CHEMICAL ENGINEERING TRANSACTIONS

VOL. 122, 2025

A publication of AIDIC

The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Jeng Shiun Lim, Bohong Wang, Guo Ren Mong, Petar S. Varbanov

ISBN 979-12-81206-23-6; **ISSN** 2283-9216

DOI: 10.3303/CET25122052

Multi-Objective Optimization of Medical Waste Management with Scheduling Considerations

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Due to the infectious nature of medical waste, it must be treated both immediately and urgently. Previous literature has considered the facility allocation of medical waste amongst the different treatment facilities. However, in real-world applications, multiple facilities are being used as part of a single pathway, and a treatment deadline is imposed. Despite this, no studies have simultaneously considered optimizing facility allocation and scheduling of medical waste management facilities. In this study, a multi-objective mathematical optimization model is formulated that allocates waste among the different facilities and identifies when to start each process by simultaneously optimizing cost and environmental impact. A case study was solved, resulting in the costs of €44,345.93 and a Life Cycle Impact Assessment (LCIA) output of 902.27 units. A scenario analysis was then provided to understand further the model's behaviour when facility allocation and scheduling are not done simultaneously. Results reveal insights as to when to process waste immediately or to wait for the next period.

1. Introduction

Medical waste from healthcare facilities poses public health risks, given its infectious nature. It is segregated at the source, treated at specific facilities, and disposed of at designated sites (Attrah et al., 2022). Each facility also has its own set of costs and environmental considerations that must be considered in facility allocation. The environmental impact is evaluated via Life Cycle Impact Assessment (LCIA) using input and output data to help identify and reduce the environmental footprint (Ahmad et al., 2019). Due to the different trade-offs in facility allocation, Joneghani et al. (2022) and Torkayesh et al. (2021) considered using multi-objective optimization in allocating wastes among the different treatment facilities based on both cost and carbon emissions. However, there are also other environmental factors that have to be considered such as wastewater output, chemical usage, and fuel consumption.

Furthermore, medical waste also has varying infection rates, it is important to consider treatment efficiency when allocating waste among the different treatment facilities. A facility's treatment efficiency is the effectiveness of a facility in reducing the waste's infection rate. Studies done by Ghannadpour et al. (2021) and Tirkolaee and Aydin (2021) took this into account by considering the risk of infection in making decisions regarding facility allocation. However, different pre-treatment and post-treatment facilities for each treatment method are used to ensure proper and efficient treatment. Since multiple facilities are used in a single pathway, potential bottlenecks can lead to treatment delays, increased costs, and increased environmental footprint. Additionally, there is also a treatment deadline of 24 to 72 h (Letho et al., 2021). Without proper scheduling on a system level, there is also a tendency to have unnecessary idle time and bottlenecks, which is why streamlined scheduling of facilities needs to be considered, since a penalty is incurred once the deadline is violated.

Previous literature has yet to consider the facility allocation and scheduling of medical waste management facilities simultaneously. By focusing only on facility allocation, wastes will be allocated to various treatment sites without considering the treatment deadline, resulting in late treatment of wastes. If scheduling decisions are made independently of facility allocation, wastes may be assigned to facilities that cannot process wastes, resulting in the most expensive and environmentally harmful options. This study considers both facility allocation and scheduling considerations while minimizing both the cost and environmental impact.

Paper Received: 30 August 2025; Revised: 4 November 2025; Accepted: 1 December 2025
Please cite this article as: Tan H.D., Elano A.J., Jurilla R.D., Lim S.L., San Juan J.L., 2025, Multi-Objective Optimization of Medical Waste Management with Scheduling Considerations, Chemical Engineering Transactions, 122, 307-312 DOI:10.3303/CET25122052

