except for the last period $t = T_{\text{Max}}$, the volume shipped to $\text{WTF}_j$ is at least the minimum demand $d_{jt}$ by this WTF at time $t \in T$. Constraint (4.5) imposes that the quantity shipped should be at least equal to the minimum quantity $d_{jt}$ required to operate the WTF efficiently. Capacity constraints are expressed in (4.6) - (4.8). In the initial time period $t=0$ there is no existing waste in the collection centre $i$ (4.6). In all time periods expect the initial time period $t=0$ the initial volume at time $t$ in collection centre $i$ is limited by the maximum storage capacity in collection centre $i$ (4.7). In the last time period $t = T_{\text{MAX}}$ all the MSW is shipped (4.8). Constraint (4.9) expresses the activation constraint of shipping MSW and therefore opening the arc $(i,j)$. The number of vehicles to be assigned for shipping MSW at time $t \in T$ is expressed in (4.10) for trucks and in (4.11) for barges. The amount of MSW that can be transported at time $t \in T$ is limited by the availability of the maximum number of trucks $N_{T_t}$ (4.12) and maximum number of barges $N_{B_t}$ (4.13). Finally variables are defined. Constraint (4.14) expresses that all transported MSW cannot be expressed by negative values. Constraint (4.15) expresses that the remaining volume of MSW in the collection centres cannot be expressed by negative values. The selection of a transportation mode is expressed by a binary value (4.16) and the number of vehicles selected for shipping MSW is expressed by integer values (4.17).

5. A case study

In this section, the model from Section 4 is applied to a business case of a Belgian WTF.

For the case under consideration, MSW is delivered mainly to the WTF by municipalities and inter-municipal organizations. Although many stakeholders desire a modal shift towards barge or train transport to reduce GHG emissions and road congestion, the municipalities are forced to favour the cheapest mode of transportation for budgetary reasons.

The MSW delivered to the WTF is stored in waste bunkers designed to hold a sufficient amount of waste to allow waste treatment installations (e.g. incinerators) to continue working for a few days even if no new MSW were to be received (safety stock). The composition of
the MSW differs over time. In summer, less solid waste (such as plastic and hardboard) is collected because of the holiday season. MSW must be transported from origin to destination within a week to prevent organic waste reactions, which generate odour nuisance and lead to an increased risk of self-combustion.

<table>
<thead>
<tr>
<th>Average external cost</th>
<th>Truck</th>
<th>Barge</th>
<th>Train</th>
</tr>
</thead>
<tbody>
<tr>
<td>€/10³ tonkm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accidents</td>
<td>5.4</td>
<td>0.0</td>
<td>1.5</td>
</tr>
<tr>
<td>Noise</td>
<td>2.1</td>
<td>0.0</td>
<td>3.5</td>
</tr>
<tr>
<td>Air pollution and climate</td>
<td>8.7</td>
<td>3.0</td>
<td>4.3</td>
</tr>
<tr>
<td>Congestion</td>
<td>5.5</td>
<td>NA</td>
<td>0.2</td>
</tr>
<tr>
<td>Infrastructure</td>
<td>2.5</td>
<td>1.0</td>
<td>2.9</td>
</tr>
<tr>
<td>Total</td>
<td>24.10</td>
<td>5.0</td>
<td>12.3</td>
</tr>
</tbody>
</table>

Table 1: External costs per transport mode applicable for the EU (EC (2008), Waterwegen en Zeekanaal NV (2009))

In order to compare the environmental and societal impact of transport modes a common basis needs to be defined. Basically, two approaches can be used: internalising the external environmental and societal costs, or multi-criteria decision modelling that associates weighting factors to the environmental and societal impact of each transport mode. Since the objective function of the MSW SNDP is a cost function, we opt for internalising the environmental and societal costs using EU figures (EC, 2008) adopted by e.g. the governmental organization Waterwegen en Zeekanaal managing the Belgian waterways (see Table 1).

It should be noted that external costs differ according to which source is consulted. The outcome of a recent study by Panteia (2013) is depicted in Table 2 based on a weighted average of each type of barge used in the EU-27. This table breaks down the total external costs of emissions to air into climate change costs, reflecting CO₂ emission, and air pollution costs, reflecting the emissions of air pollutants NOₓ and Particulate Matter (PM). In general, European barge transport performs poorly on air pollutants. This is primarily due to the longer lifetime of barge engines relative to truck engines and, secondarily, to the prevalence of truck transport relative to barge transport, which makes it economically more attractive to develop cleaner truck engines (Panteia, 2013).

