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A COMPREHENSIVE WASTE MANAGEMENT SIMULATION MODEL FOR THE ASSESSMENT OF WASTE SEGREGATION IN THE HEALTH SECTOR

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Abstract

It has been determined that a high percentage of medical waste could be classed as domestic waste due to the lack of segregation at hospitals. Better segregation could thus substantially decrease the amount of medical waste that is required to be treated as hazardous waste. This study aims to assess different segregation levels of domestic waste mixed with medical waste. To do so, the Stella and Vensim simulation packages were used to evaluate medical waste flows in the Thrace Region of Turkey. The most important advantage of the simulation modeling used in this study is the flexibility for adjusting parameters based on circumstances, e.g. in the case of an unforeseen event (such as the COVID-19 pandemic), the system parameters can be modified according to the situation. In this study, it is anticipated for the medical waste generation to increase from almost 2000 tons/year to 3000 tons/year in 2045 in the region, which is more than the capacity of current medical waste treatment plants. Projected waste generation flows show that it is possible to avoid 300 tons of medical waste annually by reducing the domestic content of medical waste to 50%. Precisely, for the current regional treatment capacity to be sufficient up to 2045, it will be crucial to reduce the domestic content in medical waste to 10% in the chronic care departments at regional hospitals. The importance of this further arises, as lack of meeting this need will result in an urgent requirement for installation of new units for the treatment of all the medical waste generated in the region.

Key words: domestic waste, hazardous waste, medical waste flows, simulation modeling, system parameters

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1. Introduction

Environmental pollution caused by improper waste management continues to create problems (Dehghanifard and Dehghani, 2018; Omran and Gavrilescu, 2008). The health sector, as one of the main industries across the world, generates large amounts of medical waste (MW), containing items such as sharps, infectious materials, blood, body parts, chemicals and pharmaceuticals, etc. (Ribeiro, 2020). In the last few years, concerns about the environmental fate and behavior of these materials have increased dramatically (Caliman and Gavrilescu, 2009; Dehghani and Rahmatinia, 2018; Morosini, 2020). Various studies have suggested that a high percentage of MW could be classified as 'domestic waste' and hence segregated out of the MW stream and treated as domestic waste (DW) (Dehghani et al., 2008; Sartaj and Arabgol, 2015). This could serve to minimize the quantities of MW generated, and consequently the costs associated with the collection, treatment and disposal of MW (Dehghani et al., 2018a, 2018b).

In Turkey, there is a great deal of published research regarding MW handling and disposal. These studies generally focus on two objectives. The first group of studies aims to measure the amount and composition of MW produced in medical institutions by taking samples or conducting surveys (Tuncsiper et al., 1999). The second group focuses on specific problems in the existing MW management system by examining the waste collection, treatment or disposal processes (Acar, 2015). Importantly, there is no unique solution to the problem of MW management, as many factors interact while influencing health, economy, culture and environment.

System dynamics modeling is a decision support tool that allows modelers to assign parameters and link them with interactions by using time steps. System dynamics simulation models are capable of answering *"what if"* questions by considering interrelated parameters within the system, where their main objective is to identify a system response over time. Such systematic tools are important as they create a user-friendly platform by executing advanced technics; allowing the tools to be used by those whose education (a feature of many more-recent school leavers and graduates) means that they are 'users of technology' rather than 'understanders of technology' (Budescu et al., 2018). In addition, system dynamic models could be used as stand-alone tools for decision support in waste management, such as Multi-Criteria Decision Making (Ghinea and Gavrilescu, 2010) and Life-Cycle Assessment (Gavrilescu et al., 2017) or in conjunction with other tools, such as analytic hierarchy process or Elimination et Choice Translating Reality (ELECTRE) (Ghinea et al., 2015).

System dynamics modelers have recently applied this approach to the management of different types of wastes, such as construction waste, packaging waste and healthcare waste, and thus suggesting new strategies to minimize these wastes as proposed in the waste hierarchy (Ciplak and Barton, 2012). While there is a great deal of system dynamics research aiming to forecast waste generation in different cities, the recent focus has been on evaluating the effects of source separation to decrease in both the amount of waste sent for disposal (Ding et al., 2018) and the related costs such as waste disposal charges (Yuan and Wang, 2014). Although all of these studies highlight the importance of waste segregation, a holistic framework including the dynamic elements of health infrastructure for quantitative analysis remains absent.