2. System Definition

The optimization model developed is based on economic and environmental objectives to decide how much waste is allocated among the different facilities, together with the start and completion times of each job, which is defined as the processing of waste in a certain facility. Examples are the shredding and grinding of waste in the shredder and grinder respectively. The heating of waste in the autoclave facility as well. The wastes of the release batches from the different sources are picked up and sent to the jobs of the various facilities. Each release batch is released at a different time. Once the waste has gone through all the facilities in its pathway, it gets disposed of. When multiple types of waste are being mixed, a job can only start once all waste has arrived in the facility. For the characteristics of mixed waste, the earliest deadline is taken, along with the highest infection rate. The constraints of this model would ensure that wastes are safe for disposal, facilities open and close on time, the make spans of each job in each facility are being followed, jobs in a facility do not overlap, and the different treatment deadlines are being considered. Given the soft deadlines, the model can also decide when to hold waste or treat it immediately. It is also to be considered that waste with a higher infection rate has earlier deadlines. Mixing of waste can only happen in the facilities.

3. Model Formulation

The Mixed Integer Linear Programming (MILP) formulation of the problem is presented below. Tables 1 to 3 provide an overview of the model's indices, decision and system variables, and parameters, respectively.

Table 1: Indices

Notation	Definition	Notation	Definition	Notation	Definition
s	Source	d	Disposal Sites	f	Facility Number
j	Job Number	g	Release Batch Number	n	Periods

Table 2: Decision and System Variables

Notation	Definition	Notation	Definition
AP_{fj}	Amount of waste in facility f job j	L_{fj}	Lateness of facility f job j
DAP_{fj}	Deadline of waste processed in facility f job j	$BSL2_{fjf'j'}$	1, if waste from facility f job j is slotted in facility f' job j'
$TR1_{sgf}$	Waste amount transported from source s release batch g to facility f	$BSL1_{sgfj}$	1, if waste from source s release batch g is slotted in facility f job j.
$TR2_{fjf'}$	Waste amount transported from facility f job j to facility f'	$SL1_{sgfj}$	Waste amount from source s release batch g is slotted in a facility f job j
$TR3_{fjd}$	Waste amount transported from facility f job j to disposal d	$SL2_{fjf'j'}$	Waste amount from facility f job j slotted in f' job j'
BAP_{fj}	1, if waste is processed in facility f job j .	S_{fj}	Starting time of facility f job j
IAP_{fj}	Infection rate of waste in facility f job j	C_{fj}	Completion time of facility f job j

Table 3: Parameters

Notation	Definition	Notation	Definition
AG_{sg}	Waste amount from source s of release batch g	TG_{sg}	Time release of source s release batch g
$TT1_{sf}$	Travel time from source s to facility f	SCF_f	Fixed waste cost in facility f
$TT2_{ff'}$	Travel time from facility f to facility f'	OCF_f	Variable waste in facility f
$TT3_{fd}$	Travel time from facility f to disposal d	CD	Disposal cost
CP	Penalty cost	l_f	Job Duration in facility f
FEF_f	Fixed facility LCIA of facility f	VEF_f	Variable facility LCIA of facility f
Cap_f	Capacity of facility f	TE_f	Treatment efficiency of facility f
$CON1_{sf}$	1, if source s transports waste to facility f	DI	Allowable infection rate for disposal
$CON2_{ff'}$	1, if facility f transports waste to facility f'	OP_n	Facilities' opening time in period n
$CON3_{fd}$	1, if facility f transports waste to disposal d	CL_n	Facilities' closing time in period n
DG_{sg}	Waste deadline from source s release batch g	IG_{sg}	Waste's infection rate from source s release batch g

3.1 Objective Functions

The economic and environmental considerations are presented in Eq(1) and Eq(2). The economic objective is composed of the fixed facility costs of using a job, the variable facility costs of how much waste is being processed in each facility, the disposal cost of the amount of waste being disposed of, and the penalty cost for every hour of lateness being incurred. Moreover, the environmental objective is the fixed facility LCIA of using a job, and the variable facility LCIA of the amount of waste being processed in each facility.

$$Min\ Cost\ = \sum_f \sum_j \left(SCF_f * BAP_{fj} + OCF_f * AP_{fj} + CP * L_{fj}\right) + \sum_f \sum_j \sum_d \left(CD * TR3_{fjd}\right) \tag{1}$$

$$Min\ LCIA\ = \sum_f \sum_j \left(SEF_f * BAP_{fj} + VEF_f * AP_{fj}\right) \tag{2}$$

