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INFECTIOUS WASTE MANAGEMENT AT REGIONAL LEVEL
KONCEPCE NAKLÁDÁNÍ S INFEKČNÍM ODPADEM NA REGIONÁLNÍ ÚROVNI

MASTER'S THESIS
DIPLOMOVÁ PRÁCE

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Assignment Master's Thesis

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As provided for by the Act No. 111/98 Coll. on higher education institutions and the BUT Study and Examination Regulations, the director of the Institute hereby assigns the following topic of Master's Thesis:

Infectious waste management at regional level

Brief Description:

The management of infectious waste is currently a very hot topic. These wastes are produced mainly in medical facilities, which must handle them in accordance with the legislation. It includes their registration, waste treatment and proper disposal. The purpose of this responsible approach is to prevent environmental contamination and the spread of infections. Infectious waste management is specific in individual EU countries and even in individual regions of these countries. These differ mainly in the amount of infectious waste produced, the technologies available for its disposal and the degree of integration of the management.

The diploma thesis will focus on the situation in the Czech Republic. Special attention will be paid to the integrated management system within the selected region.

Master's Thesis goals:

1. Review of information on health care waste in the Czech Republic and the European Union – definition, classification, legislative, production
2. Summary of existing methods for medical waste treatment
3. Mapping of production and processing capacities in a selected region of the Czech Republic
4. Proposal of a new concept of infectious waste management for this region

Recommended bibliography:

GARVIN, Michael L. Infectious waste management: a practical guide. Boca Raton, Fla.: Lewis Publishers, c1995. ISBN 9780873716376.

Safe management of wastes from health-care activities. 2. S.l.: World Health Organization, 2013. ISBN 9789241548564.

Metodika pro nakládání s odpadem ze zdravotních, veterinárních a jim podobných zařízení. Praha: Státní zdravotní ústav, 2016.

Deadline for submission Master's Thesis is given by the Schedule of the Academic year 2020/21

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L. S.

prof. Ing. Petr Stehlík, CSc., dr. h. c. Director of the Institute	doc. Ing. Jaroslav Katolický, Ph.D. FME dean

ABSTRAKT

Současná pandemická situace ukázala obrovské dopady rozšíření infekce na společnost, i přesto stále ještě chybí jednotný přístup k problematice infekčního odpadu. Cílem této práce je představení metodiky nakládání s infekčním odpadem v rámci regionu v kontextu situace v Česku a Evropské Unii. V teoretické části práce je uveden legislativní rámec, charakter produkce, možnosti dekontaminace a podmínky spalování infekčního odpadu. Na základě těchto poznatků je navržena metodika pro nakládání s infekčním odpadem v rámci regionu. V praktické části práce je pak metodika aplikována na konkrétní region – Královéhradecký kraj. V rámci metodiky jsou navrženy možné scénáře nakládání s infekčním odpadem a vybrány nejvhodnější z nich z pohledu zdravotních rizik, rozpočtové zátěže a dopadu na životní prostředí. Na závěr je metodika kriticky zhodnocena a srovnána s metodikami jiných studií na podobné téma.

Klíčová slova

infekční odpad, dekontaminace, nakládání s odpadem, sterilizační drtič

ABSTRACT

The current pandemic state has shown huge impacts of the infection spread on society, yet there is still no coherent approach to the issue of infectious waste. The aim of this thesis is to present the methodology for managing infectious waste within the region in the context of the situation in the Czech Republic and the European Union. The theoretical part of the thesis sets out the legislative framework, the character of production, decontamination options and conditions for incineration. Based on this knowledge, the methodology for managing infectious waste within the region is proposed. In the applied part of the thesis, the methodology is applied to the Hradec Králové Region. Under the methodology, possible scenarios for the infectious waste management are proposed. The most suitable one is selected from the perspective of health risks, budget burden, and environmental impact. Finally, the methodology is critically assessed and compared with the methodologies of other studies on a similar topic.

Key words

infectious waste, decontamination, waste management, sterilisation shredder

ROZŠÍŘENÝ ABSTRAKT

Teoretická část práce se zabývá rešerší informací o odpadech ze zdravotnictví v Evropské Unii a České republice. Uvádí definici infekčního odpadu, jako pojmu z Evropského katalogu odpadů, kde je tento odpad veden pod číslem 18 01 03 a řadí se tedy do skupiny zdravotnických odpadů (18) a podskupiny odpadů ze zdravotní péče o lidi (18 01). Dalším uvedeným podstatným druhem odpadu z podskupiny 18 01 je odpad 18 01 04, který může být zjednodušeně nazýván „neinfekční“. Ostatní druhy odpadu z této skupiny jsou poměrně úzce definovány a dohromady mají jen malý podíl v produkci. Likvidace těchto druhů odpadů je specifická a jejich problematika je v této práci vynechána.

Dále jsou v teoretické části uvedeny legislativní dokumenty, které se infekčního odpadu bezprostředně týkají, a doporučení Světové zdravotnické organizace, pro podmínky jeho likvidace a nakládání s ním. Odpad může být před konečnou likvidací totiž ještě dekontaminován, tedy zbaven infekčnosti, a může s ním být tedy zacházeno jako s odpadem, který nepředstavuje riziko šíření infekce. Dále se práce zabývá charakterem produkce zdravotnického odpadu v Česku a jiných zemích Evropské Unie, zejména je demonstrován rozdíl v množství vyprodukovaného infekčního odpadu mezi Českem a Německem.

Již zmíněné dekontaminaci je v práci věnována samostatná podkapitola, kde jsou uvedeny možné způsoby téměř 100% sterilizace odpadu. Mezi tyto metody patří pokročilejší technologie dekontaminace vodní párou v kombinaci s mechanickým drcením. Jindy nežádoucí přeměna mechanické energie v teplo v průběhu drcení je v tomto případě užitečná při tvorbě vodní páry. Na Ústavu procesního inženýrství byl v minulosti jeden takový sterilizační drtič testován, a proto byla modelová řada tohoto konkrétního drtiče použita k reprezentaci této technologie.

V samostatné kapitole je uveden popis nové metodiky pro hodnocení scénářů nakládání s infekčním odpadem v rámci regionu. S využitím této metodiky je možné definovat vhodnou koncepci nakládání s infekčním odpadem pro vybraný region. Posuzují se přitom tři základní kritéria: Dopad na životní prostředí, zdravotní riziko a rozpočtová zátěž. Každá z těchto oblastí je hodnocena známkou z rozsahu A–F podle definovaných kritérií kvalifikace.

Dopad na životní prostředí je kvalifikován na základě emisí oxidu uhličitého, které jsou produkovány provozem vozidel určených k přepravě odpadu. Zahrnuje tedy cesty s infekčním i neinfekčním odpadem a zpáteční cesty bez nákladu. Emise jsou stanoveny podle kombinované spotřeby paliva a druhu paliva běžně používaného vozidla pro tento účel v daných podmínkách. Jejich výše je přepočítána podle odhadu počtu najetých kilometrů, podle produkce odpadu a legislativních podmínek.

Zdravotní riziko je uvažováno jako přímo úměrné množství přepravovaného infekčního odpadu napříč regionem a vzdáleností, na kterou je tento odpad přepravován.

Rozpočtová zátěž je kritérium, které je určeno nejsložitěji. Výpočet se skládá z provozních nákladů spaloven odpadů, sterilizačních drtičů a přepravy odpadu.

Praktická část práce začíná představením Královéhradeckého kraje, jako jednoho z významných administrativních celků v České republice, který je svým charakterem blízký většině dalších krajů České republiky. Jsou zde uvedeny demografické údaje, členění kraje na obce s rozšířenou působností a rozmístění zdravotnických zařízení a spaloven infekčního odpadu, které se v kraji nacházejí. Pro účely tvorby scénářů bylo také zjištěno množství vyprodukovaného odpadu v jednotlivých obcích s rozšířenou působností a kapacita spaloven infekčního odpadu.

Při hledání vhodné koncepce bylo vytvořeno celkem devět scénářů, které kombinovaly počet spaloven a míru využití sterilizačního drtiče Converter. K tvorbě a hodnocení těchto scénářů

byla aplikována metodika z teoretické části práce. Potřebná vstupní data o produkci odpadu v jednotlivých obcích s rozšířenou působností byla získána z veřejné databáze Ministerstva životního prostředí. V rámci zefektivnění výpočtů metodika nezohledňuje produkci jednotlivých zdravotnických zařízení a za producenta odpadu administrativní centrum dané obce s rozšířenou působností bylo považováno. Údaje o kapacitě spaloven a skutečném množství spalovaného odpadu byly získány z dat Českého hydrometeorologického ústavu a Plánu odpadového hospodářství Královéhradeckého kraje.

