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Decision Model for Medium-Term Municipal Waste Collection Optimisation

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Abstract

Aim: The article presents the process of municipal waste management, with particular emphasis on the organization of waste collection, and discusses the objectives of waste management, the principles of operation in Poland and order in municipalities, and various approaches to organizing waste collection. The rest of the article presents a decision model for schedule generation based on mixed integer programming (MIP). This model aims to minimise the number of resources involved while meeting the requirements regarding the frequency of waste collection. One distinguishing characteristic of the proposed method is its premise that transport-related work should remain constant throughout the entire year, irrespective of holidays or days off. To achieve this, the model incorporates schedule substitutions which enable the strategic adjustment of schedules for collection dates affected by holidays, while preventing significant spikes in waste collection volume on those days.

Methodology: The article proposes a decision model based on mixed integer programming (MIP), minimising the maximum amount of waste collected in one day.

Results: Using the proposed decision-making model, tests were carried out on a set of 35 instances corresponding to real problems of preparing waste collection schedules in cities in the Lower Silesian Voivodeship. The test results confirmed the model's efficiency.

Implications and recommendations: The results obtained can be used in municipalities to create schedules and optimise the costs of municipal waste collection.

Originality/value: The model proposal presented in the article contains unique elements, such as a decision model for optimising municipal waste collection over the year and substitutions in the context of the waste collection schedule. Introducing test case analysis adds value by demonstrating the practical application of the model.

Keywords: municipal waste schedule, decision-making model, optimisation

1. Municipal Waste Collection

Municipal waste management is the process that includes waste collection, transportation, processing, recycling, or disposal, as well as the monitoring and regulation of these activities. The aim of municipal waste management is to minimise the impact of waste on the environment and public health, as well as recycle raw materials. In Poland, in accordance with the law, the municipality is obliged to organize the collection of municipal waste from property owners. Specifically, local authorities are responsible for this function: the head [PL. 'sołtys'] of rural communes, the administrator [PL. 'wójt'] in urban-rural communes and towns up to 100,000 inhabitants, while in cities over 100 thousand residents – the mayor [Pl. 'burmistrz'] of the city. The commune may organize waste collection itself, but these tasks are usually outsourced to specialist companies dealing with waste management. The selection of such a company is usually made through a tender procedure, and the selected company becomes the regional operator of municipal waste tasks. The commune is also obliged to organize waste segregation, i.e. divide it into different categories (e.g. glass, paper, plastics) to facilitate their subsequent processing and recycling. Waste collection is also a critical component of urban freight transport systems, serving the essential function of maintaining public health, aesthetics, and environmental quality. It involves the regular collection, transportation, and disposal of waste from residential, commercial, and industrial sources. The efficiency of waste collection impacts traffic congestion, energy consumption, and emission levels within urban centers. Thus, optimising routes, integrating waste management with other urban services, and employing advanced technologies for waste reduction and recycling are key for sustainable urban freight transport systems (see Cherrett et al., 2012; Kin et al., 2017).

2. Solutions for Municipal Waste Collection

From the viewpoint of organizing the municipal waste collection system, one can distinguish two basic solutions: a fixed collection schedule, and collection based on current information about the waste level in a container.

The first approach, municipal waste collection according to a fixed schedule, involves the regular and predictable collection of waste from specific locations on set days or days and hours. This schedule is planned in advance and does not change, regardless of how full the containers are. Residents are informed about collection dates and are obliged to make waste available in accordance with this schedule.

In the case of collection based on the current filling level of the containers, the principle of operation is different. Intelligent waste containers are equipped with sensors showing the filling level. When the container reaches a certain level of filling, it sends a signal to the headquarters of the waste collection operator, which is then used to optimise waste collection routes. Waste collection occurs when the container is full, not on a scheduled day. This allows for flexible adaptation of collection plans to actual supply of waste, which can contribute to increased efficiency and resource savings.

A fixed waste collection schedule is widely used and has its advantages. First of all, it is predictable – residents know when to put their waste out, which makes it easier for them to plan. Additionally, a fixed schedule is simple to understand and manage, without the need for advanced technology. In some places, regulations require regular waste collection, which is easy to ensure with a fixed schedule.

However, a fixed schedule also has its disadvantages as it does not take into account the variability in waste volumes – containers may be empty or overflowing at the time of collection, which is inefficient. It also lacks flexibility because it does not allow for easy changes that may be needed in the event of sudden events or changes in waste generation. Additionally, fixed schedules can lead to unnecessary consumption of resources such as fuel and labour.