<table>
<thead>
<tr>
<th>2011</th>
<th>Climate change costs</th>
<th>Air pollution costs</th>
<th>Total external costs of emissions to air</th>
</tr>
</thead>
<tbody>
<tr>
<td>Road (Truck)</td>
<td>€ 6.95</td>
<td>€ 7.00</td>
<td>€ 13.95</td>
</tr>
<tr>
<td>IWT (Barge)</td>
<td>€ 3.06</td>
<td>€10.47</td>
<td>€13.53</td>
</tr>
</tbody>
</table>

Table 2: Weighted average external costs for the emissions to air (in Euro2011/1,000 tonkm) for EU-27 (table 3.2 Panteia, 2013)

The case study consists of a network of n=8 nodes. Three nodes 0, 1, 2 are collection centres, three other nodes (3, 4, 5) are transhipment terminals at origin, node 6 is an intermediate multimodal transhipment terminal and node 7 is the terminal at destination representing the WTF (Figure 5).
At the collection centres two types of MSW are collected and stored separately to be transported to the destination within a maximum one-week period: residual household waste and bulky household waste. Neither types of waste may be combined for shipping; and MSW can be transported by both transport modes. In this case study we consider only residual household waste to be shipped to the WTF, either by direct road transport or multimodal barge and truck transport. In the latter case, pre-haulage by truck is required between the collection centre and the transhipment terminal at origin. Thereafter, MSW is transported via barge to the transhipment terminal at the destination. From this transhipment terminal, post-haulage by truck transports the MSW waste to the terminal at destination (WTF). Because there is no direct waterway connection between the transhipment terminals at origin (nodes 3, 4, 5) combined haulage by barge is impossible.

To organize the planning of the MSW transports, we consider a planning horizon of $T_{Max}=5$ days where each period corresponds to one working day.

Currently MSW is transported exclusively by truck and the external costs are not taken into consideration when comparing transport alternatives. This situation is referred to as the ‘Baseline’ scenario or Scenario 1 in our analysis. A few additional scenarios are examined. Scenario 2 is similar to Scenario 1 but takes external costs into account. Scenario 3 considers Multimodal Transportation (MMT) of MSW with trucks and barges, without the need for pre-haulage (i.e. the collection centre has a transhipment terminal on its premises allowing the MSW to be directly dumped into the barge), but taking into account additional depreciation costs for new equipment needed to load and unload the barges, as well as external costs of transport. Depreciation costs are based on expected average annual volumes to be handled. Moreover, the five-day schedule determined by our model is repeated over the investment period. Scenario 4 is similar to Scenario 3 but requires pre-haulage of MSW by truck between...
the collection centres and the transhipment points at the origin. This shortens the loading time of the barge but adds an additional transportation cost.

Scenarios 1, 2, 3 and 4 are executed by commonly used barges with a carrying capacity of 128 tons and trucks with a carrying capacity of 15 tons. Two individual barges can be combined into a convoy (requiring only one captain) in order to reduced fixed labour costs. This option is examined for Scenarios 3 and 4 in Scenarios 5 and 6. Data on the model parameters for the case is summarized in Table 3 in which: Fij – Fixed Cost for organising transport between node i and j, Vij – Variable Cost for shipping xij from node i to j, Kij – Fixed Cost per vehicle deployed between node i and j, Eij – External Cost for shipping xij from node i to j and Di j – Distance between node i and j.