Z vyhodnocení scénářů vyplynulo, že nejlepší možností je využití sterilizačních drtičů ve všech devíti nemocnicích v kraji a zachování pouze jedné spalovny. Na hodnocení zdravotního rizika a dopadu na životní prostředí mělo největší vliv množství odpadu, který byl dekontaminován v drtičích. Drtiče odpad vysušují, čímž dojde k redukci jeho hmotnosti zhruba o polovinu a úměrnému snížení objemu přepravy odpadu. Rozpočet se ukázal být nejvíce zatížen počtem spaloven, a proto v kritériu rozpočtové zátěže vítězily scénáře, ve kterých byl počet spaloven snížen na jednu.

Závěr praktické části práce je věnován diskuzi a srovnání použité metodiky a způsobu získání vstupních dat s jinými pracemi a studiemi na podobné téma. V tomto ohledu je prezentována jako nejpodstatnější dostupnost dat a jejich přesnost.

BIBLIOGRAPHIC CITATION

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AFFIRMATION

I declare that this master's thesis is original, and I have processed it on my own. I also declare that all the citations of sources are complete and that I have not infringed copyright in my work (within the meaning of the Act No. 121/2000 Sb., on copyright and related rights).

Brno, 21 May 2021

Bc. Karel Martinek

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CONTENTS

1 Introduction

The primary aim of any health care system in the world is curing people's diseases and disease prevention. Many diseases are infectious, and pathogens can stay alive on surfaces, thus medical waste can be a secondary source of infection for the public. The process of handling the waste should therefore be transparent, efficient, and designed to pose the least possible risk. [1]

Infectious waste is one of many types of waste specified in the European Waste Catalogue, where each waste type has its six-digit number. Infectious waste is identified by number 18 01 03. It belongs to the group of waste from health care (group 18), more specifically health care for people (sub-group 18 01) and is defined as: '*Wastes whose collection and disposal is subject to special requirements in order to prevent infection*'. [2]

1.1 Current situation regarding infectious waste management

Treating infectious waste in the European Union (EU) is in the competence of each national or a regional council. Every country must have a waste management plan or plans (separately for every region in a country) according to the Article 28 of the European Directive 2008/98/EC. [3]

All infectious medical waste must be either incinerated or decontaminated. According to the World Health Organisation (WHO), the temperature of incineration should be at least 1,000 °C. Before incineration, the waste is separated and stored in hospitals for a certain amount of time. Some health establishments use the decontamination of infectious waste by means of an autoclave, which allows them to treat it as non-hazardous waste. Infectious waste is either transported to incineration plants or incinerated directly in a medical facility. Most of the infectious waste in the Czech Republic is incinerated without preceding decontamination. [4], [5], [6]

The utilization of a decontamination technology at the place of waste origin has a major impact on infectious waste production. According to the official European statistics, waste generation rates are divided according to catalogue numbers, but the statistic does not reflect waste flows inside a single health-care facility. This fact allows distinguishing how common is the usage of the waste decontamination technology in general. There is a big gap between decontamination usage and waste segregation efficiency in Germany and the Czech Republic as can be seen from the waste type comparison in the fig. 1. [7]

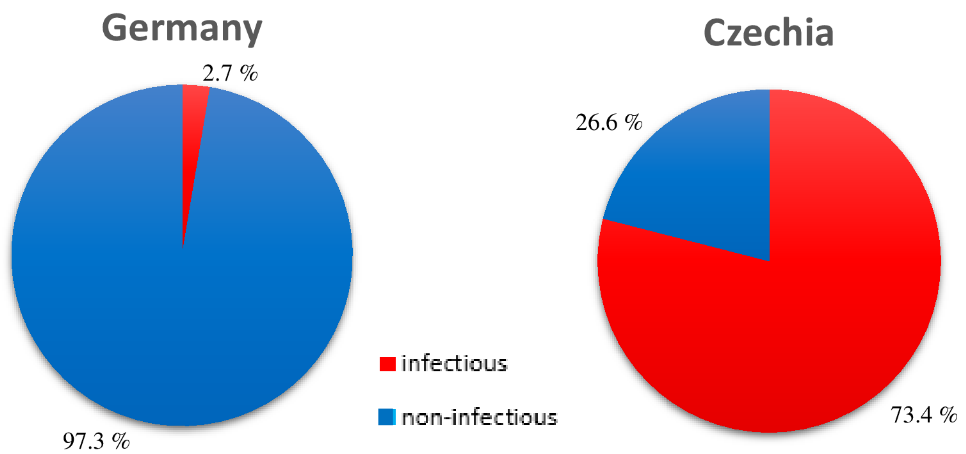

Fig. 1 Major contents of medical waste [8], [9].

As shown in the fig. 1, most of the medical waste produced in Germany is non-infectious waste, whereas it is the opposite in the Czech Republic even though the quality and availability of healthcare is similar in both countries [10]. However, the efficiency of infectious waste management efficiency improvement does not have a big impact on the hospital's public image compared to other factors, especially the healthcare itself [11]. Another cause of high infectious waste production rate is often vague infectious waste definition in internal hospital rules causing employees to consider nearly all the waste being potentially infectious. [11]

According to the survey of the Czech Ministry of the Environment, the medical waste decontamination is truly not common among Czech hospitals because only 4–5 % of facilities are equipped with such technology. [7]

Aside from lower health risk from decontaminated waste, the technology would maybe also help the hospitals' budget burden because treating decontaminated waste is expected to be cheaper than treating hazardous infectious waste. In a survey, hospitals were asked the following question: *'What are your financial costs with health care waste disposal?' [7]* with 'a), b), c), d)' options [7]. The answers of 93 hospitals [7] that answered this question (roughly one half of hospitals in total [12]) are displayed in the fig. 2.

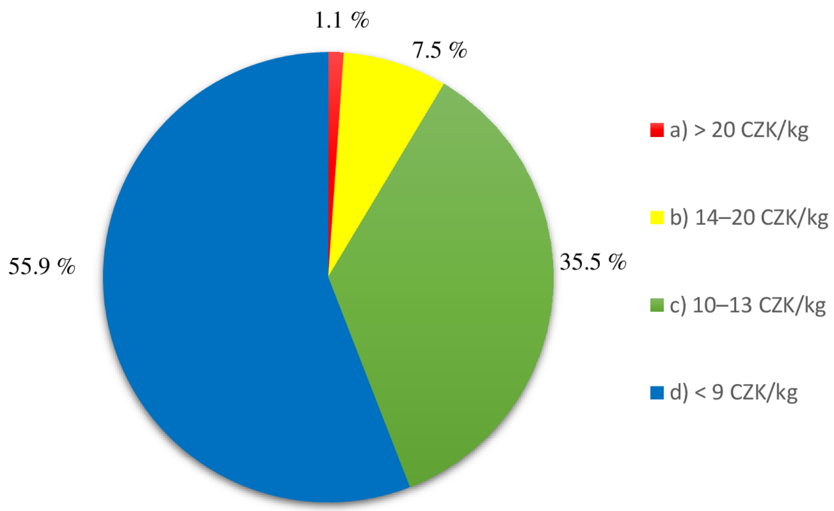

Fig. 2 Waste disposal costs in hospitals (2020). [7]

It is obvious that calculating the average price for waste processing is very difficult from the pie chart above. For example, the following assumptions would have to be used in the estimation:

- 1.1 % of hospitals pay 21 CZK/kg,
- 7.5 % of hospitals pay 17 CZK/kg,
- 35.5 % of hospitals pay 11.5 CZK/kg, and
- 55.9 % of hospitals pay 8 CZK/kg.

If those considerations were assumed true, the waste disposal costs for Czech hospitals would be roughly 10 CZK/kg on average.

1.2 Motivation and thesis methodology

In the Czech Republic, tracking waste flows is often impossible, rates of production and disposal in regions are not equal, meaning that infectious waste is being transported across the country [13]. The methodology in the regional waste management plans in the country should be updated considering environmental and human health threats which are related to uncontrolled transportation of highly dangerous infectious waste.