On the other hand, smart garbage containers that inform when they are full can help optimise waste collection routes and times, which increases efficiency. Being able to collect waste only when the containers are full saves resources. This system also allows to adapt to changes in waste supply, which adds flexibility.

The disadvantage of smart containers is certainly their cost. Both containers and their management systems are expensive, and advanced software and hardware are also required, as well as the appropriate skills to operate them. The lack of a fixed schedule may introduce some uncertainty for residents who do not know when their waste is going to be collected. Technical problems such as system or container failures are also possible (Knickmeyer, 2020).

In the discussion on the use of the approaches presented above, it is important to distinguish between waste containers for specific residents (e.g. in single-family houses or apartment blocks) and containers publicly available to everyone (e.g. in parks or containers on the streets) (Das & Bhattacharyya, 2015).

In Poland, for individual and public containers the most frequently used system is a fixed waste collection schedule. Residents receive schedules specifying the days and times for collection of various types of waste and are obliged to make waste available in accordance with this schedule. Similarly, public bins are emptied on a set schedule. In the case of smart garbage containers, the situation is different; In Poland, although smart containers are being tested, they are yet not widely used.

Smart containers, which inform when they are full, have been installed in other European countries (Fadda et al., 2018), as well as some Asian cities (Pal & Bhatia, 2022). These containers are publicly accessible, and their emptying is optimised, based on how full they are. However, the use of smart containers for specific residents is less common, although some cities and communes are experimenting with such solutions. For both individual and public containers, the use of smart waste containers can help increase efficiency and save resources. Due to the pursuit of sustainable development, it can be assumed that such solutions will be used more and more often in the future (Sosunova & Porras, 2022).

3. Fixed Municipal Waste Collection Schedule

In the collection and transport of municipal waste organized in accordance with a fixed schedule, the municipal waste collection schedule plays the key role. This document specifies the dates or dates and times on which waste will be collected from locations. It includes various types of waste, such as mixed waste, biodegradable waste, paper, glass, plastic, and metal. The schedule affects the regularity and effectiveness of waste management services. It helps residents plan when to make their waste available and waste management companies to organize their routes and resources.

In Poland, waste collection schedules are usually set by companies outsourced by the municipality to collect waste. They must consider local needs and conditions, such as the number of inhabitants, the types of generated waste, as well as the availability and location of waste treatment facilities. Schedules must be available to residents; they are usually published on the municipalities' websites, made available in dedicated Internet apps, or delivered to households in the form of leaflets. By law, the commune is obliged to ensure waste collection at least once a month for mixed waste and at least once every two weeks for bio-waste. The schedules are also adapted to seasonal changes in the generation of waste, for example they may provide for more frequent bio-waste collections in spring and summer when it increases due to gardening activities.

The current body of scientific literature lacks comprehensive research and analysis on the topic of municipal waste collection scheduling, underlining the notable gap in understanding and addressing this essential component of effective waste management strategies. The absence of research on this issue highlights the need for further investigation and exploration in order to enhance the efficiency and sustainability of municipal waste collection systems. The prevailing practice of scheduling waste collection based on geographical locations fails to incorporate the variable of waste generation rates specific to each area. This oversight in current methodologies overlooks a critical factor in optimising waste management processes for efficiency and resource allocation.

The existing literature predominantly focuses on waste collection route planning by employing diverse algorithms to address the ‘travelling salesman’ problem. Nevertheless, when adopting a fixed schedule methodology, the configuration of collection routes is contingent upon the predetermined pickup schedule, reflecting a distinct operational approach in waste management practices (see Hemidat et al., 2017; Hung-Yueh et al., 2011; Shan-Huen & Pei-Chun, 2015).

A waste collection schedule is crucial for the efficiency of waste management companies, and therefore for the payments the commune is obliged to make for providing this service. In particular, well-arranged schedules allow for:

- Route optimisation: the schedule allows to plan economically effective routes for waste collection vehicles, which translates into savings in time, fuel and resources.
- Resource management: scheduling allows companies to better manage their resources, including employees and vehicles.
- Improving inhabitants satisfaction: a regular waste collection schedule tailored to the needs of residents indicates when they should put their waste out, and encourages residents to segregate and dispose of waste properly.
- Compliance with regulations: waste management companies must comply with additional regulations set by the municipality regarding the frequency and hours of waste collection.

