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Optimization Models for Long-Term Planning of Municipal Solid Waste Management Systems: A Review with An Emphasis on Mass Balances

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ABSTRACT. The vast majority of decision-making approaches used for long-term planning of municipal solid waste management systems (LPMSWMS) are ground on scenario-based structures. However, the scenario-based structures may overlook many real-world possibilities because of their restricted mass balances. This study is the first attempt to review the current state of optimization models, which are used as a decision-making approach for LPMSWMS, by focusing on the mass balances. In line with this purpose, 146 peer-reviewed articles were examined based on a new literature evaluation scheme. According to the findings, it can be stated that a significant majority of the articles offer non-deterministic optimization models dealing with the uncertain nature of the LPMSWMS problems. Considering all optimization models examined in the study, most of the model formulations have linear mathematical forms in terms of objective and constraint functions. However, it is quite interesting that none of the models produced solutions for a management system alternative with an integrated (non-restricted) mass balance. Accordingly, it is very questionable whether the results obtained from the current models have the power to give the most suitable solution for an up-to-date management system. As a result of the review, it is highly recommended that the optimization models to be conducted for the LPMSWMS in the future should search for new mathematical approaches considering the integrated mass balances under certainty and/or uncertainty.

Keywords: decision-making, household waste, mathematical programming, optimization, uncertainty

1. Introduction

Municipal solid waste (MSW) generation is approximately 2 billion tons per year on the global scale, and it is expected to increase to around 3.4 billion tons per year by 2050 (Kaza et al., 2018). With this rapidly rising amount, MSW management becomes a critical issue for the municipalities. Decision-making approaches used for long-term planning of MSW management systems (LPMSWMS) can be grouped into two categories: 1) System engineering models including cost-benefit analysis, forecasting models, simulation models, optimization models, and integrated modeling systems, 2) System evaluation tools including management information systems, decision support systems, expert systems, scenario development, material flow analysis, life cycle assessment (LCA) or life cycle inventory, risk assessment, environmental impact assessment, strategic environmental assessment, socio-economic assessment, and sustainable assessment (Pires et al., 2011). On the other hand, most of the decision-making approaches used for the LPMSWMS are based on scenario-based structures (Allesch and Brunner, 2014). Although the scenario-based structures make it easier to model the LPMSWMS problems, these structures may ignore many real-world possibilities (Tascione et al., 2014).

Regarding the scientific studies on the MSW management realized after 2010, while almost 15% of the studies comprise review studies, almost 75% of the studies comprise the LCA applications and optimization models (Cobo et al., 2018). Considering the review studies, many of them, such as Tascione and Raggi (2012), Othman et al. (2013), Laurent et al. (2014a, b), Astrup et al. (2015), and Khandelwal (2019), take into account the current state of the LCA applications. On the other hand, a limited number of review studies, such as Juul et al. (2013) and Ghiani et al. (2014), specifically consider the current state of the optimization models.

An optimization model has a general mathematical form including objective functions, constraint functions, variables, and parameters (Boyd and Vandenberghe, 2004). Regarding the existing optimization models used for the LPMSWMS, the studies suggest different mathematical models in which the objective function and/or constraints are formulated in linear and/or nonlinear forms. The solution space of a linear mathematical model has a convex form and the local optimum point is also the global optima (Bazaraa et al., 2006). Therefore, compared to the nonlinear mathematical models, it can be stated that less computational effort is usually required to find the optimum solution

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for the linear mathematical models. However, some constraints of real-world possibilities can be modeled more realistic with non-linear equations. According to Wu et al. (2006), non-linearity can exist in various types in the modeling of environmental systems. For example, the cost functions of treatment and disposal processes may be non-linear because of the interactive effects between different model parameters such as process capacities and waste streams. The model constraints may also be non-linear because of the complex relations between the model variables and their roles in the objective function.

In terms of introducing an optimization model for the LPMSWMS, one of the critical features is the form of mass flow between waste sources, treatment processes and disposal processes. In real-world practices, the MSW masses reflect a multiple movement form, where all waste components move together. On the other hand, all different treatment and disposal processes show different responses to each waste component. Hence, it is crucial to evaluate every waste component for every process separately (Levis et al., 2013). Making such an evaluation for an integrated mass balance (i.e., a non-restricted mass balance, or a mass balance without scenario-based structures), on the other hand, may cause significant difficulties in structuring with linear constraints.

This study aims to present an evaluation of the current state of the optimization models used in the LPMSWMS, emphasizing the mass balances. To this end, a comprehensive literature survey was performed. The articles which were determined as a result of the literature survey were examined within the scope of a new literature evaluation scheme. As a result of the examination, the findings were presented, and criticism of the current state was made. In the study, we first present the basic information on the LPMSWMS problem and the new literature evaluation scheme in sections 2.1 and 2.2, respectively. Next, we describe the details of literature survey in section 2.3. After that, we present and discuss the results for all assessment stages of the evaluation scheme in section 3, separately. Finally, we make a few concluding remarks.

2. Materials and Methods

2.1. Basic Information on the LPMSWMS Problem

According to Ghiani et al. (2014), the key features to take into account in the optimization of solid waste management systems are planning period, mass balances, waste components, process capacities, economies of scale, and objectives. Additionally, Juul et al. (2013) emphasizes that the geographic focuses of models should also be considered. According to Batur et al. (2020), the optimization models which will be used in the LPMSWMS should evaluate many decision-making layers (e.g., process selection, technology selection, capacity selection, site selection, waste allocation, etc.) at the same time. The separate evaluation of these layers may cause important deviations regarding the optimal solution. For instance, the collection and transportation costs can reach extremely high levels, such as 80% of the total cost of an MSW management system (Belien et al., 2011). Therefore, it is not possible to achieve the optimal solution without simultaneously considering the decision-making layers such as site selection and waste allocation.