<table>
<thead>
<tr>
<th>Arc (i, j)</th>
<th>Fij[€]</th>
<th>Vij[€/ton]</th>
<th>Kij[€]</th>
<th>Ejij[€/tkm]</th>
<th>Distance Dij[km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(0,7)</td>
<td>20</td>
<td>20.89</td>
<td>20</td>
<td>0.0241</td>
<td>83.80</td>
</tr>
<tr>
<td>(0,3)</td>
<td>2</td>
<td>5.30</td>
<td>0</td>
<td>0.0241</td>
<td>1</td>
</tr>
<tr>
<td>(3,6)</td>
<td>20</td>
<td>6.20</td>
<td>639</td>
<td>0.0050</td>
<td>71.60</td>
</tr>
<tr>
<td>(1,7)</td>
<td>20</td>
<td>17.25</td>
<td>20</td>
<td>0.0241</td>
<td>65.40</td>
</tr>
<tr>
<td>(1,4)</td>
<td>2</td>
<td>5.30</td>
<td>0</td>
<td>0.0241</td>
<td>2</td>
</tr>
<tr>
<td>(4,6)</td>
<td>20</td>
<td>5.20</td>
<td>510</td>
<td>0.0050</td>
<td>47.88</td>
</tr>
<tr>
<td>(2,7)</td>
<td>20</td>
<td>22.44</td>
<td>20</td>
<td>0.0241</td>
<td>74.60</td>
</tr>
<tr>
<td>(2,5)</td>
<td>2</td>
<td>5.30</td>
<td>0</td>
<td>0.0241</td>
<td>1</td>
</tr>
<tr>
<td>(5,6)</td>
<td>20</td>
<td>5.95</td>
<td>639</td>
<td>0.0050</td>
<td>64.37</td>
</tr>
<tr>
<td>(6,7)</td>
<td>2</td>
<td>5.30</td>
<td>0</td>
<td>0.0241</td>
<td>5.10</td>
</tr>
</tbody>
</table>

Table 3: cost components used in the computational example

The daily supply of waste to the terminals at the origin is assumed to be constant: for terminal 0 this is estimated at 107 t/day, for terminal 1 at 174 t/day and for terminal 2 at 151 t/day. The maximum storage capacity is limited to 100 t/day for terminal 0, to 250 t/day for terminal 1 and to 200 t/day for terminal 2. The daily demand for MSW at the WTF, representing the minimum amount of waste required for efficient waste processing, is set at 300 t/day.

The MSW SNDP model for the case under consideration was modelled in Python V2.7 and optimized by the Gurobi solver V5.6.2 on a personal computer with a 1.66 GHz processor and 10.99 GB RAM memory. The computing time for all scenarios is less than 8 seconds.

In Table 4, the six scenarios are evaluated on the volume shipped by truck transport and truck/barge, and the associated total transportation costs, for a total supply of 432 t/day and a minimum demand of 300 t/day of MSW to be shipped to the WTF, which we assumed to be stable.
### Table 4: overview of scenario results (MMT = Multimodal Transport, E = External cost)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Description</th>
<th>(volume by truck; volume by truck+barge)</th>
<th>Total transportation cost over the planning horizon</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Baseline</td>
<td>(2160; 0)</td>
<td>46,406</td>
</tr>
<tr>
<td>2</td>
<td>Baseline E incl.</td>
<td>(2160; 0)</td>
<td>50,215</td>
</tr>
<tr>
<td>3</td>
<td>MMT E incl., pre-haulage excl. (barge: 128 ton)</td>
<td>(170; 1990)</td>
<td>36,895</td>
</tr>
<tr>
<td>4</td>
<td>MMT E incl., pre-haulage incl. (barge: 128 ton)</td>
<td>(1041; 1119)</td>
<td>47,031</td>
</tr>
<tr>
<td>5</td>
<td>MMT E incl., pre-haulage excl. (barge: 256 ton)</td>
<td>(7; 2153)</td>
<td>32,494</td>
</tr>
<tr>
<td>6</td>
<td>MMT E incl., pre-haulage incl. (barge: 256 ton)</td>
<td>(173; 1987)</td>
<td>42,368</td>
</tr>
</tbody>
</table>

Comparing total transportation costs of Scenario 3 to Scenarios 1 and 4 shows that a modal shift is most beneficial if MSW can be dumped directly onto a barge at the transhipment points of origin. As expected, additional pre-haulage raises costs and makes the modal shift less attractive. If two barges can be combined (Scenarios 5 and 6) total logistics costs can be reduced relative to the single barge conditions of Scenarios 3 and 4. As a result, a larger share of MSW can be shifted to multimodal transport. Please note that in Scenarios 3, 4, 5 and 6 more MSW is transported by combined truck-and-barge than by truck.

If we analyse how volumes are assigned to the two transport modes, we notice that for each time period (a day in this case) MSW is selected from the collection centres so that the demand $d_t$ of the WTF is shipped, which limits the number of MSW transportations at the terminal of origin. As such, the MSW SNDP minimizes the transportation costs in each time period and avoids violating the storage capacity limit at a terminal of origin. The remaining MSW is shipped on the last day of the planning horizon (see Tables 5 a, b).