However, the municipal waste collection schedule does not specify what routes vehicles will take to carry it out. The scheduling procedure considers primarily the amount of the generated waste, its types and the locations from which it will be collected, and on this basis, the collection frequency is determined for individual locations and types of waste. In this context, it is also important to consider all legal regulations and residents’ preferences. The tactical part is aimed at optimising the waste collection process in the context of the resources involved and minimising the impact on the environment, while ensuring an appropriate level of services for residents.

The specific routes taken by vehicles on individual days are created as part of short-term planning. At this stage, factors such as available resources (e.g. vehicles and employees), the time needed to collect waste from each location, traffic conditions, as well as the specifics of individual locations (e.g. restrictions on collection hours) are considered. The operational part aims to optimise the waste collection process at the level of individual routes and days (Mes et al., 2014).

Separating the operational part from the scheduling procedure (such as optimising the routes) allows for the more effective and precise adjustment of waste collection routes on individual days (in particular, it will allow to consider road traffic conditions, availability of resources, technical condition of vehicles or changes in the amount and type of waste).

4. The Procedure for Preparing a Municipal Waste Collection Schedule

To create an effective municipal waste collection schedule, the following key data are needed:

- Locations: geographic data regarding the locations from which waste is going to be collected.
- Amount of waste: the amount of waste generated at each location within each category is necessary for scheduling.

- Municipal requirements: municipalities often define additional requirements regarding the hours and days when waste can be collected.
- Calendar: information about the number of days and holidays.

In addition, whenever possible, it is worth considering residents' preferences regarding hours and days of waste collection. In order to meet this requirements, it was assumed that the waste collection schedule is the assignment of a collection scheme consistent with the required frequency to each combination of location, building type and waste category.

4.1. Substitutions

The holiday calendar has a direct impact on the shape of the municipal waste collection schedule, because despite the holidays, all regulations regarding the frequency of waste collection must be complied with. For example, if the regulations require waste collection every two weeks, the schedule must be adjusted to meet these requirements, even if the scheduled collection day falls on a holiday. The requirement to consider holidays is an element that makes more complex the process of manually creating a municipal waste collection schedule.

To solve this problem, an approach called substitutions was introduced. For each collection schedule that falls on a day off there is a defined substitution which contains a set of dates from which one must be selected as an additional date when the waste is going to be collected. For example, for the 'Thursday' collection scheme, according to which waste is collected every Thursday, there should be defined substitutions for the Corpus Christi holiday (this holiday always falls on a Thursday) and there should be defined at least two dates to choose from on which additional waste collection is going to be carried out. For 2024, these dates may be 29 May 2024 (the day before) and 31 May 2024 (the day after). These types of substitutions must be defined for each day off and for each collection schedule that falls on a given day off. For example, since Corpus Christi falls on an even-numbered week in 2024, a similar substitution must be defined for this holiday and the 'Thursday-Even' collection scheme, which means waste collection on Thursdays falling on even-numbered weeks. For the collection scheme 'Thursday-Odd', which corresponds to collections on every odd Thursday, the substitution does not need to be implemented.

4.2. Objective Function

Defining the objective function is a key element in the process of creating a decision model. In many decision-making situations, especially when planning at tactical level, one strives to maintain a constant level of resource utilisation. This approach helps in the efficient use of resources by minimising variability that can lead to poor performance and additional costs. In the context of organizing municipal waste collection, the stable use of resources is also preferred. This is confirmed by conversations with representatives of companies dealing with this type of activity. Maintaining a constant level of resources commitments, such as vehicles and staff, enables the effective planning and implementation of tasks, and also increases residents' satisfaction with the regularity and predictability of services.

5. Decision-making Model for Schedule Generation

Waste collection schedule optimisation aims to minimise the number of resources involved in such a way that also meets the requirements for the frequency of waste collection. Additionally, efforts are made to ensure equal distribution of the workload on each day of the year. Spreading the workload evenly throughout the year aims to avoid certain periods being busier than others. This requires the involvement of many resources in the collection process which are not used throughout the year. The use of operational research methods in this area is quite wide. Despite a thorough review of the literature, the authors were unable to find a solution to the presented problem (Ghiani et al., 2014; Hemmelmayr et al., 2014).

The decision-making model for arranging a waste collection schedule is a difficult optimisation task that requires advanced algorithms and tools from the field of operations research. Later, this paper presents the formulation of an MIP (mixed integer programming) class model, which uses binary variables (assigning locations and fractions to the schedule) and continuous variables to map the amount of waste collected on individual days of the year. The objective function was to minimise the maximum daily amount of waste to be collected, meant as the demand for transport capacity (the more waste to be collected, the more resources necessary to carry out the collection).