The aim of the thesis is to demonstrate an approach which is the golden mean between complex mathematical modelling and an intuitive elementary approach, because such study has not been published yet. The reason of bypassing the modelling might be time saving and the transparency of calculations so that even a non-mathematician can understand the approach. The process of searching for the best waste management strategy is shown in the block scheme in the fig. 3 and described below.

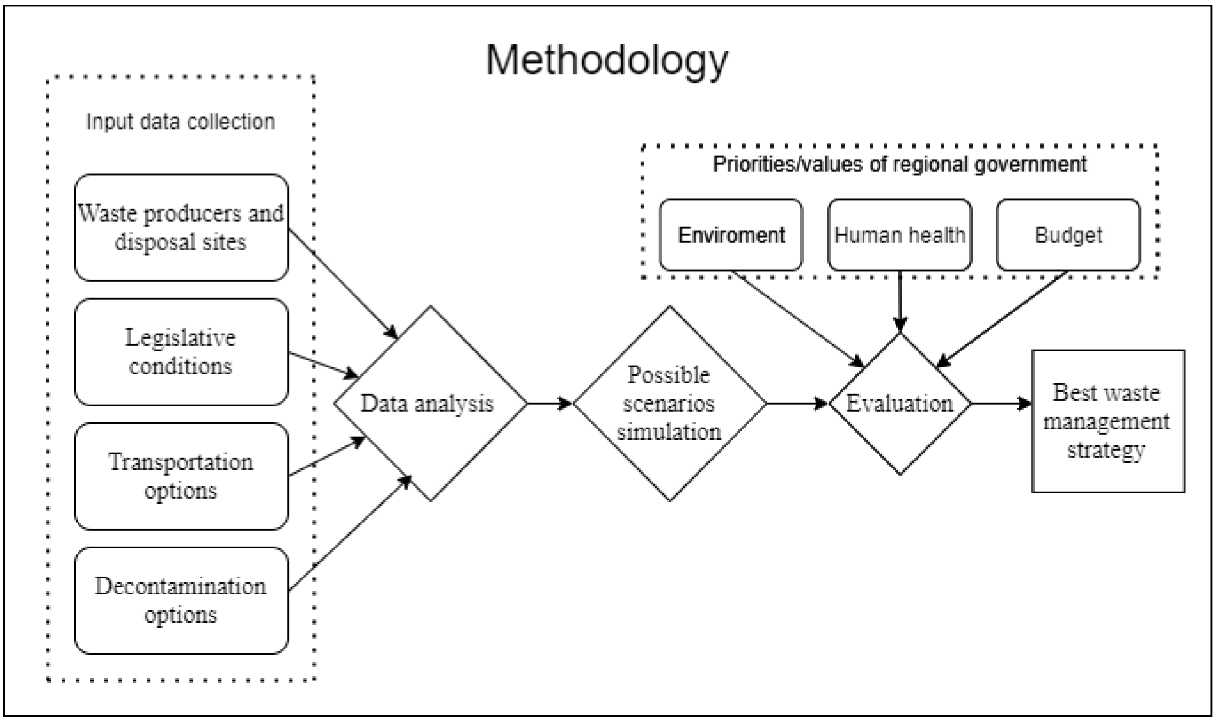

Fig. 3 The block scheme of searching for the best waste management strategy.

Input data collection (chapter 2)

The first part of the process is the information retrieval about legislation and applied technology. The legislation context may vary in different countries; however, it is always right to follow the recommendations of the WHO, too. Regarding technology, decontamination plays an important role; it decreases transportation and operating costs and bypasses a lot of legislative restrictions for infectious waste. However, it breaks the mass balance of produced and disposed waste, too, because some methods moisturize waste while other methods dry it. The most important legislative condition is the maximum allowed infectious waste storage period. The computations regarding transportation must be done differently if the production rate for a specified period is lower than a certain limit. The high cargo-space utilization should usually be the priority, but the frequency of journeys between a health-care facility and an incineration plant must always be higher or equal to the maximum allowed storage period for infectious waste. The length of the period varies among countries and can have various additional conditions, usually maximum allowed temperature of the environment where the waste is being stored.

Methodology description (chapter 3)

In the contextual framework of this thesis, methodology represents the theory which is then applied on the evaluation of infectious waste management in a certain region. The evaluation is characterized by the criterion compliance rate of the following three main criteria:

- Environmental impact
- Health risk
- Budget burden

The compliance rate is expressed by marks A–F for each criterion where ‘A’ is the best and ‘F’ the worst.

Data analysis (chapter 4)

The analysis of available production and disposal datasets. There are three common options of production data availability:

- There are no data available.
- The waste production data are available only for certain territorial units.
- Data are available for each health-care facility in the region.

If there are no waste production data available, we have no other option but to calculate estimations. A common way to do so is to create a certain factor that is used for multiplying the number of inpatients or the number of beds present in studied health-care facility or facilities [14]. However, no general value of the factor exists because it must be estimated for locally specific conditions [14].

Reliable production data availability for sufficiently small territorial units is the premise that is going to be applied. The largest hospital in a certain subregion or simply an administrative centre can be assumed as the place of waste origin. If there is an incineration plant located at the same place as the largest hospital, the rate of transported waste from such subregion is assumed to be zero.

It would be too much time-consuming to identify and analyse waste production of every single source of medical waste because there are too many of them. However, if such reliable dataset already exists, it is naturally the most accurate way to obtain inputs.

The waste disposal data can but do not necessarily have to help us obtain or verify waste production because the rate of disposal can differ from the rate of production. This fact can be caused by import or export between the region and other regions that are not part of the study, by uncertainties, or by the motivation of waste disposal companies to show higher rates than the real ones to gain higher profit [13]. The information about importing and exporting medical waste is usually provided in the waste management reports that are published at regional or national level across the European Union.

Possible scenarios simulation (chapter 5)

The scenarios simulation consists of three main parts:

- Transportation
- Waste processing approach
- Costing

The transportation part is about estimating distances for waste transport according to the weight limits and the quickest available road. Weight limits should also be considered when choosing the suitable vehicle for waste transportation. Vehicles should always have a large cargo space where the maximum allowable weight-load should be the significant factor for distinguishing. The maximum allowable weight of the load is more important than the maximum allowable volume because medical waste has high bulk mass. In Europe, vehicles of total weight below 3.5 t can take nearly any road, which makes the route planning simpler. When considering 90% utilisation of the cargo space, such a vehicle of the total weight of 3.5 t can take roughly 1 t of medical waste. This consideration makes calculations simpler and allows the resulting transportation rate in [km·t] to be interpreted as a distance multiplicated by the projected number of journeys per year.

There are two main branches of waste processing approach:

- Incinerating infectious waste.
- Incinerating waste which has been sterilised.

There are several methods of waste decontamination. The process often changes the mass and volume balance of a waste flow, which can have either positive or negative impact on the defined criteria that should be met. Decontamination methods are described in the chapter 2.3. The process can be done either at the place of the waste origin or in another catchment health-care facility.

Incinerating is in a close relationship with the cost estimation, because the number of incineration plants is the most significant element of budget burden. However, estimating costs is the most complex and uncertain part of the methodology because the price level and wages differ depending on the time and place. All the estimations that were obtained from the past should be multiplied by an inflation factor which can be different than the increase in wages in the same period.

Evaluation (chapter 5)

Scenarios are evaluated according to the fulfilment of defined environmental impact, health risk for public and budget burden criteria. These three criteria are the ones most frequently mentioned in technical articles. However, it is not easy to compare values of the criteria between each other. It seems more like a philosophical problem than a scientific one. When comparing the fulfilment of criteria, several statistical misinterpretations can also occur. For example, the best possible case of all does not necessarily have to be the good one and vice versa. Also, there can be factors which end up being the only ones affecting the grade while other ones are supressed. Changes and solutions in waste management at the regional level often require initial investments. However, the willingness of local authorities to invest into new solutions and technologies can be unpredictable, thus there could be more best-case scenarios for each case of initial investment.