Therefore, this study aims, (i) to address the existing situation of MW collection, treatment and disposal in the Thrace Region of Turkey (including three provinces of Tekirdağ, Kırklareli and Edirne), (ii) to determine the relations between the factors, that influence MW generation, and (iii) to assess the potential of minimizing MW generation by implementing robust segregation schemes at medical institutions. To meet these aims, a comprehensive simulation model was applied to include the dynamic relationships of the factors involved in MW generation in the region. The model, which was developed for this study, can be used to better understand key drivers of MW production in the region and beyond. The results can benefit and aid decision-makers, such as city development organizations and environmental consulting agencies, in designing or proposing suitable waste management strategies.

2. Material and method

The Thrace Region of Turkey was selected for the analysis as it is representative of other regions across Turkey in terms of health investments and migration patterns. The region is strategically important in terms of its location, which connects the Europe to Anatolia and hence, to the Middle East. Its proximity to Istanbul, which is the most developed city of Turkey in terms of economy and culture, ensures that health investments are concentrated in and around the region. The region, with an estimated population of 2 million people (Turkstat, 2020), has eight central hospitals in service; four of which are state hospitals, including research and university clinics, whilst the other four are private institutions (Turkstat, 2019).

The MW collected in the region is treated by four central autoclave units. Two (Nyir Clave 1000 models) are located in Edirne and treat MW generated from Edirne only, and the other two are located in Kırklareli and Tekirdağ. The total throughput capacity of these units is 2500 tons/year. Considering that MW production from the region's hospitals is currently 2000 tons/year, and given that the production of MW increases by more than 500 tons per year, the existing capacity does not seem to be sufficient for meeting the needs of the region.

This study takes a system dynamics approach by using the Stella and Vensim software packages. The regional MW management system was modeled, using a stock and flow structure, from the point of MW production through to treatment and disposal at a sanitary landfill. The main data used in the model were collected from the literature review (Alagoz and Kocasoy, 2008), including statistical reports published periodically by governmental organizations (Environmental Ministry of Turkey, 2017; Turkish Ministry of Social Security, 2003).

The theoretical model shown in Fig. 1 shows the primary connections that cause changes in the waste management system over time. There are also smaller institutions that produce MW, such as pharmacies, laboratories, dental and veterinary clinics. However, MW generation from these small institutions is negligible in comparison to the hospitals, and so, this study has only taken into account the MW generated from hospitals. To better estimate the dynamics of MW production, in this model, it was assumed that there are two types of care at hospitals; acute treatment (A), and chronic treatment (C). Treatment C requires patients to stay at the hospital overnight, while A involves treatments completed within a day. At hospital wards in Turkey, such as neurology, urology, general surgery, cardiology, etc. (C units), *specialists* make diagnoses and provide examinations. There are also some *practitioners* who work for acute care at hospital departments, such as accident and emergency (acute-A units).

The model takes into account the assignment of both (practitioners and specialists), depending on the regional patient demand, which is based on *getting infected frequencies* (i.e. the number of hospital admissions per capita) and *treatment types of patients* (as mentioned; C and A). Fig. 2 illustrates the model structure with the main variables and relations between them (single arrows). Furthermore, the mathematical details of stocks, flows, auxiliary variables and constants in the model are shown in Tables 1-4).