In balancing the achievement of optimality in both objectives, each objective is first optimized individually to get the best and worst possible outcomes for each objective. The efficiency for each objective is equivalent to the actual value subtracted by the worst possible value divided by the best possible value minus the worst possible value. The less efficient function is maximized, ensuring that both objectives are optimized while minimizing the sacrifice in the other objective as shown in Eq(3). This method has proven to be effective by studies such as airline fuel loading (Uy and San Juan, 2024), Algal biofuel production (Solis and San Juan, 2021), and microalgal cultivation and harvesting (San Juan et al., 2020).

$$Max\ min\ \left[\frac{Cost_{worst} - Cost}{Cost_{worst} - Cost_{best}}, \frac{LCIA_{worst} - LCIA}{LCIA_{worst} - LCIA_{best}}\right] \tag{3}$$

3.2 Constraints

Eq(4) presents one of the network constraints that indicate whether waste can be transported from one location to another. Eq(5) indicate how much waste is being slotted and transported from one location to another. Eq(6) is the capacity constraint of each facility. Eq(7) defines a switch variable for when a job is being used and whenever waste is being slotted from one location to the next.

$$BSL1_{sgfj} \le CON1_{sf}\ \forall\ s, g, f, j \tag{4}$$

$$AG_{sg} = \sum_f \sum_j SL1_{sgfj}\ \forall s, g \tag{5}$$

$$AP_{fj} \le Cap_f * BAP_{fj}\ \ \forall f, j \tag{6}$$

$$SL1_{sgfj} \le M * BSL1_{sgfj}\ \forall s, g, f, j \tag{7}$$

Eq(8) ensures that the highest infection rate is always considered when different wastes are being mixed in a job together. Eq(9) ensures that the infection rate of all waste after treatment passes the allowable infection rate for disposal. Eq(10) enforces that a job can only start when all waste slotted has arrived in the facility. Eq(11) makes sure that the earliest deadline for all mixed waste is being taken.

$$IAP_{fj} \ge IG_{sg} + (BSL1_{sgfj} - 1) * M\ \ \forall s, g, f, j \tag{8}$$

$$IAP_{fj} * (1 - TE_f) \le DI\ \ \forall j, f \tag{9}$$

$$S_{fj} \ge\ TG_{sg} + TT1_{sf} + (BSL1_{sgfj} - 1) * M\ \forall s, g, j, f \tag{10}$$

$$DAP_{fj} \le DG_{sg} + \left(1 - BSL1_{sgfj}\right) * M\ \forall s, g, f, j \tag{11}$$

Eq(12) ensures that jobs end on time. Eq(13) ensures that jobs do not overlap. Eq(14) and Eq(15) ensure that the facilities open and close on time, respectively. Eq(16) defined the lateness of the jobs in treatment facilities.

$$C_{fj} = S_{fj} + BAP_{fj} * l_f\ \forall f, j \tag{12}$$

$$C_{fj} \le S_{f,j+1}\ \forall f, j\ \in \{1, 2, 3, 4, \ldots., J - 1\} \tag{13}$$

$$S_{fj} \geq OP_n \; \forall f, n, j \in \{first\ job\ of\ period\ n\} \quad (14)$$

$$C_{fj} \leq CL_n \; \forall f, n, j \in \{last\ job\ of\ period\ n\} \quad (15)$$

$$L_{fj} \geq C_{fj} - DAP_{fj} \quad \forall j, f \in \{Treatment\ Facility\} \quad (16)$$

4. Illustrative Case Study

The illustrative case study contains 3 sources, 4 release batches per period, 5 facilities, 2 disposal sites, and 2 periods. Table 4 contains each facility's different costs, LCIA, and make span. The LCIA values were obtained using he method of Kumar et al. (2023). The shredder is a pre-treatment for both the autoclave and microwave facilities, whereas the grinder is the pre-treatment for the chemical disinfection facility. Moreover, the penalty cost is €175.86 per hour of lateness (Thakur, 2022). More comprehensive data regarding the illustrative case study will be available upon request.