In the case of this study, each criterion is going to be graded A–F. The main purpose of marks is to allow quick comparison and easy orientation for the reader. Marks were assigned according to specified values as follows:

- Environmental impact: The frequency and the length of journeys during a year between health-care facilities and incineration plants while carrying medical waste of any type or with empty cargo-space. The value is represented by the amount of carbon dioxide (CO_2) emitted by the combustion engine of the chosen vehicle according to its fuel type and average fuel consumption.
- Health risk: The frequency and the length of journeys during a year between health-care facilities and incineration plants while carrying infectious waste.
- Budget burden: The estimated amount of money that needs to be spent for significant parts of waste management process.

The lowest value that is assigned to a criterion defines the lower bound of the range and receives the mark ‘A’ and vice versa. The lower and upper bounds of each criterion define the range of the interval, which is divided into six sub-intervals of the same size with respective marks. In the evaluation, the best-case scenario should be given the best marks.

2 Health care waste in European Union and Czech Republic

The theoretical part of this thesis begins with the summary of theoretical inputs that must be specified to show possibilities when solving the problem of infectious waste management in the Czech Republic or possibly in any other country of the European Union. This chapter consists of four sub-chapters:

- **2.1 Legislation:** Summary of important legislative documents regarding waste.
- **2.2 Production:** Waste production characteristics in European countries.
- **2.3 Decontamination technologies:** Description of common decontamination methods.
- **2.4 Incineration:** Description of medical waste incineration specifics.

2.1 Legislation

The Union's legislation about waste is covered by the directive 2008/98/EC, the directive defines the hazardous property 'infectious' (HP 9) with the well-known warning symbol 'biohazard'. The important part of the Union's legislative is the waste catalogue, described in the Commission decision 2014/955/EU, that unifies waste categories, defining each waste type by six-digit number. Categories and subcategories specified in the Commission notice on technical guidance on the classification of waste C/2018/1447. The truncated list of medical waste subcategories regarding the catalogue chapter 18 *"Wastes from human or animal health care or related research"* is in the tab. 1. [3], [2], [15]

Tab. 1 Chapter 18 of Waste catalogue (truncated) [2].

Number	Content	Hazardous
18 01	Wastes from human health care	-
18 01 01	Sharps (except 18 01 03)	No
18 01 02	Body parts including blood bags (except 18 01 03)	No
18 01 03	**Subjected to special requirements to prevent infection**	**Yes**
18 01 04	**Not subjected to special requirements to prevent infection**	**No**
	(…)	
18 01 10	Amalgam from dental care	Yes
18 02	Wastes from veterinary care	-
18 02 01	Sharps (except 18 02 02)	No
18 02 02	Subjected to special requirements to prevent infection	Yes
18 02 03	Not subjected to special requirements to prevent infection	No
	(…)	

The thesis aims at subcategories 18 01 03 and 18 01 04 from the table above, because those two waste types represent most of the medical waste produced in health-care facilities [9]. However, stats about waste production sometimes mix more categories together. [16]

The legislation must be respected in each country of the EU. Every country implements it into national legislation which includes far more specific conditions. In the Czech Republic, the waste legislation is included in the Act No. 541/2020 Sb. [17]. The waste catalogue is an exact copy of the Union's one in the Act No. 8/2021 Sb. [18]. The methodology for the management of waste from health, veterinary and similar facilities is provided from the National Institute of Public Health [4]. The storage periods and conditions for medical waste are included in the section 10, paragraph 5 of the Act No. 306/2012 Sb. on conditions for the prevention and spread of infectious diseases and on hygiene requirements for the operation of health and social care facilities [19].

The legislative is very detailed and exact at most points. Allowed storage periods and other legislative conditions are considered in the methodology in the chapter 3.

2.2 Production

European stats of the waste production are provided by Eurostat. However, the European data does not display health-care waste production on its own, but as part of the category "W05", described as "Medical and biological waste" divided on hazardous and non-hazardous subcategories as follows: [16]

- Hazardous: 18 01 03 and 18 02 02. [16]
- Non-hazardous: 18 01 01, 18 01 02, 18 01 04, 18 02 01 and 18 02 03 [16]

The following chart in the fig. 4 shows the significant difference in production of countries in the EU per capita in 2018. The lowest production of infectious waste is in Austria (0,1 kg per capita), the highest in France (6,91 kg). The Czech production (2,84 kg) is slightly above the Union's average (2,44 kg). It is obvious, that production of non-infectious waste in Austria and Germany relates to significantly low production rate of infectious waste. However, among all the countries of the EU, the correlation coefficient between hazardous and non-hazardous medical waste production rates is close to zero. In other words, there is no proper indirect proportion between hazardous and non-hazardous medical waste production, thus there must be other factors affecting the proportion than just the decontamination rate. [20], [21]

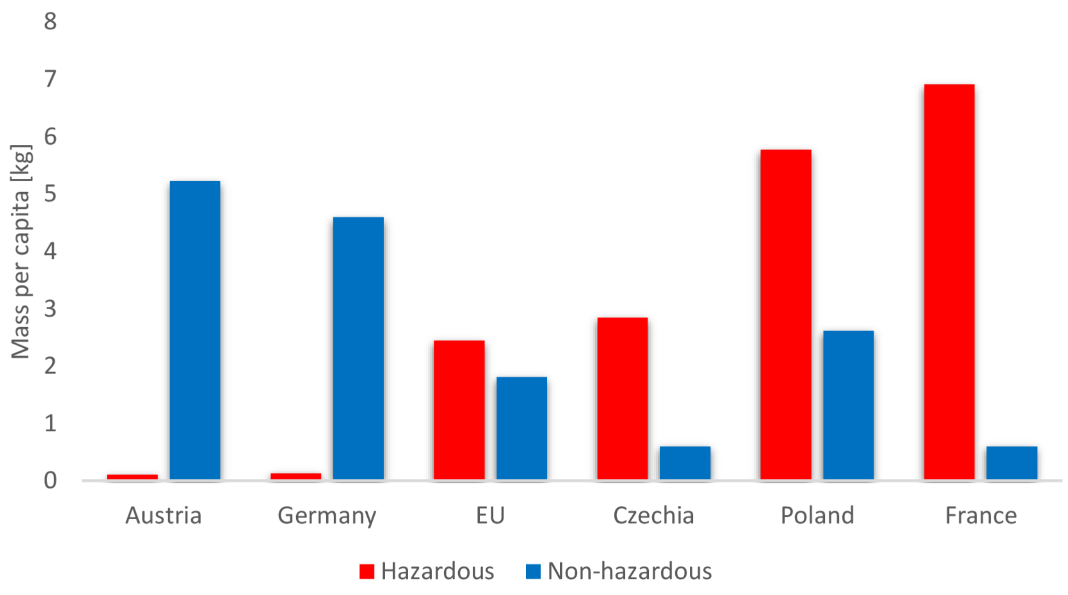

Fig. 4 Medical waste production in EU [20], [21].

Although the correlation between infectious and non-infectious waste production was not proven among all the EU countries, the extremely low rate of infectious waste production in Germany and Austria is most likely caused by better sorting and decontamination.

The following pie chart in the fig. 5 shows the content of the category W05 in the Czech Republic. As shown, other categories than 18 01 03 and 18 01 04 have only 4% impact on the result. [9], [16]

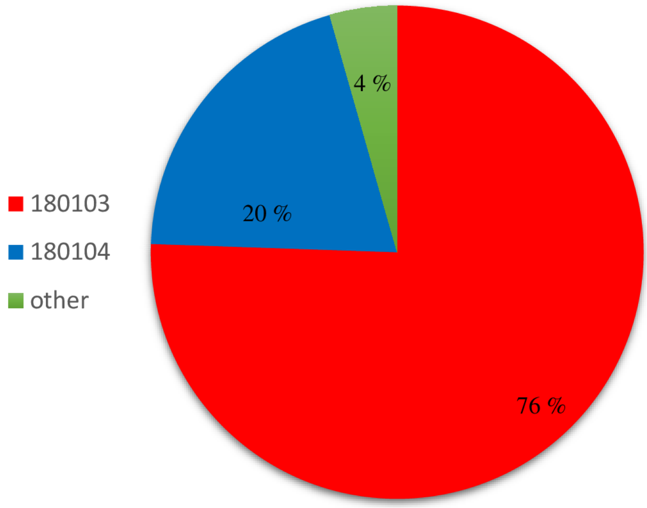

Fig. 5 Contents of category W05 in Czechia, 2019 [9], [16].