Since the model parameters included in Table 3 might change in the future, a sensitivity analysis is conducted to assess the robustness of our findings. In Table 6, the variable cost $V_{ij}$ and fixed cost $K_{ij}$ of barge transport is increased for the three routes linking each collection centre ($n= 3,4,5$) with the transhipment terminal at destination ($n=6$). The sensitivity analysis is carried out on Scenario 4, as the total transportation costs over the planning horizon of this multimodal scenario are closest to the baseline scenario of truck transport. In particular, the sensitivity analysis will assess the reduction in volume transport by barge over the planning horizon when an increase of $V_{ij}$ with 2€/t (denoted as Scenario 7) and $K_{ij}$ with 200€ (denoted as Scenario 8) would take place. The results show that an increase in variable or fixed costs for barge transport will soon lead to a lower share to be transported by barge. For Scenario 4, as soon as the variable costs $V_{ij}$ are increased by approximately 4€/t, or as the fixed costs $K_{ij}$ increase by 420 € per transport, barge transport will no longer be used.
### Scenario 3

<table>
<thead>
<tr>
<th>Arc</th>
<th>$t=0$</th>
<th>$t=1$</th>
<th>$t=2$</th>
<th>$t=3$</th>
<th>$t=4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{Truck (0,7)}$</td>
<td>7</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$\text{Truck (1,7)}$</td>
<td>37</td>
<td>44</td>
<td>44</td>
<td>0</td>
<td>18</td>
</tr>
<tr>
<td>$\text{Truck (2,7)}$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>20</td>
<td>0</td>
</tr>
<tr>
<td>$\text{Truck (0,3)}$</td>
<td>0</td>
<td>128</td>
<td>128</td>
<td>65</td>
<td>207</td>
</tr>
<tr>
<td>$\text{Truck (1,4)}$</td>
<td>128</td>
<td>128</td>
<td>0</td>
<td>87</td>
<td>384</td>
</tr>
<tr>
<td>$\text{Truck (2,5)}$</td>
<td>128</td>
<td>0</td>
<td>128</td>
<td>128</td>
<td>351</td>
</tr>
<tr>
<td>$\text{Truck (6,7)}$</td>
<td>256</td>
<td>256</td>
<td>256</td>
<td>280</td>
<td>942</td>
</tr>
<tr>
<td>$\text{Barge (3,6)= (0,3)}$</td>
<td>0</td>
<td>128</td>
<td>128</td>
<td>65</td>
<td>207</td>
</tr>
<tr>
<td>$\text{Barge (4,6)=Truck (0,4)}$</td>
<td>128</td>
<td>128</td>
<td>0</td>
<td>87</td>
<td>384</td>
</tr>
<tr>
<td>$\text{Barge (5,6)=Truck (0,5)}$</td>
<td>128</td>
<td>0</td>
<td>128</td>
<td>128</td>
<td>351</td>
</tr>
<tr>
<td><strong>Total shipped</strong></td>
<td><strong>300</strong></td>
<td><strong>300</strong></td>
<td><strong>300</strong></td>
<td><strong>300</strong></td>
<td><strong>960</strong></td>
</tr>
</tbody>
</table>

### Scenario 4

<table>
<thead>
<tr>
<th>Arc</th>
<th>$t=0$</th>
<th>$t=1$</th>
<th>$t=2$</th>
<th>$t=3$</th>
<th>$t=4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{Truck (0,7)}$</td>
<td>7</td>
<td>0</td>
<td>0</td>
<td>65</td>
<td>79</td>
</tr>
<tr>
<td>$\text{Truck (1,7)}$</td>
<td>165</td>
<td>172</td>
<td>44</td>
<td>87</td>
<td>402</td>
</tr>
<tr>
<td>$\text{Truck (2,7)}$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>20</td>
<td>0</td>
</tr>
<tr>
<td>$\text{Truck (0,3)}$</td>
<td>0</td>
<td>128</td>
<td>128</td>
<td>0</td>
<td>128</td>
</tr>
<tr>
<td>$\text{Truck (1,4)}$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$\text{Truck (2,5)}$</td>
<td>128</td>
<td>0</td>
<td>128</td>
<td>128</td>
<td>351</td>
</tr>
<tr>
<td>$\text{Truck (6,7)}$</td>
<td>128</td>
<td>128</td>
<td>256</td>
<td>128</td>
<td>479</td>
</tr>
<tr>
<td>$\text{Barge (3,6)=Truck (0,3)}$</td>
<td>0</td>
<td>128</td>
<td>128</td>
<td>0</td>
<td>128</td>
</tr>
<tr>
<td>$\text{Barge (4,6)=Truck (0,4)}$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$\text{Barge (5,6)=Truck (0,5)}$</td>
<td>128</td>
<td>0</td>
<td>128</td>
<td>128</td>
<td>351</td>
</tr>
<tr>
<td><strong>Total shipped</strong></td>
<td><strong>300</strong></td>
<td><strong>300</strong></td>
<td><strong>300</strong></td>
<td><strong>300</strong></td>
<td><strong>960</strong></td>
</tr>
</tbody>
</table>