In the model, the symbol *I* denotes a set of combinations of parameter values: area (predefined set of locations)/category/building type (hereinafter referred to as the collection group). The symbol *J* is the set of collection schemes, *S* is the set of defined substitutions. *K* is the set of days of the period for which the schedule is generated (the whole year by default). Additionally, it was assumed that *i, j, s, k* denote the elements of the sets of reception groups, reception patterns, substitutions, and days, respectively.

The following parameters were also used in the decision model formulation:

- w_i – capacity of the container/containers in collection group *i*;
- $a_{jk} = 1$ day *k* is scheduled in scheme *j*, 0 otherwise;
- $b_{js} = 1$ substitution *s* applies scheme *j*, 0 otherwise;
- c_j frequency of scheme *j*;
- d_i requested frequency of reception group *i*;
- J_s^2 set of additional schemes for substitution *i*, subset *J*;
- J_f^3 set of reception patterns consistent with frequency *f*, subset *J*.

The model also used two groups of decision variables. The first binary variable denoted as x_{ij} is equal to the value of 1 when collection group *i* is served according to collection scheme *j* and 0 otherwise. The second is a technical variable marked with the symbol y, which corresponds to the amount of waste collected on the day of the year when the most waste is collected, it is a continuous variable.

$$y \to min \tag{1}$$

$$\sum_{j \in J_{d_i}^3} x_{ij} = 1 \qquad \forall\, i \in I \tag{2}$$

$$\sum_{j \in J, i \in I} x_{ij} w_i a_{jk} \leq y \qquad \forall\, k \in K \tag{3}$$

$$\sum_{j' \in J_s^2} x_{ij'} = x_{ij} \qquad \forall\, i \in I, s \in S, j \in J : b_{js} = 1 \tag{4}$$

In the model expressed by formulas (1) to (4), the objective function (1) was defined as the minimisation of the decision variable *y*, i.e. minimisation of the maximum amount of waste planned to be collected in one day. Constraint (2) ensures that each collection group is associated with an appropriate collection scheme, i.e. one that has the same frequency as that required for the collection group. This is achieved by summing up the variable x_{ij} only for the subset of all collection schemes with the frequency required for the collection group, i.e. from the set J_f^3. Constraint (3) links x_{ij} variables with *y* variable and ensures that the value of the *y* variable is constrained from below by the amounts of waste collected on subsequent days, which will result in taking the largest of them. The last constraint (4) is responsible for ensuring that each collection group is assigned to one of the collection dates from each of the substitutions defined for the collection scheme assigned.

To sum up, the presented model comprehensively incorporates and methodically accounts for the full array of stakeholder requirements, ensuring these are accurately reflected within the decision-making process. The model's efficacy in capturing stakeholder needs is validated through iterative consultations with stakeholders and reinforced by scenario analysis, which assesses the model's robustness and adaptability to changing conditions (e.g. different types of waste or scheduling requirements).

6. Computational Tests

In order to prove the correctness of the formulation and verify the effectiveness of the presented decision model, a series of tests were carried out on a set of 35 test instances corresponding to real problems of scheduling waste collection in cities in the Dolnośląskie Voivodeship. In each case, streets were taken as the area. Moreover, for the city of Wrocław (as it is in reality), the optimisation procedure was performed separately for three sectors from which waste is collected by different operators and the optimisation procedure was carried out applying the CBC optimisation engine, using a computer equipped with an i7 class processor.

Table 1. List of test instances solved

No	Terytory code	City	Solution time [*s*]
1	202011	Bielawa	86
2	221011	Boguszów-Gorce	2
3	201011	Bolesławiec	156
4	209011	Chojnów	32
5	208011	Duszniki-Zdrój	4
6	202021	Dzierżoniów	95
7	203011	Głogów	94
8	205011	Jawor	99
9	221021	Jedlina-Zdrój	21
10	261011	Jelenia Góra	37
11	207011	Kamienna Góra	54
12	206011	Karpacz	10
13	208021	Kłodzko	56
14	206021	Kowary	16
15	208031	Kudowa-Zdrój	37
16	262011	Legnica	55
17	210011	Lubań	81
18	211011	Lubin	171
19	208041	Nowa Ruda	50
20	215011	Oława	117
21	214011	Oleśnica	3
22	206031	Piechowice	25
23	202041	Piława Górna	18
24	208051	Polanica-Zdrój	17
25	219011	Świdnica	153
26	219021	Świebodzice	55
27	210021	Świeradów-Zdrój	14
28	221031	Szczawno-Zdrój	5
29	206041	Szklarska Poręba	2
30	265011	Wałbrzych	82
31	226011	Wojcieszów	6
32	264011	Wrocław	637
33	225011	Zawidów	1
34	225021	Zgorzelec	69
35	226021	Złotoryja	1

Source: own study based on calculations.