2.3 Decontamination technologies

The destruction of the entire microbiological contamination in waste is nearly impossible. The efficiency of decontamination is expressed by the State and Territorial Association on Alternate Treatment Technologies (STAATT) classification system, which has four levels according to the reduction rate of specified highly resistant microorganisms, where the level IV is the highest level. The common standard of microbiological inactivation is the STAATT level III, defined as: *'Inactivation of vegetative bacteria, fungi, lipophilic/hydrophilic viruses, parasites and mycobacteria at a 6 log10 reduction or greater; and inactivation of Geobacillus stearothermophilus spores and Bacillus atrophaeus spores at a 4 log10 reduction or greater' [22],* where the '6 log10 reduction' means the reduction of 99,9999 % of specified microbiological life and 99,99 % for '4 log10 reduction' respectively. [22]

Common ways of infectious waste decontamination:

- Hot steam
- Microwaves
- Dry heat
- Chemicals

Hot steam is used in an autoclave, where it penetrates the treated waste at high pressure for a certain time. Autoclaves have a wide use, except for chemicals that emits dangerous fumes, such as mercury, alcohols, phenols, and formaldehyde. [22]

Microwave technology is in fact a hot steam process of decontamination, where steam is produced by heating the molecules of water inside the treated material [22]. Generally, that kind of medical waste that can be treated in an autoclave, can also be treated in a microwave system [23]. It is a common misconception that metals cannot be treated using microwave technology, the opposite is true [23].

Dry heat treatment uses conduction, convection, or radiation to heat up the treated waste. Longer exposure periods and higher temperatures must be used compared to the hot steam technology, and therefore they are not commonly used in large-scale facilities. [22]

Chemicals, commonly: *'chlorine compounds, aldehydes, lime-based powders or solutions, ozone gas, ammonium salts and phenolic compounds' [22]* are suitable for liquid waste, treating solid waste has several limitations [22].

Advanced hot steam technologies

Those technologies are based on the combination of mechanical shredding and autoclaving. Shredding is used before, during or after hot steam treatment. The last part of the process is drying or compaction resulting to reduction of weight and volume. [22]

The sterilization crusher Converter by Italian company OMPECO srl. was chosen to represent this technology, because this device was being tested at the Institute of Process Engineering of Brno University of Technology. Converters are made in eight models of different capacity described in the tab. 4 [24]. The biggest impact on waste flow has the reduction of mass by 50 % and volume by 80 %, [24]. Treated waste is disinfected at the STAATT level IV [25], which is the highest one, meaning that at least 99,9999 % of *'vegetative bacteria, fungi, lipophilic/hydrophilic viruses, parasites, mycobacteria and Geobacillus stearothermophilus' [22]* are inactivated. The process of waste decontamination in the Converter consists of several parts as follows:

- Shredding while heating up using the heat from both friction from the shredding process [24] and an electric heating spiral around the perimeter of the Convertor's chamber.
  - Rapid increase in temperature to the boiling point of water [24].
  - Evaporation of the water from waste at the boiling point [24].
  - Superheating up to 151 °C [24].
- Injection of water which immediately turns to steam, while the temperature is held on 151 °C. This process takes 3 minutes.
- Cooling down by water injection to the boiling point, then to 60 °C by ventilation.

However, according to the survey among Czech hospitals done by the Ministry of the Environment, there are only 4–5 % of hospitals in the country, that treat waste by any of decontamination technologies [7].

2.4 Incineration

Infectious waste must be incinerated or decontaminated, non-infectious waste including decontaminated waste may be incinerated, landfilled, or recycled. The important parameter of waste incineration is the 'lower heating value' (LHV). Medical waste, which usually contains large quantities of plastic, typically has a high LHV (above 16.7 MJ/kg), but moisture can significantly reduce it. The rate of moisture in waste should be less than 30 % for feasible incineration and the LHV at least 8.3 MJ/kg. Despite combustion is the preferred way of disposal, some contents of medical waste must not be incinerated (or just at negligible rate). Those include for instance any radioactive content, halogenated materials like polyvinyl chloride (PVC), heavy metals (mercury), and extremely thermally stable pharmaceuticals (5-fluorouracil). [26]

There are two main types of large-scale incinerators of medical waste: [26]

- Dual-chamber starved-air incinerators [26]
- Rotary kilns [26]

Starved-air incineration is also called *controlled-air incineration*, *pyrolytic incineration*, *two-stage incineration*, or *static hearth incineration*. The incinerator consists of primary and secondary chamber and the technology for cleaning the flue gas. The primary chamber is used for thermal decomposition of waste in an oxygen-deficient environment at the temperature range of 800–900 °C including a fuel-burner used when the process starts. The secondary chamber burns the gases from the primary chamber using an excess of air at the temperature range of 1,100–1,600 °C, the temperature must not drop below 1,100 °C. If the temperature is about to drop below 1,100 °C, an additional thermal energy must be supplied by a gas or fuel burner. [26]

Incineration in a rotary kiln follows the same principle as the dual-chamber starved-air incineration, moreover, the primary chamber is represented with the rotary kiln which allows higher temperature, up to 1,200 °C, allowing better decomposition of heat resistant chemicals. [26]

The bottom and fly ash from incineration cannot be landfilled because the ash includes heavy metals, chlorine, and other harmful compounds, therefore it is bad for human health and environment. Instead, it is commonly solidificated by adding into Portland's cement. Chlorine can be absorbed by water as pre-treatment before solidification, which reduces the amount of cement required. [27]

3 Methodology for regional infectious waste management

Defining methodology is the last chapter from the theoretical part of this thesis, the new concept development progresses as follows:

- Summary of legislation and possibilities (chapter 2).
- Analysing available data of production, disposal, and distances in the Hradec Králové Region (chapter 4).
- Creating possible scenarios of waste management for the Region (chapter 5).
- Identifying the best-case scenario as the new concept for the Hradec Králové Region.

Environmental impact, health risk, and budget burden are three main qualifiers for the concept. For simplicity, each of them is going to be graded by marks A–F, while ‘A’ is the best and ‘F’ the worst. The purpose of this chapter is describing the calculation of each criterion value.

3.1 Environmental impact

For simplicity, environmental impact is measured by CO_2 emissions from transportation of all kinds of medical waste (**infectious and non-infectious**). Emissions amount is estimated according to a combined fuel consumption of a common vehicle used for waste transportation [28]. It is important to know how heavy load the vehicle can carry, and it should be considered, that it cannot be filled over 90 % of its capacity [28].

The weight limit is more important than the volume of the vehicle’s cargo space because the bulk mass of non-shredded waste is at least 100 kg/m3 [29]. In other words, 1 average ton of waste has the volume of 10 m^3. Shredded waste has naturally even higher bulk mass.

There is a legislative condition that infectious waste in the Czech Republic cannot be stored for longer than 30 days [19]. Therefore, there must be at least 12 waste transports annually.

Emissions are doubled with respect to return journeys, although this correction cannot affect the comparison of scenarios. The interval between the maximum and minimal CO_2 emissions rate, presented in following scenarios, is divided in six subintervals of the same size. Each subinterval is going to represent a grade A–F.

3.2 Health risk

Health risk for public is directly proportional to amount of infectious waste transported across the region. This parameter is the best measurable one. For this study, it does not matter how many vehicles are involved. Vehicles of weight below 3.5 t should be preferred, because they are less likely to face weight restrictions on the road. The only important parameter on a vehicle regarding this criterion is the maximum weight it can carry.

Qualification of this priority is determined according to the sum of products of transported **infectious** waste mass and distance, where the waste mass represents the frequency of certain journeys annually. The calculation is shown in the following equation:

$$w_{tr} = \sum d_i \cdot m_i \tag{1}$$

Where:

d_i	distance between certain facilities [km],
m_i	mass of produced waste [t],
w_{tr}	annual infectious waste transportation rate [km·t].

The results are divided in six subintervals of the same size representing marks A–F.