The parameter, "*MW*", in the model represents the MW mixed with DW due to incorrect placement of DW (Fig. 2). The "*Pure MW*" is divided into two parameters of, 'medical waste for incineration (Inc-MW)', and 'medical waste for alternative treatment (AT-MW)'. The latter is finally sent to a disposal site ("*Sanitary Landfill*" in the model), after being treated by alternative technologies, such as autoclaves, hydroclaves, irradiation, plasma, chemical technologies, etc. This type of waste includes swabs, soiled dressings, gloves, etc. On the other side, Inc-MW consists mostly of hazardous waste such as cytotoxic and cytostatic chemicals for cancer treatment for which incineration is the only option. An MW composition table, developed by healthcare researchers (Alagoz and Kocasoy, 2008), shows that 64% of MW is DW (with the remaining 36% pure MW). Out of this 36%, 18% is suitable for alternative treatment, and the rest (18%) is medicinal wastes, pressurized containers and pathological wastes, which are required to be treated in an incinerator. The differentiation of these two MW streams at hospitals highly depends on the success of medical staff who receives training courses, which is represented by the "*effect of training*" in the model (Fig. 2).

At hospitals in Turkey, training courses on waste management are undertaken regularly for practitioners and specialists to improve their awareness of waste segregation. This is represented in the model by the parameter, "*chance to get training*" (Fig. 2).

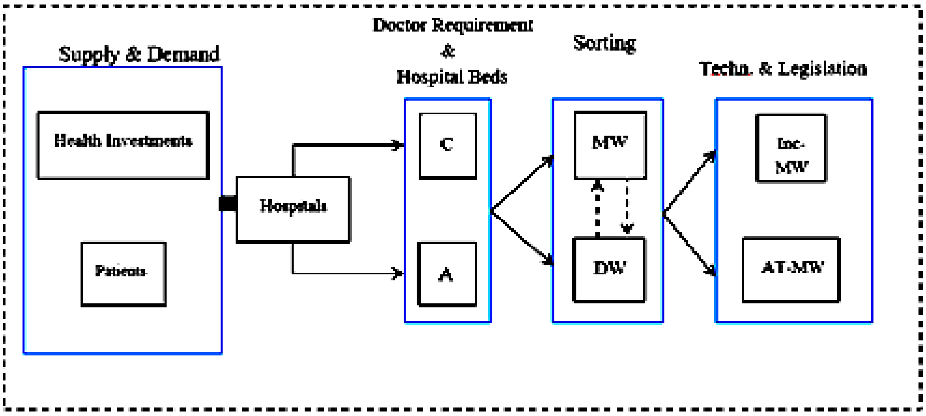

Fig. 1. Theoretical model (C: Chronic Treatment, A: Acute treatment, DW: Domestic waste, MW: Medical waste, Inc-MW: Medical waste for incineration, AT-MW: Medical waste for alternative treatment)

Table 1. Details of stock parameters in the simulation model

Name	*Unit*	*Equation*
Sanitary Landfill	tons	INTEG (waste from hospitals - disposal out of control + DW)
C Demand	people	INTEG (getting infected - stop waiting - meeting C demand)
Population	people	INTEG (births - deaths + migration in – migration out)
Practitioners	doctors	INTEG (recruiting practitioners – upgrading - getting retired)
Specialists	doctors	INTEG (recruiting specialists + upgrading - leaving)

Table 2. Details of flows in the simulation model

Name	*Unit*	*Equation*
meeting C demand	people/year	MIN (C Demand / waiting time, current C capacity)
recruiting practitioners	doctors/year	MAX (0, (practitioner requirement - Practitioners) / time to recruit practitioners)
recruiting specialists	doctors/year	Specialists / time to recruit specialists
stop waiting	people/year	C Demand / queue
getting infected	people/year	Population / (time to get infected * health effects)
migration in	people/year	Population / migration in rate
births	people/year	Population * births rate
deaths	people/year	Population / average lifetime
leaving	doctors/year	Specialists / time to leave
waste from hospitals	tons/year	AT-MW
DW	tons/year	DW production rate * Population
getting retired	doctors/year	Practitioners / years at work
disposal out of control	tons/year	Sanitary Landfill * uncontrolled waste disposal rate