The tests included an analysis of the correctness of the obtained solutions (in particular the correctness of the use of substitutions) and performance in the context of real problem instances. These tests aimed to assess the effectiveness of the model in solving the scheduling problem, considering the different city sizes. The results of these tests confirmed the correctness of the model and its high model performance. Firstly, it was proved that the model allowed to obtain a solution for each instance, even for such a large city as Wrocław. The larger the city for which the schedule was prepared, the greater the solution time. Moreover, the solutions for all the presented cities considered holidays and maintained appropriate pickup frequencies, which means that they were correctly calculated.

Table 1 shows the solution times for 35 real-life problem instances. All the times presented are considered acceptable, which proved the effective functioning of the decision-making model and the solution method.

7. Discussion and Conclusions

The article presents the successful implementation of a decision-making model aimed at optimising the waste collection schedule from urban areas. This model was successfully used to solve the described problem in 35 selected cities in the Dolnośląskie Voivodeship. Thanks to the use of the model, it was possible to quickly generate a schedule that meets the municipality's requirements regarding the frequency of collections and at the same time guarantees a stable collection workload on every day of the year. Substitutions, which allow for non-working days to be taken into account and guarantee that the required collection rates are maintained, are new in this formulation.

The study draws attention to the possibility of obtaining solutions to real problems using this decision model, which may be an inspiration for other scientists dealing with waste management to use similar solutions to improve their processes. Ultimately, the discussed decision-making model is an example of successful implementation of operational research tools in practice, which may contribute to the effective management of complex municipal waste collection processes.

Although this has not yet been confirmed, the use of the discussed model in practice can potentially bring significant benefits in optimising the waste collection process and reducing its operating costs. In the context of highly complex constraints that complicate this problem, the results of the first implementation of the model were promising. Positive results were achieved, which has led to an improvement in the process of scheduling waste collection, increased efficiency in the use of available resources, and eventually may bring a reduction in operating costs.

The presented research is only an introduction to extensive research aimed at optimising the waste collection process in municipal areas. Continuing this research may bring operational solutions, such as daily route optimisation, which is a natural step in further work. The issues discussed in the article have the potential to further develop operational research tools, which may significantly contribute to the effective management of processes related to waste collection and management for urban areas in line with the trends presented in the latest research (Marseglia et al., 2022).

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Model decyzyjny optymalizacji zbiórki odpadów komunalnych w horyzoncie średnioterminowym

Streszczenie

Cel: W artykule przedstawiono proces zarządzania odpadami komunalnymi, ze szczególnym uwzględnieniem organizacji zbiórki odpadów. W tekście omówiono cele gospodarki odpadami, zasady funkcjonowania w Polsce zgodnie z ustawą o utrzymaniu czystości i porządku w gminach oraz różne podejścia do organizacji zbiórki odpadów. W dalszej części tekstu przedstawiono model decyzyjny generowania harmonogramu, oparty na programowaniu całkowitoliczbowym (MIP). Model ten ma na celu minimalizację liczby zaangażowanych zasobów przy spełnieniu wymagań dotyczących częstotliwości odbioru odpadów.

Metodyka: W artykule zaproponowano model decyzyjny oparty na programowaniu całkowitoliczbowym (MIP), minimalizujący maksymalną ilość odpadów odbieranych w jednym dniu.

Wyniki: Za pomocą zaproponowanego modelu decyzyjnego przeprowadzono testy na zestawie 35 instancji odpowiadających rzeczywistym problemom układania harmonogramu zbiórki odpadów w miastach województwa dolnośląskiego. Wyniki testów potwierdziły poprawność modelu oraz jego wydajność.

Implikacje i rekomendacje: Uzyskane wyniki można wykorzystać w gminach do tworzenia i optymalizacji kosztów zbiórki odpadów komunalnych.

Oryginalność/wartość: Przedstawiona w artykule propozycja modelu zawiera unikalne elementy, takie jak model decyzyjny optymalizacji zbiórki odpadów komunalnych w horyzoncie roku oraz substytucje w kontekście harmonogramu zbiórki odpadów. Wprowadzenie analizy przypadków testowych dodaje wartość, pokazując praktyczne zastosowanie modelu.

Słowa kluczowe: harmonogram odpadów komunalnych, model decyzyjny, optymalizacja