3.3 Budget burden

Estimating transportation and incineration costs is the most difficult task. Costs are calculated separately for:

- Incineration plants
    - Wages
    - Maintenance, reinvestment, and waste treatment
- Sterilisation crushers
- Waste transport

Incineration plants

Incineration costs were estimated based on formulas in [30] with adjustments due to the significant difference between wage growth and inflation rate since the time when the dissertation thesis [30] was completed. The distinction between municipal waste incineration and hazardous (infectious) waste incineration was neglected. Following equations were used:

- The equation of **wages** considering the wage growth [30]:

$$C_p = (2.5537 \cdot W_a + 106.84) \cdot (1 + \frac{w_g}{100}) \tag{2}$$

- The equation of **maintenance, reinvestment, and waste treatment** [30]:

$$C_{mr} = i_{CZK} \cdot 29.974 \cdot e^{0.0863 \cdot W_a} \tag{3}$$

$$C_{wt} = i_{CZK} \cdot 9.324 \cdot W_a \tag{4}$$

The respective symbols in equations (2) – (4) have the following meaning:

C_{mr}	maintenance and reinvestment costs [CZK],
C_p	wages [CZK],
C_{wt}	waste treatment costs [CZK],
e	Euler's number [–],
i_{CZK}	inflation rate of Czech koruna [%],
W_a	annually processed waste [kt],
w_g	wage growth [%].

Sterilisation crushers

The operational **crushing costs** are mainly defined by the price of electric energy (the total price recalculated to the unit price of 1 kWh). The calculation is determined using the following equations:

$$C_s = W_s \cdot E_e \cdot C_e \tag{5}$$

Where the respective symbols have the following meaning:

C_e	unit price of electricity [CZK/kWh],
C_s	shredding costs [CZK],
E_e	electric energy consumption per ton of waste [kWh/t],
W_s	annually shredded waste [t].

Waste transport

Transportation costs are estimated separately for infectious and non-infectious waste. The cost of non-infectious waste transportation should be estimated according to a selected transportation company which operates in the studied region. Infectious waste transportation costs are more difficult to establish. The best way is obtaining costs from similar studies, which have been done in the same country, because the price level may vary among different countries, especially wages. After that, an interpolation should be made between costs and annually travelled distances presented in such study.

This approach is way easier than trying to estimate costs of fuel, tyre wear, insurance, administrative and other operational overheads, labour costs and amortisation.

Overall costs

The overall cost estimation is the sum all the costs mentioned above, described by the equation:

$$C_o = C_{ti} + C_s + C_{wt} + C_{mr} + C_p \quad (6)$$

Where the respective symbols have the following meaning:

C_{mr}	maintenance and reinvestment costs [CZK],
C_o	overall costs [CZK],
C_p	wages [CZK],
C_s	shredding costs [CZK],
C_{ti}	costs of infectious waste transportation [CZK],
C_{wt}	waste treatment costs [CZK].

As well as previous priorities, the overall costs, presented in following scenarios, are divided in six subintervals of the same size labelled with grades A–F.

4 Production and processing capacity in Hradec Králové Region

This chapter is the beginning of the applied part of the thesis. The purpose of this chapter is:

- Describing the specific system of lower administrative units in the Czech Republic and the Hradec Králové Region as one of the administrative units in the country.
- Showing the current infectious waste production character and progress along with current disposal options.
- Describing the current state of infectious waste management in the Hradec Králové Region.

The Czech Republic is divided in 13 administrative regions and the capital city Prague as one exceptional example. Those regions are furtherly divided into sub-regions, so called ‘municipalities with extended powers ‘, while the capital city is divided into city districts. Different regions include different number of municipalities as shown in the fig. 6, where the Hradec Králové Region is highlighted in red.

Fig. 6 Map of municipalities and districts in Czechia. [31]

The Hradec Králové Region was selected because it has many sub-regions for which the data are provided meaning there are many possible scenarios of waste transportation. The region, shown in the fig. 7, has 550,000 inhabitants, it is 4,800 km^2 large and divided into 15 districts, called ‘municipalities with extended powers ‘. The region has similar character compared to other regions of the Czech Republic.

Fig. 7 The map of municipalities in the Hradec Králové Region [32].

There are nine hospitals in the region, including one university hospital and other 1,419 health care facilities [33], [34]. The locations of all the hospitals of the region are shown in the map in the fig. 8. As shown in the map, these hospitals are always in the centre of a certain municipality.

Fig. 8 The map of main hospitals in the region. [34]

The number of inhabitants in each district strongly correlates with the produced medical waste (shown in the tab. 2), the Pearson product-moment correlation coefficient has the value of 0.974 [9].

Tab. 2 Production in each district of the region (2019) [35], [9].

Municipality with extended powers	Population	All medical waste [t]	Only 18 01 03 [t]	Only 18 01 04 [t]
Broumov	15,876	32.0	24.4	7.5
Dobruška	20,190	53.5	30.7	22.6
Dvůr Králové nad Labem	26,949	73.6	31.4	41.7
Hořice	18,377	80.9	50.4	29.3
Hradec Králové	146,899	1,131.2	929.8	162.8
Jaroměř	19,273	27.9	27.5	0.0
Jičín	48,382	102.9	100.7	0.1
Kostelec nad Orlicí	24,892	2.7	1.8	0.0
Náchod	60,595	289.1	140.5	146.8
Nová Paka	13,286	17.9	1.0	16.0
Nové Město nad Metují	14,214	13.6	13.4	0.0
Nový Bydžov	17,384	49.4	49.3	0.0
Rychnov nad Kněžnou	34,301	97.9	74.5	22.0
Trutnov	63,419	304.2	125.4	150.5
Vrchlabí	27,610	66.8	45.1	19.9
Total	551,647	2,344	1,646	619

According to the production data from the tab. 2, most of the medical waste is represented either by infectious waste 18 01 03 or non-infectious waste 18 01 04. Therefore, other categories can be neglected. The shares are demonstrated in the pie chart in the fig. 9.

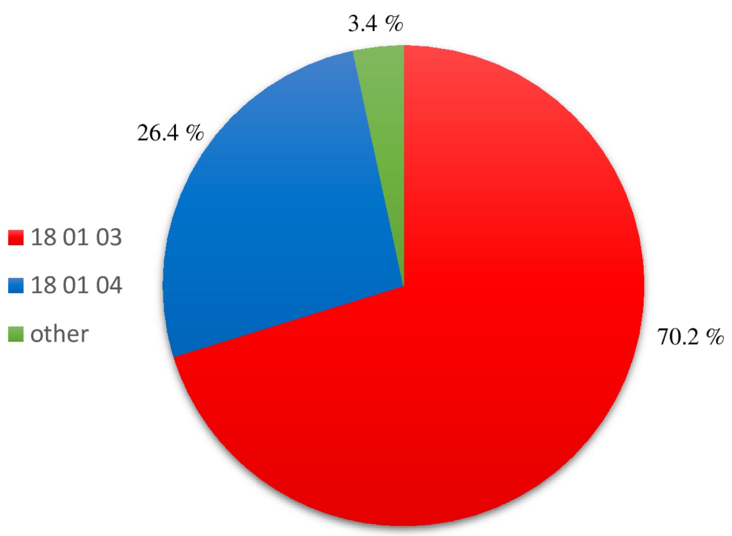

Fig. 9 Contents of medical waste in Hradec Králové Region. [9]

The biggest producer is the University Hospital Hradec Králové with capacity of 1,375 beds and approximately 715,000 outpatients treated annually [36]. The hospital is equipped with an incinerator with capacity of 1,900 tons per year, however, only 835 tons were incinerated in

2019 [37]. The second biggest producer, the hospital in Trutnov, is equipped with an incinerator with capacity of 1,000 tons per year, however, similarly like in Hradec Králové, only 151 tons were incinerated in 2019 [38]. Those are the only two incinerators in the region and they are 51 km away from each other by the fastest route. [39], [13], [40]

The methodology in the chapter 3 assumes that all the waste is produced and disposed within one region. Assuming the regional council of Hradec Králové Region would be willing to dispose all the infectious waste in the region, the capacity of incinerators is big enough. In case of minimizing the distance of transport, majority of the waste would be disposed in the University Hospital Hradec Králové – 1,278 tons annually which is 67.3 % of capacity. The resting 368 tons of waste could be disposed in Trutnov utilising 36.8 % the local incinerator's capacity.