Table 4: Economic and Environmental Considerations per Facility

Facility	SCF_f (€)	OCF_f (€)	$FEF_f(units)$	$VEF_f(units)$	l_f (h)
Shredder	486.26	0.11	0.09	0.0176	2
Grinder	444.06	0.11	0.05	0.0136	1.5
Autoclave	954.94	0.10	10.8	0.1080	1.5
Microwave	910.97	0.10	4.5	0.0496	0.75
Chemical Disinfection	901.30	0.46	1.18	0.0846	2

The results of the multi-objective optimization and single-objective optimizations are in Table 5. Given that the economic objective considers both facility allocation and scheduling, it creates a trade-off between fixed facility costs and penalty costs. Treating more waste together lowers the fixed facility cost but may lead to lateness. The model then must identify when to wait and when to treat it immediately. In selecting which facilities to use, when optimizing based on cost alone, the model prefers to use the autoclave over the microwave facility. Without an environmental penalty for lateness, the environmental objective would focus solely on facility allocation. The model also prefers to allocate waste to the microwave facility compared to the autoclave facility when minimizing the LCIA components. Given this, when the environmental considerations are optimized, the penalty cost resulted in a total of €88,102.39. In considering both objectives simultaneously, the model made decisions based on both economic and environmental considerations, resulting in a cost of €44,345.93 and a LCIA score of 902.27 units.

Table 5: Solution of Single and Multi-objective Optimizations

Considerations	Economic (Single)	Environmental (Single)	Multi-Objective
Economic (€)	42,006.80	128,111.52	44,345.93
Environmental (units)	982.62	901.99	902.27

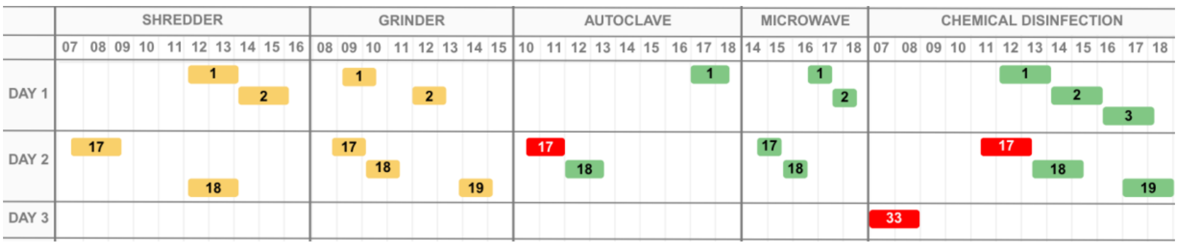

Figure 1: Gantt Chart of Facilities

The Gantt chart of jobs of each facility is shown in Figure 1. Jobs in yellow are those in the pre-treatment facilities. Jobs in green are on time, whereas the red jobs are the late jobs. The facility allocation amongst the different jobs is based on the cost, environmental impact, treatment efficiency and capacity of the different facilities. The shredder and grinder are facilities with lower fixed facility costs and fixed facility LCIA with a larger capacity in comparison to the treatment facilities. Due to the low fixed facility cost and LCIA, the model decided to have more jobs in these facilities since it will be economically and environmentally cheaper than having more jobs in the treatment facilities itself and in incurring penalties. Additionally, the autoclave has a treatment efficiency of 95 % whereas the microwave facility only has a treatment efficiency of 80 %. Since the shredder is the pre-treatment facility being used for both these facilities, it must separate the jobs with waste going to each individual facility. Jobs 1 and 17 of the shredder have a 90 % infection rate and are sent to the autoclave facility, while jobs 2 and 18 have a 70 % infection rate and are going to the microwave facility. This shows the model's ability to prioritize more infectious wastes in assigning to highly effective treatment facilities.