The multi-layered decision problem mentioned above can be summarized as follow: since the LPMSWMS is a strategic decision-making process, the planning period is one of the primary inputs for the problem. For a given planning period, the waste collection procedure and the specific locations of the MSW sources from which the wastes will be collected have to be decided (i.e., selection of collection type and collection zoning, respectively). The next stage for the LPMSWMS is forecasting the amount of MSW components for each MSW source. For this stage, prediction of many other model parameters, such as costs and benefits, process capacities, environmental effects etc., is another fundamental issue to obtain realistic results. In addition to the estimation of model parameters, the current technological state in MSW management necessitates the evaluation of a complex mass balance for different waste streams to be collected. For each waste stream, there may exist more than one process alternative in the MSW management system. Therefore, it should be decided about which process, technology, and capacity alternatives will be used (i.e., process selection, technology alternative assessment, and capacity assessment, respecttively), and in which locations these alternatives will be constructed (i.e., site selection). Furthermore, all these decision layers bring along the questions of what amount of waste/residual/product will be carried when, where, and how (i.e., waste allocation). For this stage, the frequency of the collection of the wastes and vehicle routing plans should be additionally included. Finally, all these decision layers necessitate evaluating issues such as the specific waste transformation ratios of the processes for the waste components (i.e., cumulative or component-based waste transformation) and the scope of the mass balance to be used (i.e., restricted or non-restricted mass balance).

A schematic view of a non-restricted (integrated) mass balance that may be valid in existing MSW management applications is presented in Figure 1. To be clear, let us think about just the thermal process echelon for an MSW management system (please see Figure 1). The possible waste inputs for the thermal process echelon may not only come from the MSW sources but also from the transfer process echelon, mechanical process echelon, biological process echelon, and thermal process echelon (the echelon itself). After the incoming waste streams are treated in the thermal process echelon, they may be channeled towards other echelons. This structure gets even more complicated for an optimization model in case the waste collection method is a separate collection (e.g., recyclable wastes, biodegradable wastes). The waste streams and their every waste component coming to the thermal process echelon are different decision variables for the question of process selection in an optimization model. This situation creates the issue of non-linear form for the mass balance constraints which are structured with the component-based waste transformation approach. Batur et al. (2020) claimed that the issue of non-linear form causes the models with linear mass balance constraints not to consider all the possible model echelons at the same time. This claim raises the need for a careful examination of the mass balances used for optimization models. In this sense,

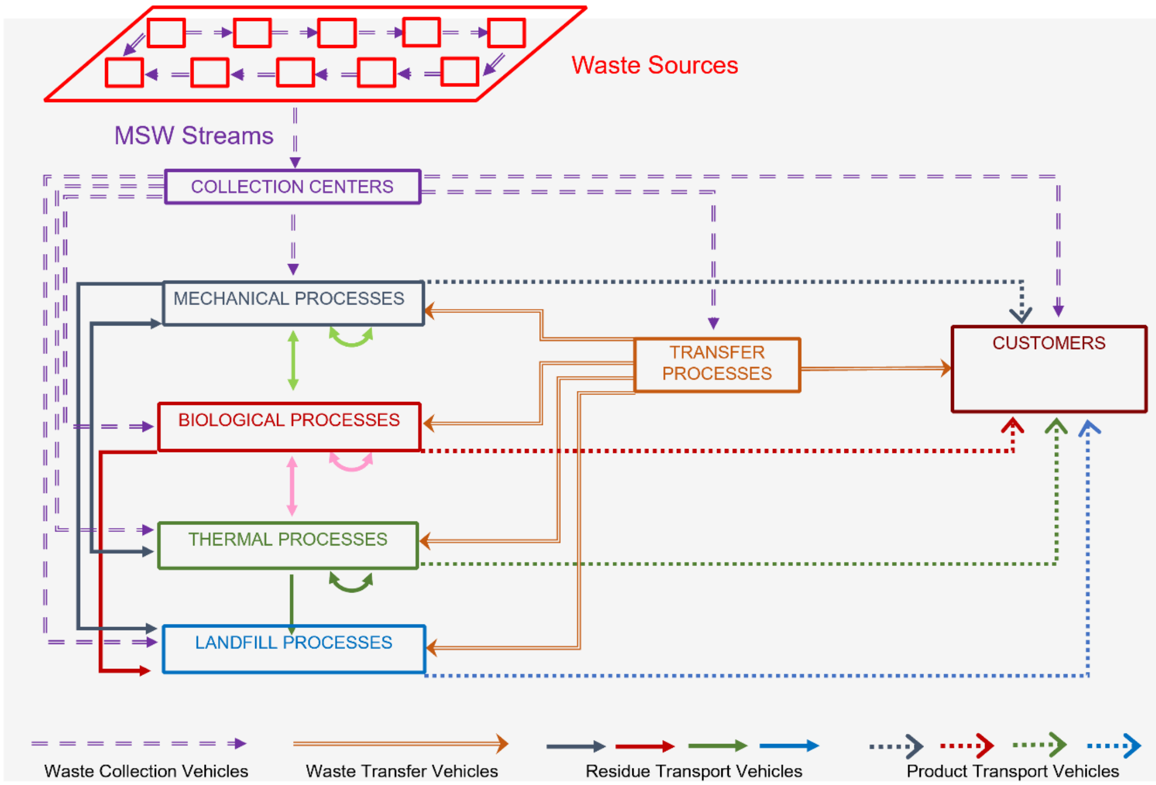

Figure 1. The schematic view of an integrated mass balance that may be valid in existing MSW management applications.

the main focus of this review study was determined as the mass balances.

2.2. Literature Evaluation Scheme

Regarding the basic information on the LPMSWMS presented above, a new literature evaluation scheme was established to be used for the evaluation of optimization models which are used for the LPMSWMS. The evaluation scheme was formed into three steps: programming components, decision components, and managerial components.