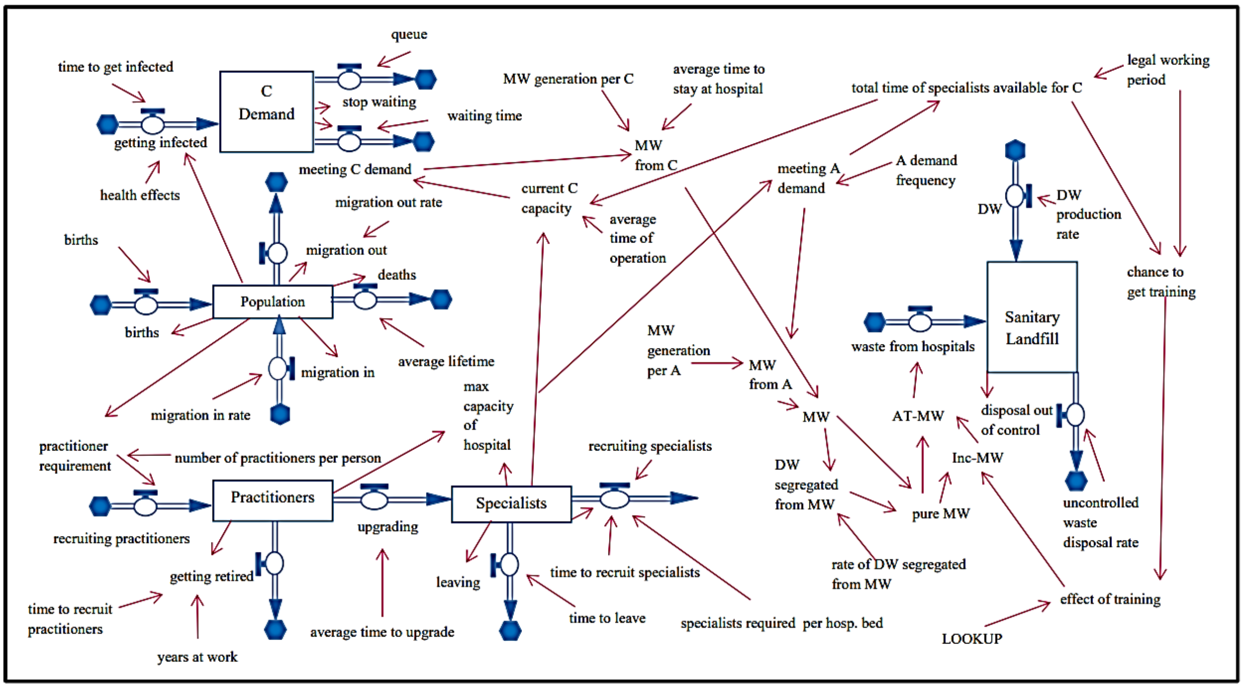

Fig. 2. Simulation model structure

Table 3. Details of auxiliary variables in the simulation model

Name	*Unit*	*Equation*
meeting A demand	people	MIN (A demand frequency * Population, max capacity of hospitals)
pure MW	tons	MW - DW segregated from MW
chance to get training	dimensionless	MAX (0, (legal working period - total time of the specialist available for C))
max capacity of hospitals	doctors	Practitioners + Specialists
AT-MW	tons	pure MW – Inc-MW
Inc-MW	tons	pure MW * effect of training
DW	tons	DW production rate * Population
total time of the specialist available for C	hours/year	legal working period - meeting A demand (with corrected units)
practitioner requirement	doctors	Population * number of practitioners per person
MW	tons	MW from A + MW from C
MW from A	tons	meeting A demand * MW generation per A
DW segregated from MW	tons	rate of DW segregated from MW * MW

Table 4. Details of constants in the simulation model

Name	*Unit*	*Value*	*Source*
MW generation per A	tons/people	0.00022	Environmental Ministry of Turkey (2017)
rate of DW segregated from MW	dimensionless	0.64	Alagoz and Kocasoy (2008)
legal working period	hours/year	45 (hours/week) x 52 (weeks/year)	Turkish Ministry of Social Security (2003)

The MW generation from A units depends on the appointment capacity of hospitals and the number of practitioners, or the patient demand for A. If the patient demand for A is larger than the appointment capacity, the capacity determines MW production; otherwise, the patient demand for A defines MW production. Similarly, MW generation from C is based on the patient demand for C but is limited by the capacity of hospitals (particularly hospital beds) and the number of specialists in the region. It is worth mentioning that defining the dynamics of some factors in the model, such as an effect of training, with a single equation is very difficult. For this reason, a set of equations is defined and relations between input and output are noted by using lookup functions.