The simplest way of disposing medical waste seems to be transporting it to the closest incinerator, either to Hradec Králové or Trutnov. Resulting from the dates above, this scenario does not take place, at least did not in years 2019 and 2013. As mentioned in the introduction, all the infectious waste produced (catalogue No. 18 01 03) must be incinerated. In total, 1,646 tons of infectious waste were produced in 2019, meanwhile, just 986 tons were incinerated. The resting 660 tons had to be transported out of the region. In 2013, the inequality was even more significant, there were 2,013 tons of infectious waste produced while no more than 935 tons incinerated. It means that current situation is barely analysable because the waste can be both exported and imported. [9], [41]

The computation of distances between health-care facilities and incinerators was simplified. There is assumed one big health-care facility producing all the medical waste from a district, located in each centre of 15 districts of the region. If a health-care facility is in the same district as an incinerator, the distance between them was neglected. The following tab. 3 shows the sorted distances between each district's centre and both incinerators in the region, considering the fastest possible route. In the current state, the average waste transport distance is 13.6 km. [9], [37], [38], [34]

Tab. 3 Distances between health-care facilities and incinerators. [35]

Municipality with extended powers	Way to Hradec Králové [km]	Way to Trutnov [km]
Hradec Králové	0	50.7
Jaroměř	24.0	28.8
Hořice	26.3	39.1
Kostelec nad Orlicí	33.2	68.8
Dobruška	33.5	49.5
Nové Město nad Metují	33.8	45.7
Nový Bydžov	46.1	58.7
Rychnov nad Kněžnou	39.9	68.9
Jičín	51.3	53.1
Trutnov	50.7	0
Dvůr Králové nad Labem	37.2	20.4
Vrchlabí	73.6	32.9
Náchod	45.6	36.7
Nová Paka	52.8	35.9
Broumov	75.7	45.7

It would be even possible to dispose all the infectious waste just in the incinerator in Hradec Králové, the production is 1,646 per year, filling the capacity by 86.6 % [9], [6]. However, the spare capacity should be at least 20 % according to production data from the 10 years period shown in the fig. 10 to cover usual deviations. Although the production was most likely a lot higher in 2020 due to the pandemic of COVID-19 according to the data from foreign countries [42]. Data regarding waste production rates in the Czech Republic in 2020 were not published before the submission of this thesis. According to linear approximation, the infectious waste production in 2022 is going to be approximately 1,656 t, neglecting the impact of the current pandemic state.

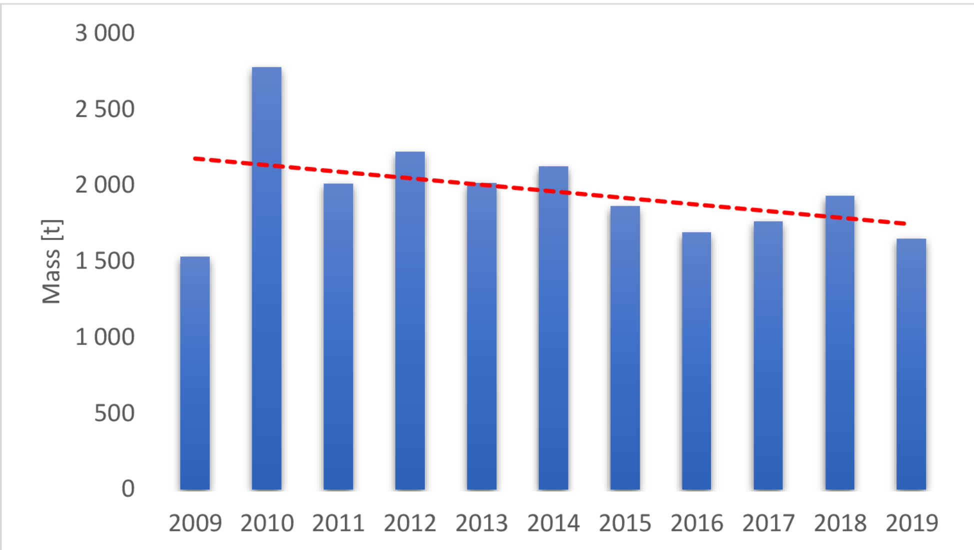

Fig. 10 Progress of infectious waste production in previous decade. [9]

5 New concept of infectious waste management in Hradec Králové Region

The purpose of this chapter is the application of the methodology on several possible scenarios of infectious waste management in the Hradec Králové Region, its evaluation, and identification of the best-case scenario. The chapter is divided in the following five subchapters regarding:

- Application of the methodology on the Hradec Králové Region.
- Scenarios, where sterilisation **shredders are not involved**. Thus, the scenarios without initial investments.
- Scenarios, where sterilisation **shredders are involved**. Thus, an initial investment is required.
- Evaluation of scenarios and identifying the best one.
- Discussion and comparison with other theses and studies.

The current state of the infectious waste management in the region is considered to be insufficient because the entire amount of produced waste is not being disposed withing the region, which is mentioned in the chapter 4 [13]. The current state cannot be evaluated by the presented methodology from the chapter 3, because of the lack of data regarding waste transportation from and to the region.

5.1 Applied methodology on Hradec Králové Region

The required waste production data were obtained from the database of the Czech Ministry of the Environment and the data regarding waste incinerators capacity were obtained from the Czech Hydrometeorological Institute. The datasets are presented in the chapter 4. The scenarios modelling was done respecting legislative conditions as a constraining factor. Legislation regarding infectious waste management is presented in the chapter 2.

The scenarios were created according to the current state and possible options in the region. According to the distribution of waste production within the region, it seems ineffective to build any new incineration plant. Both the existing incineration plants are well placed in the middle of the catchment areas of Hradec Králové and Trutnov, thus there is not any better place for them. The scenarios were created according to following options:

- No utilisation of sterilisation shredders and thus no reduction of incinerators capacity.
  - Two incinerators remain (scenario 1).
  - Only the bigger one incinerator remains (scenario 2).
- Utilisation of sterilisation shredders and thus reduction of incinerators capacity.
  - Shredding at the place of an incinerator.
    - Only one incinerator (scenario 3).
    - Two incinerators (scenario 4).
  - Shredding in the two biggest catchment areas, while incinerating only in the biggest one (scenario 5).
  - Shredding in each municipality, where the production rate is above 3 t/a.
    - Only one incinerator (scenario 6).
    - Two incinerators (scenario 7).
  - Shredding at hospitals.
    - Only one incinerator (scenario 8).
    - Two incinerators (scenario 9).

Environmental impact, health risk, and budget burden are the three main qualifiers for the concept. For simplicity, each of them is going to be graded by marks A–F, while ‘A’ is the best and ‘F’ the worst.

Environmental impact

Environmental impact is measured by CO_2 emissions from transportation. CO_2 emissions are estimated from combined diesel consumption of 10.8 l/100 km of the Renault Master 2.3 dCi 170, a common vehicle used for waste transportation [28]. The average CO_2 emissions rate of the vehicle is 290 g/km [43]. The vehicle can carry 1.1 t of load [44] but only roughly 1 t considering 90 % capacity utilised [28]. In other words, the waste production of each producer is equal to the theoretical number of transports per year. The vehicle cargo space volume is either 21.252 m^3 or 29.645 m^3 [28], while the bulk mass of non-shredded waste is at least 100 kg/m^3 [29]. In other words, 1 average ton of waste has the volume of 10 m^3, which is obviously less than the cargo space volume.

Emissions are doubled in respect of return journeys, although it cannot affect their comparison. The interval between the maximum and minimal CO_2 emissions was divided into 6 subintervals. Each subinterval represents the grade A–F as shown in the tab. 4.

Tab. 4 Scaling of environmental impact based on CO_2 emissions.

Mark	**Lower bound [t/a]**	**Upper bound [t/a]**
A	6.939	9.028
B	9.028	11.117
C	11.117	13.207
D	13.207	15.296
E	15.296	17.385
F	17.385	19.474

Health risk

The selected vehicle, Renault Master 2.3 dCi 170, has a weight of 3.5 t [28], meaning there is only a small possibility of weight restrictions on the road against the vehicle of such weight. The vehicle can carry roughly 1 ton of waste, considering 90 % of capacity is utilised [28]. This fact simplifies the following calculation. Qualification of this priority is determined according to the sum of products of transported infectious waste mass and distance, where the waste mass represents the frequency of certain journeys annually. The calculation is shown in the following equation:

$$w_{tr} = \sum d_i \cdot m_i \qquad (1)$$

Where:

d_i distance between certain facilities [km],

m_i mass of produced waste [t],

w_{tr} annual waste transportation rate [km·t].

The results, presented in following scenarios, are divided in six subintervals of the same size representing grades A–F as shown in the tab. 5.

Tab. 5 Scaling of health risk based on infectious waste mass and transport distance.