The autoclave facility is the cheapest facility, has the largest capacity amongst the treatment facilities, and has the highest treatment efficiency. However, it is the most environmentally harmful. Aiming to minimize the total LCIA, the model aimed to lessen the total number of jobs of this facility. Job 17 of the autoclave facility has a lateness of 11.54 h since it decided to wait for waste coming from period 2 before starting treatment. This scheduling decision was done to lessen the LCIA by 10.8 units by batching wastes, while incurring €2,029.42 in penalties. Moreover, the microwave facility is the environmentally friendly option but has the smallest capacity and lowest treatment efficiency. As it is only capable of treating a limited amount of waste, there is no incentive to wait for the next period for treatment to start, which is why jobs in this facility get treated immediately for it to not incur any penalties.

Among the three facilities, the chemical disinfection facility has the most jobs since it is the most balanced facility both economically and environmentally. However, it has a long make span. Job 17 has waste coming from both days, which resulted in a late job with a lateness of 1.54 h. The model considered the penalty of €270.82 being cheaper than another job since the fixed facility cost and LCIA. Additionally, waste from day 2 has to be treated on or before the 56th hour before a penalty is incurred. Given that there are 4 jobs, the total make span is 8 h, which starts on the 35.54 h timestamp. However, it is important to consider that the facility closes at hour 43 and opens again at hour 55, which results in a pause in treatment. Despite this, there is just a lateness of 1 hour, resulting in €175.86.

5. Scenario Analysis

As current models of medical waste management solely consider facility allocation without scheduling, this scenario analysis aims to compare the results of when facility allocation is done before scheduling; planning is performed sequentially instead of simultaneously. In this scenario, Eq(16) to Eq(25) is removed along with the penalty cost in the objective function for economic considerations. The results of the facility allocation, a job shop scheduling model will be run, aiming to minimize the penalty cost. Table 6 compares the solution between this scenario and the base run, while Figure 2 summarizes the treatment schedule in a Gantt chart. Jobs in yellow are those in the pre-treatment facilities, whereas the jobs in red are the late jobs.

Table 6: Solution of Scenario and Base Run

Considerations	Scenario	Base Run
Facility Allocation Costs (€)	39,456.34	41,869.77
Penalty Costs (€)	42,194.95	2,476.16
Total Costs (€)	81,651.29	44,345.93
Environmental (units)	920.89	902.27

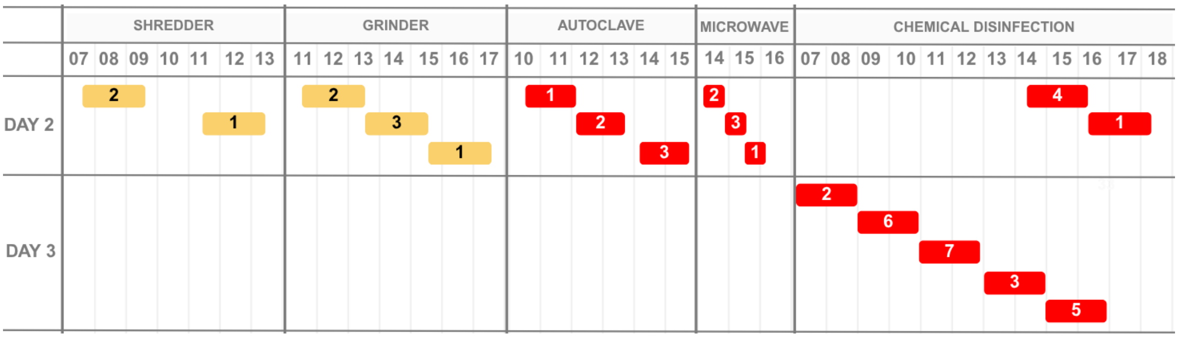

Figure 2: Gantt Chart of Facilities

Given that facility allocation is optimized solely, the model will aim to lessen the total number of jobs, lowering fixed costs and LCIA. The model also opted for the decrease in facility allocation costs to be worth the increase in the total LCIA. Since the model aims to maximize the capacity and mix as much waste as possible. Given the larger capacities of the shredder and grinder facilities, the model was able to lessen the number of jobs in these facilities, saving both fixed facility costs and LCIA. The number of jobs in the shredder went from 4 to 2 and the number of jobs in the grinder went from 5 to 3 in comparison to the base run. Since the model opted to maximize the capacities to lower the fixed facility costs and LCIA, this resulted in earlier deadlines of multiple jobs with the make spans not being able to keep up which resulted in all jobs in the treatment facilities being late. A total of 239.93 h in terms of lateness, resulting in a penalty of €42,194.95. This scenario is more expensive and environmentally harmful than the base run due to the €37,305.36 increase in cost and 18.62 units increase in LCIA.