2.2.1. Programming Components of the Evaluation Scheme

The evaluation criteria used in the programming components step of the evaluation scheme are: (1) the form of the objective function (i.e., linear, quadratic, fractional, non-linear), (2) the form of model constraints (i.e., linear, quadratic, fractional, non-linear), (3) the form of model variables (i.e., continuous, integer, mixed), (4) the form of model parameters (i.e., deterministic, stochastic, fuzzy, hybrid), (5) the form of model echelons (i.e., collection, transfer processes, mechanical processes, biological processes, thermal processes, landfill processes, and customers), (6) the form of mass balance (i.e., restricted mass balance or integrated mass balance), (7) the form of the waste transformation in the processes (i.e., cumulative transformation or component-based transformation).

2.2.2. Decision Components of the Evaluation Scheme

The evaluation criteria used in the decision components step of the evaluation scheme are: (1) compliance with the condition that the waste sources are more than one (i.e., collection zoning), (2) compliance with the calculation of the distribution of wastes between processes (i.e., waste allocation), (3) compliance with the evaluation of capacity alternatives and capacity extension (i.e., capacity assessment), (4) compliance with answering the process selection question (i.e., process selection), (5) compliance with the selection of technology alternatives of processes (i.e., technology alternatives), (6) compliance with the location selection for processes (i.e., site selection).

2.2.3. Managerial Components of the Evaluation Scheme

The evaluation criteria used in the managerial components step of the evaluation scheme are: (1) the method of waste collection (i.e., mixed collection or separate collection), (2) the parameter used for hypothetical or a specific geographic area (i.e., geographic focus), (3) whether or not the distances are considered for the waste transportation (i.e., distances), (4) the cost and benefit types used for objective functions (e.g., construction cost, operation cost, transportation cost, revenues, etc.), (5) other components used for objective functions (e.g., environmental and/or social damage minimization, etc.), (6) planning period (i.e., 1 ~ 15 years or > 15 years).

2.3. Literature Survey

The scientific research within the scope of this review study were determined as a result of a comprehensive literature survey performed in January 2021 through the Scopus search engine without a date limitation (i.e., the first survey stage). The search pattern used in this first survey was described as [("solid waste" or "waste management") and ("decision making" or "decision" or "selection" or "planning") and ("optimization" or "optimisation" or "programming")] for titles, abstracts, and keywords. In the wake of the first survey stage, 889 scientific research were determined. The greatness of this number necessitated a further elimination process, in which only the articles written in English and published in peer-reviewed journals were selected (i.e., the generic surveillance stage). Due to the number of these articles was still too large (i.e., 627 articles), a new elimination process was made by considering just the peer-reviewed journals which accepted many articles in the field of MSW management (i.e., the specific surveillance stage). Here, the main assumption for this elimination was that the scientific journals which accepted many articles on a specific research area have the potential to give a more precise idea for the related research area. Accordingly, only peer-reviewed journals which include at least 5 articles related to MSW management were taken into consideration. As a result of this elimination, 343 articles, which were published in 26 peer-reviewed journals, were obtained (please see Table S1 for the related journals). The remaining 284 articles which were published in 135 peer-reviewed journals were used to validate the major findings of the study (i.e., the verification articles).

The 343 articles mentioned above were first subjected to a bibliometric analysis using by VOSVIEWER software, version 1.6.18. In the bibliometric analysis, the keywords, authors, and countries of the articles were separately examined. Following the bibliometric analysis, the scope of the 343 articles was further narrowed. From the 343 articles, 124 articles that satisfy the following three criteria were determined: (1) the articles which are directly related to the LPMSWMS problem, (2) the articles which are published in 2010 and later, (3) the articles whose full text could be reached. Among the 124 articles, the ones which were not related to the entire multi-layered structure of the LPMSWMS problems, but only related to singular layers such as waste collection, routing, and/or site selection were excluded from the scope. At the end of this elimination process, the number of articles to be evaluated was defined as 72. After the evaluation of 72 articles through the new literature evaluation scheme (i.e., the first assessment), the critical issues which were indicated by the results of the evaluation were taken into account. Regarding the assessment made at this stage, 6 of 72 articles that were assumed to have met the critical issues were subjected to a more detailed examination (i.e., the critical assessment).

Lastly, to examine whether any solutions were suggested to the critical issues before 2010, 219 articles (i.e., 124 ~ 343 articles) that were published before 2010 were also evaluated (i.e., the last assessment). When the 219 articles were evaluated as in the evaluation made during the decrease from 124 articles to 72 articles, the number of remaining articles was 54. Furthermore, the verification articles were also evaluated in the last assessment stage to verify whether any solutions were suggested