The lookup functions (Fig. 2) allow modelers to define relationships between a parameter and its causes in the form "f(x) = y", where y is altered by x. In the model, "*chance to get training*" was used as the input variable, x, which itself is affected by the "*time left for training*" (i.e. specialists' and practitioners' remaining time from A and C). Accordingly, x determines the output variable, y, the *effect of training*. Through the lookup function, y was thus altered by x.

The time horizon of the model was taken as 2015 to 2045. The initial time was set as 2015 to conduct a historical behavior test by comparing the statistical data and simulation results for 2015 to 2019.

In this model, *population* and *MW* parameters were chosen to carry out the historical behavior test. The model simulation results for the parameters of *Population* and *MW* were compared with the actual population and MW statistical values gathered from Turkstat (2020), Turkstat (2019) and the Environmental Ministry of Turkey (2017).

3. Results and discussion

One of the most significant validation tests of system dynamics modeling is a historical behavior test. In this model, *population* and *MW* parameters were chosen to carry out this test. Fig. 3a and Fig. 3b show that the model results are consistent with the statistical values (Turkstat, 2019, 2020;Environmental Ministry of Turkey, 2017).

The model was run for the years 2015-2045. Fig. 4a and Fig. 4b represent the results for *population* and *MW* in the project region. As seen from Fig. 4a, the population of the region increases from almost 2 million to 3 million people in 2035. It then starts to decrease slightly after 2035 and reaches almost 2.8 at the end of the period. This is as the migration leaves the region after 2035, which outweighs the births and internal migration, resulting in a decrease in the total population of the region (Fig. 2).

As previously mentioned, MW production is strongly influenced by the level of waste segregation. Fig. 4b shows that MW generation increases from almost 2000 tons to 3000 tons in 2045, which is more than the annual capacity of the current medical waste treatment units in the region.

The amount of MW can be minimized by improving DW segregation at hospitals. To test the sensitivity of MW production to any differentiation in DW segregation rate, the model was simulated three times by assigning different rates to the parameter *"rate of DW segregated from MW"* (level-0.64, level-0.50 and level-0.10). A level-0.64 represents the current segregation rate, i.e. 64% of MW is DW, which is the case in Istanbul (Alagoz and Kocasoy, 2008). A level-0.50 and a level-0.10 indicate segregation rates that reduce the DW content of MW to 50% and 10% respectively.

Fig. 5a shows that a decrease of DW content in MW from 64% to 50%, results in the MW generation being almost 300 tons/year lower after 2030, i.e. 300 tons of DW is prevented from getting mixed with MW. Moreover, MW goes down by almost 600 tons/year after 2030 if the DW content of MW decreases to 10%. This corresponds to an approximately 20% decrease in the amount of MW produced annually beyond 2030.

It is also evident that for the current regional capacity to be sufficient until 2045, the domestic content in MW must be reduced to 10% (level-0.10). Failure to achieve this, demands for urgent installation of new units to treat all the MW generated in the region.

The model was run two further times to analyze the influence of reduction in the DW content of MW to 10% in C units only and A units only. Fig. 5b shows that the reduction of DW content to 10% in the A units only does not eliminate the need for a new capacity. However, if this reduction is achieved in the C units only, the total MW from the region remains below the current installed capacity, 2500 tons/annum, throughout the model period.

The model behavior can also be investigated via sensitivity testing, which involves altering the model input parameters' value and observing the magnitude by which the outputs change. A sensitivity test of the software applies this procedure automatically. The variables in the model with minimum and maximum values are chosen to conduct a sensitivity test. The model is initially run with the current values, followed by additional simulations while the chosen parameters are varied within a distribution between the minimum and maximum values.

The model contains two uncertain parameters; *specialists required per hospital bed* and the *number of practitioners per person*. The value for the *specialists required per hospital bed* was initially set as 0.1, as reported by the Turkish Statistical Institute (Turkstat, 2019). However, it is estimated that this rate is likely to increase with the improvement of health sector investments during the harmonization period of Turkey for the European Union (EU) membership. It is reported by the European Statistics (EuroStat, 2011) that the number of specialists required per hospital bed is approximately 0.3.