**Table 5: volume shipped each time period in scenarios 3 and 4**

In Scenario 7, the variable costs $V_{ij}$ over the planning horizon encompass the exploitation costs, the loading and unloading costs and the variable investment costs; and in Scenario 8, the fixed costs $K_{ij}$ for barge transport consists of wages and port dues.

<table>
<thead>
<tr>
<th>Arc</th>
<th>$V_{ij}$ [€/ton]</th>
<th>$K_{ij}$ [€]</th>
<th>$V_{ij}$ [€/ton]</th>
<th>$K_{ij}$ [€]</th>
<th>$V_{ij}$ [€/ton]</th>
<th>$K_{ij}$ [€]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(3,6)$</td>
<td>6.2</td>
<td>639</td>
<td>8.2</td>
<td>639</td>
<td>6.2</td>
<td>839</td>
</tr>
<tr>
<td>$(4,6)$</td>
<td>5.2</td>
<td>510</td>
<td>7.2</td>
<td>510</td>
<td>5.2</td>
<td>710</td>
</tr>
<tr>
<td>$(5,6)$</td>
<td>5.95</td>
<td>639</td>
<td>7.95</td>
<td>639</td>
<td>5.95</td>
<td>839</td>
</tr>
</tbody>
</table>

| Volume by truck | 1041 | 1427 | 1169 |
| Volume by barge | 1119 | 733  | 991  |
| **Total Transportation Cost [€]** | **47,031** | **49,199** | **48,888** |

**Table 6: Sensitivity analysis for Scenario 4**
The demand and supply rates in our case can be assumed to be constant given that the variation over time due to e.g. holidays is small. However, to better illustrate how the model and method perform in other practical situations a sensitivity analysis is performed by varying demand and supply quantities/rates. Computational results show that a change in demand of +/-10% for Scenario 4 results in no change in volumes shipped by truck and barge and in only a very small increase in total logistics costs (no more than 21€ over a time horizon of five days). A randomly varied daily supply rate of 432 t/day in the collection centres, as illustrated in Table 8, results in a total logistics cost of 46,928€ and volume of 1076 ton shipped by truck and 1084 ton shipped by barge, over a five-day planning horizon. Scenario 9 shows that random variations of more than 30% in the daily supply rate in the collection centres result in low variations of around 3% in the volumes shipped by truck and barge, as compared with Scenario 4. Please note that the daily total supply rate in the collection centres is identical for Scenario 4 and Scenario 9 and equal to 432 t/day. Also the daily minimum demand of the WTF (d=300 t/day) is identical.

<table>
<thead>
<tr>
<th>Scenario 9</th>
<th>t=0</th>
<th>t=1</th>
<th>t=2</th>
<th>t=3</th>
<th>t=4</th>
</tr>
</thead>
<tbody>
<tr>
<td>d=300 [ton/day]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Supply collection centers 0,1,2 [ton/day]</td>
<td>107,174,151</td>
<td>90,242,100</td>
<td>120,200,112</td>
<td>20,210,202</td>
<td>140,120,172</td>
</tr>
<tr>
<td>Truck (0,7)</td>
<td>7</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>86</td>
</tr>
<tr>
<td>Truck (1,7)</td>
<td>165</td>
<td>172</td>
<td>135</td>
<td>104</td>
<td>370</td>
</tr>
<tr>
<td>Truck (2,7)</td>
<td>0</td>
<td>0</td>
<td>37</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Truck (0,3)</td>
<td>0</td>
<td>128</td>
<td>128</td>
<td>0</td>
<td>128</td>
</tr>
<tr>
<td>Truck (1,4)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Truck (2,5)</td>
<td>128</td>
<td>0</td>
<td>0</td>
<td>200</td>
<td>372</td>
</tr>
<tr>
<td>Truck (6,7)</td>
<td>128</td>
<td>128</td>
<td>128</td>
<td>200</td>
<td>500</td>
</tr>
<tr>
<td>Barge (3,6)</td>
<td>0</td>
<td>128</td>
<td>128</td>
<td>0</td>
<td>128</td>
</tr>
<tr>
<td>Barge (4,6)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Barge (5,6)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>200</td>
<td>372</td>
</tr>
<tr>
<td>Total shipped</td>
<td>300</td>
<td>300</td>
<td>300</td>
<td>304</td>
<td>956</td>
</tr>
</tbody>
</table>