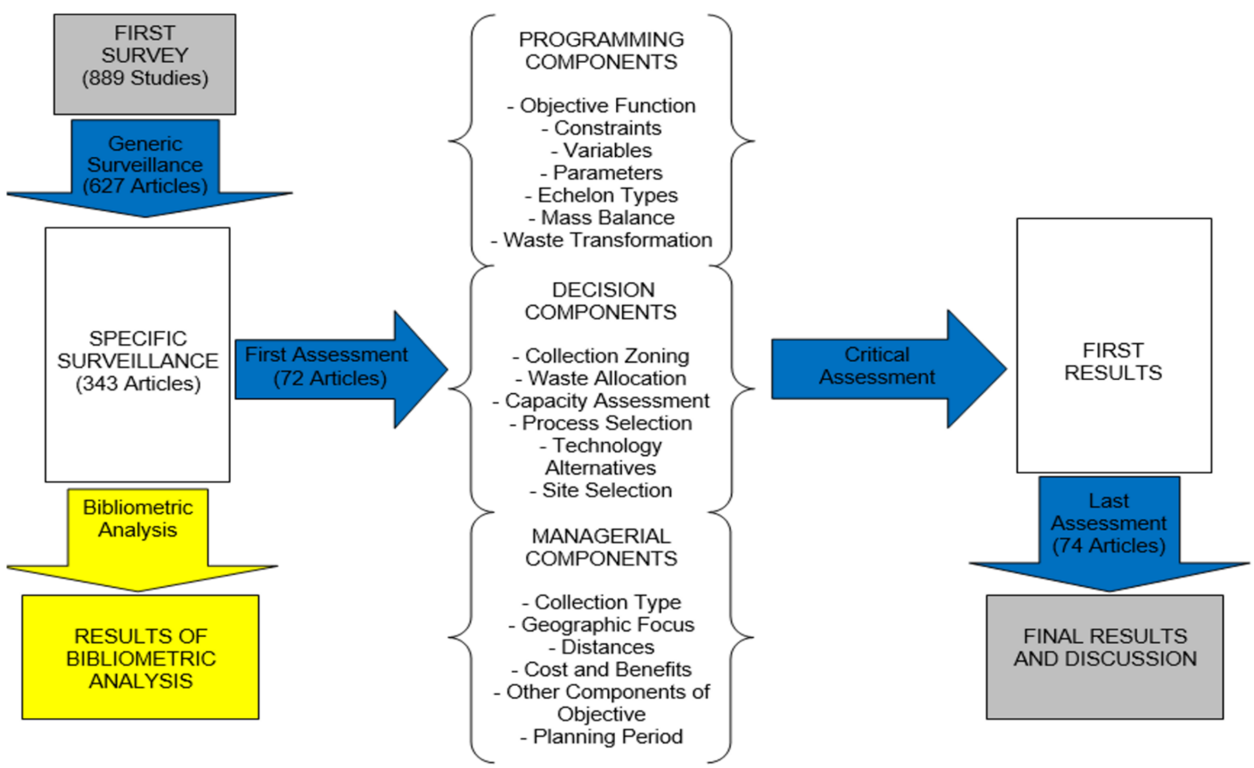

Figure 2. The literature evaluation scheme and the related article numbers.

to the critical issues. When the 284 verification articles were evaluated as in the evaluation made during the decrease from 124 articles to 72 articles, the number of remaining articles was 20. Therefore, the number of articles reviewed at the last assessment stage was 74 (i.e., 54 + 20 articles). The whole evaluation scheme used in this study and the related article numbers mentioned above are presented in Figure 2.

3. Results and Discussion

The generic surveillance stage conducted in this study dates back to the mid-1970s when the first optimization models for the solid waste management were introduced (e.g., Kuhnert and Harrington, 1975). Considering the first survey, the generic surveillance, and the specific surveillance stages (889, 627, and 343 articles, respectively), Figure 3 presents the temporal distribution of the articles for the three time periods: pre-2000, 2000 ~ 2010, and post 2010. The temporal distribution of the 146 articles examined in the first assessment and the last assessment stages is also presented in Figure S1. According to the distributions given in Figure 3 and Figure S1, it can be stated that the article elimination procedures applied in the literature survey of this study did not cause any important deviation in terms of the temporal distribution of the MSW management literature.

3.1. Results for the Bibliometric Analysis

The bibliometric analysis results for the co-occurrence network of author keywords are presented in Figure 4 (for the details of the bibliometric analysis results, please see Figure S2 and Figure S3). According to the results, there are 67 keywords that occur at least 5 times. Out of total 1,437 keywords, “uncertainty” (84 occurrences), “optimization” (76 occurrences), “waste management” (61 occurrences), “solid waste management” (54 occurrences), and “environment” (42 occurrences) have the most occurrences in the articles. According to the results obtained in the bibliometric coupling analysis of countries, there are 32 countries that occur at least 5 times. Out of total 69 countries, the most productive countries include the United States, Canada, and China, respectively (please see Figure S2). According to the results of co-authorship analysis, there are 33 authors that occur at least 5 times. Out of total 1,371 authors, the most productive authors include “Huang, G.H.” (92 documents), “Li, Y.P.” (30 documents), and “Huang, G.” (27 documents). Consisting with this finding, the visualization of co-authorship analysis reveals the “Huang, G.H.” node represents a central position (please see Figure S3).

3.2. Results for the First Assessment Stage

Figure S4 summarizes the findings of the first assessment stage based on the main components of the new literature evaluation scheme, where the basic information on the findings is given in below (for the details of the findings, please see Table S2, Table S3, and Table S4).

3.2.1. Objective Functions, Constraints, and Variables

As seen in Figure S4, the objective functions and constraints of almost all the optimization models examined in the first assessment stage have a linear structure. In addition to the linear/nonlinear classification of the models, another critical finding is that almost 78% of the models are formulated for system costs, while remaining models consider multi-objective functions to assess environmental and/or social damages together with the system costs. Furthermore, a limited number of articles integrate factors such as the environmental pollution, the emission reduction, or the environmental externalities into the cost function or presents these factors by constraints as a system restriction. Therefore, these models are also evaluated as a single-objective optimization model in this study. According to the findings, only one of the single-objective optimization model (i.e., Tascione et al., 2016) focuses on a different objective rather than system costs (i.e., the environmental impact minimization).

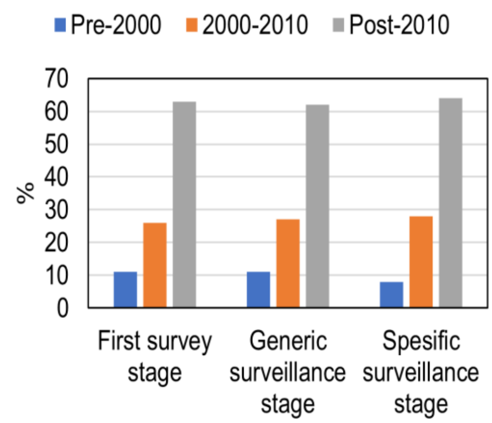

Figure 3. The temporal distributions of the articles for three time periods.

While an important portion of the models are solved in platforms such as LINGO, PHYTON, GLPKLAB, GAMS, MATLAB, IBMILOG, OPTQUEST, SIMAPRO, EXCEL, K-NITRO, and GUROBI, a very small part of the models include information about the numbers of model variables and constraints. Likewise, there is limited information about the solution process of models (model performances, etc.). According to the findings, 66% of the optimization models are formulated based on mixed integer programming approaches, in which both integer and continuous variables are used in formulations. Regarding MSW management, binary variables as an integer variable type are commonly used to seek answers to the questions of whether a new process will be established (i.e., process selection) and/or an existing facility will be used (i.e., capacity assessment). According to the findings of the first assessment stage, on the other hand, only 32% of the models which have mixed-integer variables seek answer to the question of process selection (please see Table S2).