6. Conclusion

Given the urgency of treating medical waste and using multiple facilities as part of a single pathway, there is a need to consider both facility allocation and scheduling simultaneously. This study created a multi-objective optimization model that makes decisions regarding facility allocation and scheduling based on different economic and environmental considerations. A case study was solved to demonstrate model capability and understand model behaviour. In the base run, the model decided which wastes to mix in the different jobs and the start and completion time of each job in the various facilities. The model also decided which period to treat each waste. A scenario was also conducted to provide a benchmark of previous literature, which performed facility allocation and scheduling sequentially in separate models. When solely facility allocation is being considered, the model will attempt to lessen the total amount of jobs to decrease the amount of fixed facility costs and LCIA being incurred. However, this has a trade-off when it comes to scheduling, since it will increase the total lateness being incurred by the system, since jobs will be forced to start on a later period. For future studies, additional scheduling characteristics can be added, such as variable make spans depending on the amount of waste inputted and factors of uncertainty like facility breakdowns and maintenance.

References

Ahmad R., Liu G., Santagata R., Casazza M., Xue J., Khan K., Nawab J., Ulgiati S., Lega M., 2019, LCA of hospital solid waste treatment alternatives in a developing country: the case of District Swat, Pakistan, Sustainability, 11(13), 3501.

Attrah M., Elmanadely A., Akter D., Rene E.R., 2022, A review on medical waste management: treatment, recycling, and disposal options, Environments, 9(11), 146.

Ghannadpour, S.F., Zandieh, F. and Esmaeili, F., 2021, Optimizing triple bottom-line objectives for sustainable health-care waste collection and routing by a self-adaptive evolutionary algorithm: A case study from Tehran province in Iran, Journal of Cleaner Production, 287, 125010.

Joneghani N.M., Zarrinpoor N., Eghtesadifard M., 2022, A mathematical model for designing a network of sustainable medical waste management under uncertainty, Computers and Industrial Engineering, 171, 108372.

Kumar V., Gaurav G., Khan V., Choudhary S., Dangayach G.S., 2023, Life cycle assessment and its application in medical waste disposal, Materials Today: Proceedings. In Press.

Letho Z., Yangdon T., Lhamo C., Limbu C.B., Yoezer S., Jamtsho T., Chhetri P., Tshering D., 2021, Awareness and practice of medical waste management among healthcare providers in National Referral Hospital, PLoS ONE, 16(1), e0243817.

San Juan, J.L.G., Mayol, A.P., Sybingco, E., Ubando, A.T., Culaba, A.B., Chen, W.H. and Chang, J.S., 2020, A scheduling and planning algorithm for microalgal cultivation and harvesting for biofuel production, IOP Conference Series: Earth and Environmental Science, 463, 012010.

Solis C.M., Juan J.L.S., 2021, Multi-Objective Target-Oriented Robust Optimization of Algal Biofuel Production Integrating Resource Recirculation, Chemical Engineering Transactions, 88, 565-570.

Thakur, S., 2022, Medical dialogues, Medical Dialogues <medicaldialogues.in/5-year-jail-1-lakh-fine-to-breaking-biomedical-waste-rules-delhi-govt> accessed 12.04.2025.

Tirkolaee, E.B., Aydın, N., 2021, A sustainable medical waste collection and transportation model for pandemics, Waste Management and Research, 39(1), 34–44.

Torkayesh A.E., Vandchali H.R., Tirkolaee E.B., 2021, Multi-objective optimization for healthcare waste management network design with sustainability perspective, Sustainability, 13(15), 8279.

Uy J.G., San Juan J.L., 2024, Airline Fuel Loading Optimization Considering Sustainable Aviation Fuel, Chemical Engineering Transactions, 114, 181-186.