Table 7: Random variations in the daily supply rate of the collection centers over a five day planning horizon

Given the aforementioned results, and since the purpose of the case study simulation is to demonstrate the feasibility of multimodal truck-barge transport for MSW over a given time horizon, we conclude that the assumption of constant daily supply and demand rates is appropriate to demonstrate the effect of the scenarios listed in Table 4 on the modal choice for the MSW SNDP problem.

Finally, in order to simulate a current situation in which multimodal transport would take place, the sensitivity of the outcome of Scenario 4 was tested on excluding external costs from the decision making process. This resulted in a slightly increased volume for truck transport (1169 ton) and, consequently, a smaller volume to be shipped by barge (991 ton). Using external costs leads to a reduction of 5.9% of truck transport in case of Scenario 4. The total transportation costs decrease to 44,844€.
The real-life case that we have used consists of a limited number of collection centres and associated transhipment terminals. To test the performance of the model on larger problems, we examine a hypothetical case consisting of 9 collection centres and 9 associated transhipment terminals at origin, 1 transhipment point at destination and 1 WTF (i.e. in total 20 nodes). Table 7 depicts the program execution time of the MSW SNDP model for a planning horizon $T_{\text{max}}$ ranging from 1 to 100 periods. The results in Table 8 show that the model output is generated in a reasonable computation time even when a large number of periods is considered.

<table>
<thead>
<tr>
<th>$T_{\text{max}}$</th>
<th>1</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>n=8</td>
<td>1</td>
<td>8</td>
<td>16</td>
<td>24</td>
<td>37</td>
<td>47</td>
<td>68</td>
<td>89</td>
<td>195</td>
</tr>
<tr>
<td>n=20</td>
<td>4</td>
<td>29</td>
<td>67</td>
<td>111</td>
<td>151</td>
<td>226</td>
<td>334</td>
<td>425</td>
<td>952</td>
</tr>
</tbody>
</table>

Table 8: Program execution time in sec for the MSW SNDP model for a given planning horizon $T_{\text{max}}$ and two networks sizes

6. Conclusions

In this paper we examined the feasibility of a modal shift for MSW bulk transport on distances shorter than 100 km formulating the problem as a tactical planning problem of assigning trucks and/or barges to the MSW transport over a scheduling horizon. Multimodal barge transport is generally believed to be more expensive than truck transport on such short distances. However, policy makers want to stimulate a modal shift to barge transport to reduce the environmental and societal impact of MSW transport. To support MSW modal shift decision-making a discrete multi-period dynamic SNDP model was developed for MSW bulk transport. The MSW SNDP model is tested on a real-life case of MSW transport in Belgium. Computational experiments illustrate the performance of the model and its potential to support decision-making and evaluate scenarios. For the case and scenarios under consideration, multi-modal barge-road transport turns out to be a viable option when MSW is transported in bulk.

As such, the study confirms that generic recommendations of Bontekoning and Priemus (2004) to lower the break-even distance are also valid for the MSW bulk transport. Simulations also showed that taking external costs into account is favourable for a shift to waterborne barge transport. Moreover, we demonstrated that dropping the MSW directly into a barge near the collection centres and linking up barges make a shift towards multimodal barge transport more attractive.

The MSW SNDP presented in this paper considers only the transport between the collection centres of MSW and the WTF. It can be further extended to cover total logistics costs, encompassing warehouse costs at collection centres and operations at several waste treatment facilities (WFTs).
Acknowledgements and disclaimer

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