3.2.2. Decision Layers

According to the findings, an important portion of the articles examined in the first assessment stage seek answers to

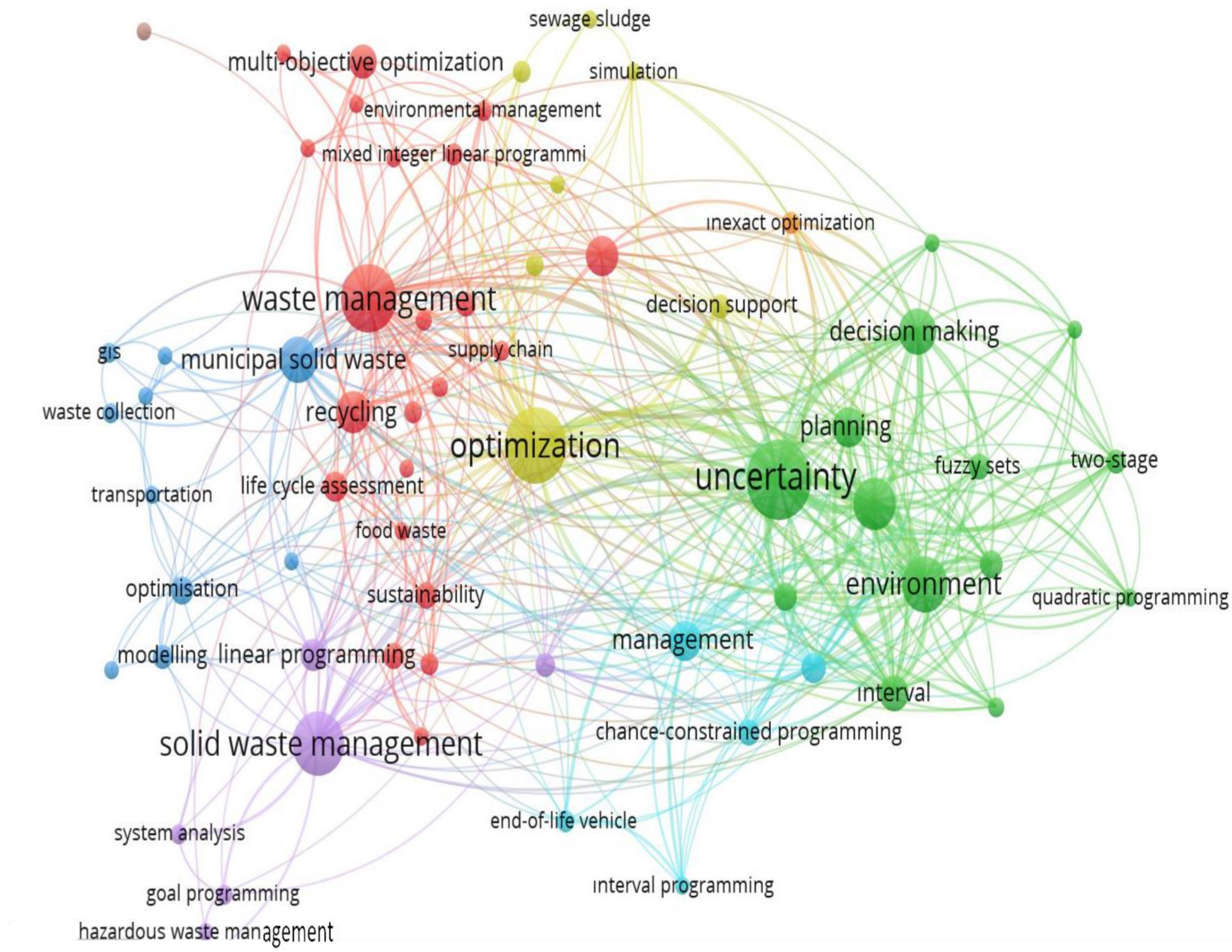

Figure 4. The co-occurrence network of author keywords in publications.

the questions related to the decisions of collection zoning, capacity assessment, and waste allocation. On the other hand, process selection or assessment of technology alternatives is taken into account by a limited number of articles. Additionally, the questions of site selection for processes and distances between locations are not considered in many articles. Besides, a very small portion of the articles can reflect the modeling of separate collection and component-based waste transformation (i.e., 28% and 20%, respectively).

3.2.3. Planning Period, Geographic Focus, Cost and Benefits, and Mass Balances

According to the findings, a very small portion of the optimization models (i.e., 15%) are formulated for a planning period over 15 years. Furthermore, 25% of the optimization models have no information on the planning periods. A certain number of the articles examined in the first assessment stage are hypothetical studies in which real-world data for a specific geographic area is not taken into account. For these studies, the operation-maintenance costs are considered in almost all the articles, while a limited number of articles deal with the construction costs. The main reason for this situation is that just a few articles deal with the question of process selection. The other costs mostly discussed in the articles come to the fore as the transportation costs and revenues. Finally, a small number of optimization models have the ability to consider the model echelons of collection centers, transfer stations, mechanical processes, biological processes, thermal processes, landfill processes, and customers, at the same time.