The *number of practitioners per person* was initially calculated as 0.003, based on the averages of EU member countries according to European Statistics (EuroStat, 2019). However, in the medium term, it is unlikely that the Turkish national health sector could make investments comparable to these EU countries. For instance, the Turkish Statistical Institution (Turkstat, 2019) suggests that there are only 0.002 primary care practitioners per capita in Turkey.

The sensitivity test was, therefore, conducted to analyze the effect of *specialists per hospital bed* (varying between 0.1 and 0.3) and also the *number of practitioners per person* (varying between 0.003 and 0.002) on the amount of AT-MW. Increasing *specialists required per hospital bed* from 0.1 to 0.3 should have a growing effect on patient demand for C ('*C Demand*' stock parameter in the model shown in Fig. 2). This is because patients, who cannot get treated due to the lack of specialists at the hospitals, could now receive care. More treatment will result in higher generation of MW, and eventual rise in AT-MW. In contrast, reducing the *number of practitioners per person* from 0.003 to 0.002 reduces the number of patient assignments for A, since there will be a smaller number of practitioners in the region.

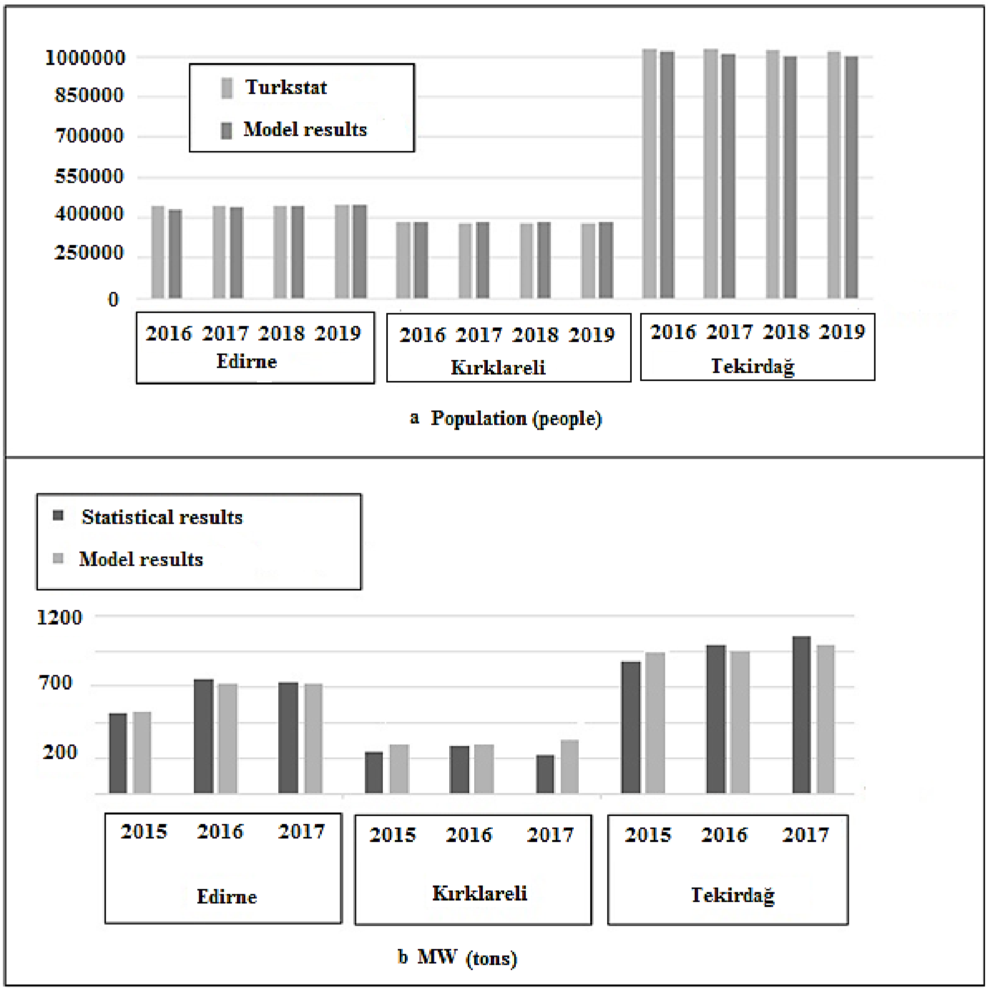

Fig. 3. Historical behavior test results

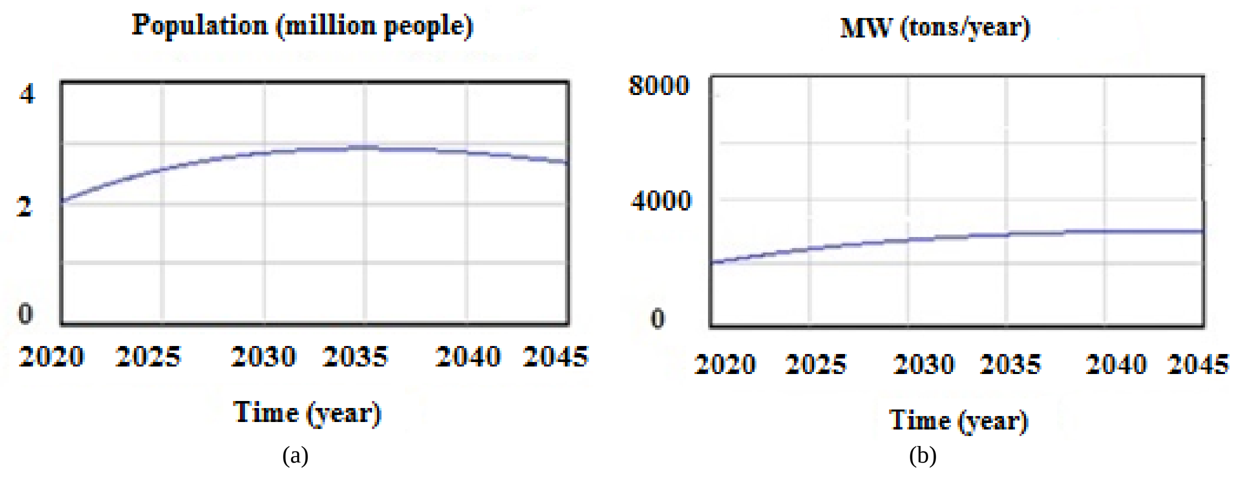

Fig. 4. Population and MW generation in the region, (a) the population projection, (b) the projection of MW generation

This will result in less MW being generated, but also more DW mixed with MW, due to less chance for practitioners to engage in waste management training courses. Fig. 6 presents sensitivity test results for AT-MW. As it is seen in Fig. 6, there is an increase in 2025 in all confidence bounds. This is because the *number of specialists per bed* (the original value is 0.1, as mentioned above) was previously insufficient to meet patient demand for C. With the recruitment of more specialists after 2025, the *number of specialists per bed* is no longer a restricted factor on the generation of AT-MW, and hence the amount of AT-MW starts to rise with increasing patient demand for C.