3.2.4. Model Parameters

The articles examined in the first assessment stage of this study exhibit a dual distinction in terms of model parameters: non-deterministic model parameters and deterministic model parameters. According to the findings, a significant portion of the articles have the modeling approaches developed to structure the model parameters under uncertainty. Such approaches used in these articles will be referred to as non-deterministic optimization models in this study. The remaining articles (i.e., deterministic optimization models), on the other hand, do not focus

Table 1. The Findings for the Non-Deterministic Optimization Models Examined in the First Assessment Stage

Objective Function	Constraints	Variables	Parameters	Integrated Mass Balance Possibility	Waste Transformation	References
Linear	Linear	Mixed	Fuzzy/interval	No P. S.	Cumulative	Li and huang, 2010a[1]
Linear	Linear	Mixed	Stochastic/interval	No P. S.	Cumulative	Li and huang, 2010b
Linear	Linear	Mixed	Stochastic/interval	No P. S.	Cumulative	Xu et al., 2010[1]
Linear	Linear	Continuous	Fuzzy/stochastic/ interval	No P. S.	Cumulative	Tan et al., 2010a[1]
Quadratic	Linear	Continuous	Stochastic/interval	No P. S.	Cumulative	Sun et al., 2010[1]
Linear	Linear	Continuous	Fuzzy /interval	No P. S.	Cumulative	Zhang and huang, 2010[1]
Linear	Linear	Mixed	Fuzzy/interval	No P. S.	Cumulative	Guo and huang, 2010
Linear	Linear	Mixed	Stochastic/interval	No P. S.	Cumulative	Su et al., 2010
Linear	Linear	Continuous	Fuzzy /interval	No P. S.	Cumulative	Zhang et al., 2010[1]
Linear	Linear	Continuous	Radial interval	No P. S.	Cumulative	Tan et al., 2010b[1]
Linear	Linear	Mixed	Fuzzy/interval	No P. S.	Cumulative	Tan et al., 2010c[1]
Linear	Linear	Mixed	Random/intervals	No P. S.	Cumulative	Cui et al., 2011
Linear	Linear	Continuous	Fuzzy/stochastic/ interval	No P. S.	Cumulative	Li and chen, 2011
Quadratic	Linear	Mixed	Fuzzy /interval	No P. S.	Cumulative	Guo and huang, 2011[1]
Linear	Linear	Mixed	Fuzzy /interval	No P. S.	Cumulative	Li and huang, 2011
Fractional	Linear	Continuous	Stochastic	No P. S.	Cumulative	Zhu and huang, 2011[1]
Linear	Linear	Mixed	Interval	No P. S.	Cumulative	Dai et al., 2011
Linear	Linear	Continuous	Interval	No P. S.	Cumulative	Zhang et al., 2011[1]
Linear	Linear	Mixed	Fuzzy	Yes	Cumulative	Srivastava and nema, 2011
Linear	Linear	Continuous	Fuzzy /interval	No P. S.	Cumulative	Tan et al., 2012[1]
Linear	Linear	Mixed	Fuzzy/stochastic/ interval	No P. S.	Cumulative	Wang et al., 2012[1]
Linear	Linear	Continuous	Interval	No P. S.	Cumulative	Dai et al., 2012
Linear	Linear	Continuous	Fuzzy /interval	No P. S.	Cumulative	Sun et al., 2012[1]
Linear	Linear	Mixed	Fuzzy/stochastic	No P. S.	Cumulative	Zhang and huang, 2013[1]
Linear	Linear	Continuous	Stochastic/interval	No P. S.	Cumulative	Chen et al., 2014[1]
Linear	Linear	Mixed	Stochastic/interval	No P. S.	Cumulative	Dai et al., 2014[1]
Linear	Linear	Mixed	Fuzzy	No P. S.	Cumulative	Zhang and huang, 2014[1]
Linear	Linear	Continuous	Fuzzy	No P. S.	Cumulative	Fan et al., 2014[1]
Linear	Linear	Continuous	Stochastic	No P. S.	Cumulative	Zhang et al., 2014[1]
Linear	Linear	Continuous	Fuzzy	No P. S.	Cumulative	Xu et al., 2014a[1]
Linear	Linear	Mixed	Fuzzy	No P. S.	Cumulative	Xu et al., 2014b[1]
Linear	Linear	Mixed	Stochastic	No P. S.	Cumulative	Chen et al., 2016a
Quadratic	Linear	Continuous	Interval	No P. S.	Cumulative	Kong et al., 2016
Linear	Linear	Continuous	Interval	No P. S.	Cumulative	Zhai et al., 2016[1]
Linear	Linear	Mixed	Fuzzy/stochastic/ interval	No P. S.	Cumulative	Chen et al., 2016b
Fractional	Linear	Mixed	Stochastic	No P. S.	Cumulative	Zhou et al., 2016[1]
Linear	Linear	Continuous	Interval	No P. S.	Cumulative	Zhu et al., 2016[2]
Linear	Linear	Mixed	Fuzzy	-	Cumulative	Xu et al., 2016
Linear	Non-linear	Mixed	Interval	-	Component-based	Yadav et al., 2017[1]
Linear	Linear	Mixed	Deterministic/ stochastic	-	Cumulative	Habibi et al., 2017[2]
Linear	Linear	Continuous	Interval	No P. S.	Cumulative	Zhu and huang, 2017
Linear	Linear	Mixed	Fuzzy	-	Cumulative	Ma et al., 2017
Linear	Linear	Continuous	Stochastic/interval	No P. S.	Cumulative	Wu et al., 2018
Linear	Linear	Mixed	Stochastic	-	Component-based	Diaz-barriga-fernandez et al., 2018[2]
Linear	Linear	Mixed	Stochastic	-	Cumulative	Kudela et al., 2019
Linear	Linear	Mixed	Stochastic/interval	No P. S.	Cumulative	Li et al., 2019
Linear	Linear	Mixed	Stochastic	No P. S.	Cumulative	Gambella et al., 2019

[1] Hypothetical studies.
[2] Separate collection.
N P. S. Study doesn't consider the process selection question.

on studying under uncertainty.

(1) Non-deterministic optimization models: the model-parameters used in the optimization models for the LPMSWMS are the modeling entities that are affected by many different factors, and they may include various uncertainties. Previously, many articles that desired to model the LPMSWMS under uncertainty were proposed, and most of them relied on stochastic, fuzzy, and interval programming approaches (Tan et al., 2010a; Xu et al., 2010). These studies can be grouped as two-stage stochas-tic programming, chance-constrained programming, fuzzy flexible programming, fuzzy robust programming, interval-parameter programming, inexact mixed-integer programming, inexact multiple-objective programming, and inexact non-linear program-ing (Sun et al., 2014). Stochastic mathematical programming can deal with various probabilistic uncertainties; however, the increased data requirements for specifying the probability distributions of parameters can affect their practical usage (Li and Huang, 2010). Fuzzy mathematical program-ming is effective in reflecting ambiguity and vagueness in decision-making problems (Li and Huang, 2010); however, fuzzy models cannot effectively incorporate inherent uncertainties with imprecise co-efficients of the objective function and constraints (Yadav et al., 2017). As one of the major methods tackling uncertainties, the interval mathematical method can effectively deal with interval parameters in left-hand side coefficients; however, it has difficulties when the right-hand side parameters are highly uncertain, especially with probability or possibility distribution informa-tion (Chen et al., 2014).

Regarding the first assessment stage of this study, almost 65% of the articles (i.e., out of 72 articles, 47 non-deterministic structure) present a non-deterministic optimization model. A summary of 47 non-deterministic optimization models is presented in Table 1, where the details of these articles can be accessed in the Tables S2, S3, and S4.

According to the first survey stage of this study, the first examples of the non-deterministic optimization models are seen in the early 1990s (Huang et al., 1992, 1993). In the remaining period of almost 30 years, all the articles conducted in this field have made important contributions for overcoming the parameter uncertainties of MSW management. The non-deterministic optimization models examined in this study have been adopted by many approaches (e.g., robust, chance-constrained, superiority inferiority, min-max regret, Nguyen's method, support vector regression, inexact reverse logistics, queuing theory, duality theorem, factorial analysis, etc.) to handle the parameter uncertainties. When the findings in Table 1 are examined, it can be seen that almost all the articles including non-deterministic optimization models are hypothetical studies, which treat the waste transformations in the processes cumulatively, construct their constraints linearly, and evaluate the waste collection process as a single stream. Additionally, a considerable number of the articles use only continuous decision variables. Based on these findings, it is possible to say that these kinds of studies have made little effort regarding the up-to-date modeling prob lems such as the process selection, the component-based waste transforma-

Table 2. The Findings for the Deterministic Optimization Models Examined in the First Assessment Stage

Objective Function	Constraints	Variables	Integrated Mass Balance Possibility	Waste Transformation	References
Linear	Linear	Mixed	-	Cumulative	Galante et al., 2010
Non-linear	Linear	Integer	-	Cumulative	Chatzouridis and Komilis, 2012
Linear	Linear	Continuous	No P. S.	Cumulative	Chang et al., 2012[1]
Linear	Linear	Mixed	Yes	Component-based	Levis et al., 2013[1]
Linear	Linear	Mixed	Yes	Component-based	Mavrotas et al., 2013[1]
Linear	Linear	Continuous	No P. S.	Cumulative	Chang and Lin, 2013a
Non-linear	Linear	Continuous	No P. S.	Component-based	Minoglou and Komilis, 2013[1]
Linear	Linear	Continuous	No P. S.	Cumulative	Chang and Lin, 2013b[1]
Linear	Linear	Mixed	-	Component-based	Santibanez-Aguilar et al., 2013[1]
Linear	Linear	Mixed	-	Cumulative	Eiselt and Marianov, 2014
Linear	Linear	Mixed	-	Cumulative	Tan et al., 2014[1]
Linear	Linear	Mixed	-	Cumulative	Münster et al., 2015
Linear	Linear	Mixed	-	Cumulative	ThiKimOanh et al., 2015
Linear	Linear	Mixed	-	Cumulative	Lee et al., 2016
Non-linear	Linear	Continuous	No P. S.	Component-based	Asnoune et al., 2016[1]
Linear	Linear	Continuous	No P. S.	Component-based	Tascione et al., 2016[1]
Linear	Linear	Mixed	-	Component-based	Harijani et al., 2017[1]
Linear	Linear	Mixed	No P. S.	Cumulative	Asefi and Lim, 2017
Linear	Linear	Mixed	No P. S.	Component-based	Santibanez-Aguilar et al., 2017[1]
Linear	Non-linear	Mixed	-	Cumulative	Li et al., 2017
Linear	Non-linear	Mixed	-	Cumulative	Sharif et al., 2018[1]
Non-linear	Non-linear	Mixed	Yes	Component-based	Rizwan et al., 2018
Linear	Linear	Mixed	-	Cumulative	Rathore and Sarmah, 2019[1]
Linear	Linear	Mixed	Yes	Component-based	Mohammadi et al., 2019[1]
Linear	Linear	Mixed	Yes	Cumulative	Yousefloo and Babazadeh, 2020[1]

[1] Separate collection.

N P. S. Study doesn't consider the process selection question.

tion, and the separate waste collection. It is quite in-teresting that only 7 of the non-deterministic optimization models dealt with the question of process selection and that among these, only Srivastava and Neman (2011) had a mass balance that can be termed as an integrated mass balance.

(2) Deterministic optimization model: a summary of 25 deterministic optimization models is presented in Table 2. All the details of the findings obtained from these studies can be accessed in the Tables S2, S3, and S4.

Regarding the findings given in Table 2, it may be asserted that almost all the articles that include deterministic optimization structures are non-hypothetical studies based on the real data of different countries dispersed worldwide. Furthermore, an important portion of these articles use mixed-integer variables, and a significant portion of them use linear structures in terms of the objective and constraint functions. Unlike the non-deterministic optimization models, almost half of these models evaluate the component-based waste transformations for the treatment and disposal processes. Furthermore, a large number of the articles take separate waste collection into consideration. While an important portion of the deterministic optimization models (i.e., 68%) deal with the process selection question, only five of them (Levis et al., 2013; Mavrotas et al., 2013; Rizwan et al., 2018; Mohammadi et al., 2019; Yousefloo and Babazadeh, 2020) consider a mass balance which can be called as integrated mass balance. On the other hand, it seems extremely essential to re-evaluate these articles from the perspective of the integrated mass balance. Whether these studies suggested a solution to the issue of non-linear form is examined in the critical assessment stage of this study.