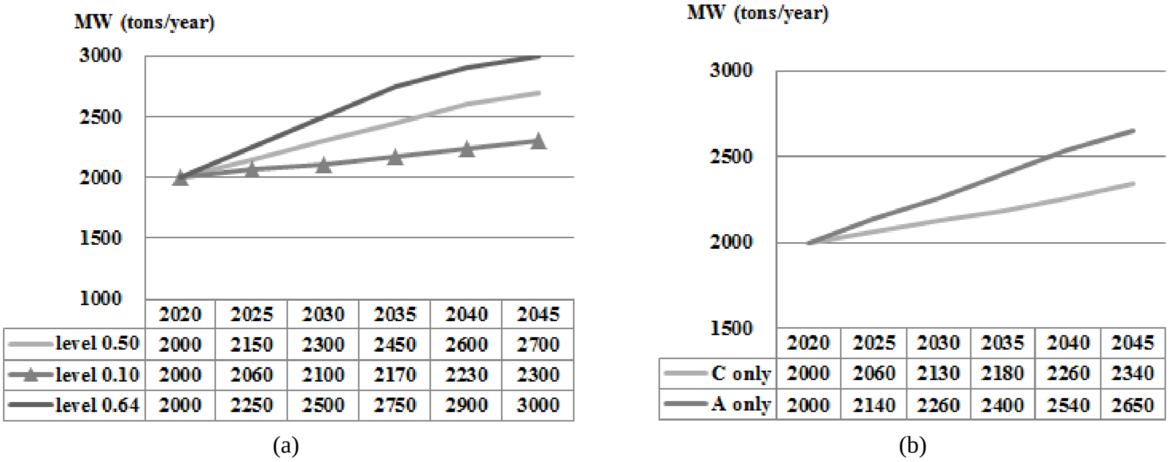

Fig. 5. Simulation results: (a) MW generation with different rates of DW content, (b) MW generation in A and C units

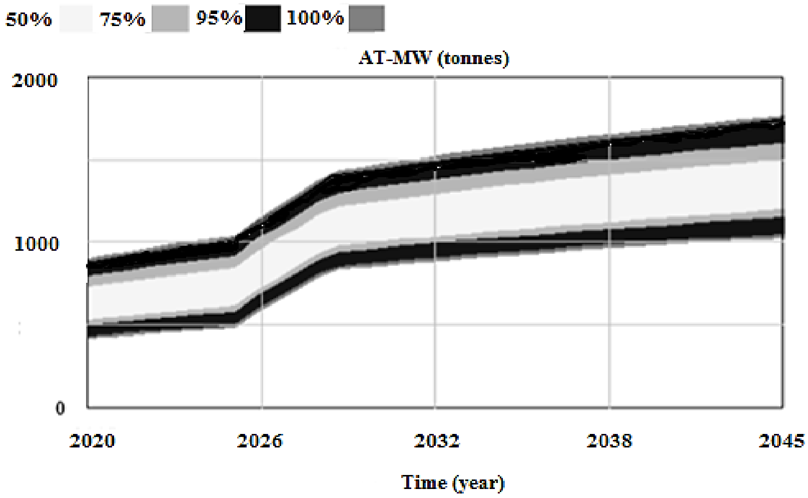

Fig. 6. Sensitivity test of AT-MW

4. Conclusions

• Dissemination of *personnel training* to separate Inc-MW from AT-MW, and to minimize the mixture of MW and DW, will not only reduce the amount of MW, but also decrease treatment costs. This highlights the importance of waste management training activities provided to medical staff.

• *The production of MW* will increase over the next 25 years, mainly due to the growth of the regional population. Importantly, if the existing MW treatment capacity in the region is to be sufficient up to 2045, the DW content in MW must be reduced substantially in comparison to current levels. Further research should, therefore, be undertaken as a matter of urgency to determine whether reducing the DW content of MW to 10% can be achieved in Turkish hospitals. Waste management training activities have a high potential to be effective in this context.

• As in every region, the relevant authorities are struggling to strengthen the health and environmental service infrastructure, and to create *a complete database* of waste quantities. In this sense, there are currently important deficiencies and inconsistencies in the regional infrastructure, especially in MW reporting, and the design of effective alternative approaches for waste management requires reliable data to be available. Therefore, it is crucial for the relevant authorities (especially environment and health municipalities) in the Thrace Region to regularly report health statistics along with MW quantities and compositions.

• *Sensitivity analysis* gives useful results in conditions where the values of the model variables can be reasonably estimated. However, in Turkey, producing strategic plans, including targets for limiting MW generation, has recently gained improved attention by decision-makers. In this sense, it is obvious that sensitivity analysis will give a more realistic range of results, thus guiding with the introduction of new investment targets in the near future.

• One of the advantages of a simulation modeling is that when *an unexpected situation* occurs, the system parameters can be modified according to this situation. This makes it very beneficial in predicting the establishment of an infrastructure required for the correct separation of infectious medical wastes, especially personal protective equipment waste, such as masks and single-use plastics, which have increased unexpectedly during the COVID-19 pandemic.

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