3.3. Results for the Critical Assessment Stage

In the section 3.2.4, it was emphasized that 6 of the 72 articles belonging to the period after 2010 (i.e., Srivastava and Nema, 2011; Levis et al., 2013; Mavrotas et al., 2013; Rizwan et al., 2018; Mohammadi et al., 2019; Yousefloo and Babazadeh, 2020) included a mass balance which can meet the needs of an integrated mass balance for the LPMSWM problems. Among these articles, Rizwan et al. (2018) differs from the others in terms of the non-linearity in its constraint functions. The remaining 5 models have linear structures in terms of their constraint functions. On the other hand, for a mass balance which can be termed as an integrated mass balance to be structured with linear approaches, the issue of non-linear form has to be eliminated.

The issue of non-linear form occurs when the number of waste streams to come any model echelon that has to send residual and/or products to another echelon is more than one. Each of these waste streams is one of the main factors that determine the residual and/or product masses in the output of the echelon. In other words, these streams and their waste components are separate decision variables for the optimization models dealing with the question of process selection. Structuring a mass balance constraint in the same echelon for more than one decision variable, on the other hand, is not possible with current linear approaches. Batur et al. (2020) is the most recent effort that attempt to solve the issue of non-linear form by developing a new mathematical approach. The approach called "the divided process approach", proposed in the study, is able to model an integrated mass balance that may be used for the LPMSWMS through linear constraints. On the other hand, certain possible disadvantages of this approach, such as increasing the model volume and the computation time, should be discussed in the future studies.

The optimization model introduced by Srivastava and Nema (2011) provides an opportunity to take waste streams from more than one point for a specific echelon. On the other hand, the article in question is not based on the component-based waste transformation approach, where the only existing processes are used in the network (i.e., no process selection question). Similarly, the model presented by Levis et al. (2013) ignores the possibility of many alternatives. For example, the mass balance obtained in the study is provided by a "'what if" limitation. The model is structured to include a minimum of one of the templates determined for the mixed waste mass and a maximum of one of the templates determined for the other two mass streams (i.e., biodegradable and recyclable) in the final decision. In this sense, this scenario-based mass balance is far from reflecting an integrated mass balance. Likewise, although the study conducted by Mavrotas et al. (2013) has processes that seem to have more than one input, it finds the solution based on specific scenarios (i.e., a restricted mass balance). In a similar manner, the optimization model introduced by Yousefloo and Babazadeh (2020) allows multiple inputs for a specific echelon. However, it simplifies the mass balance through ways such as directly transmitting the outputs of the mechanical and biological processes to the customer. Therefore, this study is not appropriate for a mass balance that will embody all the possibilities such as thermal process and landfill echelons, either. Also, it uses a cumulative waste transformation approach in the processes. Similarly, Mohammadi et al. (2019) does not involve any mass flow from waste treatment processes to landfills. In this sense, it can be stated that none of the articles belonging to the period after 2010 have the power to answer the question of process selection for an integrated mass balance.

To the best of our knowledge, the first effort to solve the issue of non-linear form was made by Solano et al. (2002a, b). On the other hand, the mathematical model used by those researchers was a system evaluation tool, which did not include the construction costs of the processes. In other words, it did not address the process selection question. Accordingly, it should be evaluated whether the issue of non-linear form taken into consideration by those other than Solano et al. (2002a, b) among the articles belonging to the period before 2010. This evaluation is done in the last assessment stage of this study.

3.4. Results for the Last Assessment Stage

Out of the 219 articles belonging to the period before 2010, 54 articles were examined (please see Section 3.2). Furthermore, the verification articles (i.e., 20 articles) were also added to this examination, and the findings were presented in Table S5.

According to the information presented in Table S5, an important portion of the articles are hypothetical studies focusing on uncertainties. Similarly, they are not interested in the question of process selection, and they are based on the cumulative waste transformation instead of the component-based waste transformation. On the other hand, 3 of these models (Chang and Wang, 1996; Chang and Wang, 1997; Li and Huang, 2009b) have mass balances that can be considered as an integrated mass balance. However, as in the studies mentioned in section 3.3, these mass balances also have restricted mass balances and/or they are structured for the existing facilities (i.e., no process selection question). Among the limited number of the articles presents deterministic optimization model, 4 of them (Chang et al., 1996; Chang and Lu, 1997; Fiorucci et al., 2003; Costi et al., 2004) provide an integrated mass balance possibility. However, like the non-deterministic models mentioned above, they also restrict their mass balance with certain scenarios, and/or they are structured for the existing facilities. In this sense, it can also be stated that none of the articles belonging to the period before 2010 have the power to answer the question of process selection with no restrictions in their mass balance (similar to the articles belonging to the period after 2010).

4. Conclusions

In this study, the current state of the optimization models used for the LPMSWMS was reviewed with an emphasis on mass balances. In the study, 146 peer-reviewed articles were examined based on a new literature evaluation scheme. According to the findings, a significant part of the related literature has been dominated by the non-deterministic optimization models, where the model parameters are structured under uncertainty. Furthermore, most of the models have linear mathematical structures in terms of objective and constraint functions. The main contribution of the study is to reveal that none of the models with linear mass balance constraints examined in this study presents an answer about the process selection question for an integrated mass balance. The issue of non-linear form, which emerges as a result of the existing complicated management possibilities, may be pushing the researchers of the models to ways such as restricting the mass balances of the models through various scenarios, simplifying the model structure by disabling one or more of the decision layers (especially the process selection), moving towards multi-step structures or turning to non-linear constraint structured optimization models. This obstacle may also be one of the main factors that move the models away from the global optima. In this context, it is highly recommended that the optimization models to be conducted in the future should search for alternative approaches that can be used for the solution to the issue of non-linear form.

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