Mark	Lower bound [km·t]	Upper bound [km·t]
A	829	6,287
B	6,287	11,745
C	11,745	17,203
D	17,203	22,660
E	22,660	28,118
F	28,118	33,576

Budget burden

Estimating transportation and incineration costs is the most difficult task. Costs are calculated separately for:

- Incineration plants
  - Wages
  - Maintenance, reinvestment, and waste treatment
- Sterilisation crushers
- Waste transport

Incineration costs were estimated based on formulas in [30] with adjustments due to the significant difference between wage growth and inflation rate since the time when the thesis [30] was completed. The distinction between municipal waste incineration and hazardous (infectious) waste incineration was neglected. Following equations were used:

- Wage growth in the Czech Republic between 2010 and 3Q/2020 [45]:

$$w_g = 48.35\ \% \tag{7}$$

- Inflation rate of the Czech koruna (CZK) between 06/2010 and 09/2020 [46]:

$$i_{CZK} = 20.03\ \% \tag{8}$$

- The equation of **wages** with the consideration of wage growth [30]:

$$C_p = (2.5537 \cdot W_a + 106.84) \cdot (1 + \frac{w_g}{100}) \tag{9}$$

- The equation of **maintenance, reinvestment, and waste treatment** [30]:

$$C_{mr} = i_{CZK} \cdot 29.974 \cdot e^{0.0863 \cdot W_a} \tag{10}$$

$$C_{wt} = i_{CZK} \cdot 9.324 \cdot W_a \tag{11}$$

The respective symbols in equations (7) – (11) have the following meaning:

C_{mr}	maintenance and reinvestment costs [CZK],
C_p	wages [CZK],
C_{wt}	waste treatment costs [CZK],
e	Euler’s number [–],
i_{CZK}	inflation rate of Czech koruna [%],

W_a annually processed waste [kt],

w_g wage growth [%].

The sterilisation crusher has relatively high consumption of electricity, 0.4–0.6 kW/kg based on the waste moisture content [47]. Assuming the middle value of 0.5 kW/kg and the fact that one treating cycle takes *'less than 30 minutes' [24]*, one average ton of waste needs 250 kWh of electrical energy. The price of 1 kWh of energy in the Czech Republic is considered at 4.5 CZK/kWh [48]. According to the assumptions described above, the **crushing cost** calculation is determined using the following equations:

$$C_s = W_s \cdot E_e \cdot C_e \quad (12)$$

Where:

C_e unit price of electricity [CZK/kWh],

C_s shredding costs [CZK],

E_e electric energy consumption per ton of waste [kWh/t],

W_s annually shredded waste [t].

Transportation costs were estimated separately for infectious and non-infectious waste. The cost of non-infectious waste transportation was estimated according to the price list of a transportation company based near Hradec Králové, which puts the price at 15 CZK/km for a 3.5t vehicle [49]. Infectious waste transportation costs were estimated according to the case-study [28] of another region of the Czech Republic about infectious waste transportation between health-care facilities and an incineration plant. The mentioned case-study reveals transportation costs per certain cumulative distances that each vehicle would travel annually [28]. The transportation costs included cost of fuel consumed, tyre wear, insurance, administrative and operational overheads, labour costs and amortisation [28]. The values should be increased according to inflation rate and wage growth to the referential 3Q/2020 because the case-study was published in April 2019. The values for each scenario are shown in the tab. 6.

Tab. 6 Transportation costs of infectious waste [28], [45], [46].

Travel distance [km]	Wages [CZK/t]	Other costs [CZK/t]	Inflation rate [%]	Wage growth [%]	Updated overall costs [CZK/t]
26,208	4,169	2,875			7,331
44,408	2,493	2,172	4.02	4.12	4,855
61,152	1,561	1,619			3,309

The dependency between infectious waste transportation and the distance travelled is exponential and can be expressed by following exponential equation, which is also displayed in the fig. 11:

$$C_{ti} = 13{,}321 \cdot e^{-2\cdot 10^{-5}\cdot D_a} \quad (13)$$

Where:

C_{ti}	Costs of infectious waste transportation [CZK],
D_a	Distance that vehicles travel annually [CZK],
e	Euler's number [–].

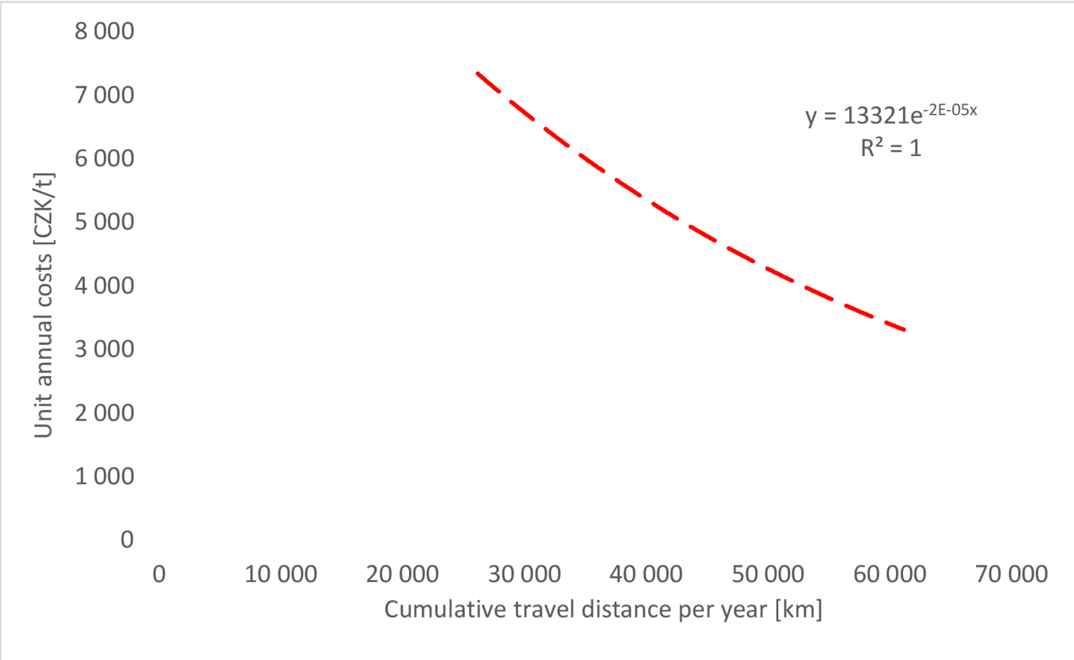

Fig. 11 The dependency between the cumulative travel distance and costs.

The overall cost estimation is the sum all the costs mentioned above, described by the equation:

$$C_o = C_{ti} + C_s + C_{wt} + C_{mr} + C_p \quad (14)$$

Where:

C_{mr}	maintenance and reinvestment costs [CZK],
C_o	overall costs [CZK],
C_p	wages [CZK],
C_s	shredding costs [CZK],
C_{ti}	costs of infectious waste transportation [CZK],
C_{wt}	waste treatment costs [CZK].

As well as previous priorities, the overall costs, presented in following scenarios, are divided in six subintervals of the same size. Each subinterval represents the grade A–F as shown in the tab. 7.

Tab. 7 Evaluation of budget burden

Mark	Lower bound [million CZK]	Upper bound [million CZK]
A	221	259
B	259	297
C	297	335
D	335	373
E	373	412
F	412	450

Value of each criterion

The ‘weight’ of each criterion can be quantified as the interval width of each mark and the impact of the change between upper and lower bound. In other words, the aim is quantifying the difference between each mark, for example between the middle value of A and the middle value of B. Interval lengths are shown in the tab. 8.

Tab. 8 Value of criteria.

Criterion	Interval length	Unit	Object
Environmental impact	2.2	t/a	CO_2
Health risk	5,496	km·t/a	Cumulative travel distance
Budget burden	$39\cdot 10^6$	CZK/a	money

5.2 Possible scenarios without initial investment

Scenarios 1 and 2 does not require any initial investment, they respect the current capacity of both incinerators in Hradec Králové and Trutnov and do not involve waste pre-treatment.

Scenario 1:

- Use of the current incinerators in Hradec Králové (1,900 t/a) and Trutnov (1,000 t/a).

The simplest scenario prefers the closest incinerator. The transportation scheme is shown in the fig. 12.

Fig. 12 Transportation scheme of scenario 1. [32]

The product of waste amount and overall transportation distance is 23,099 km·t [9], [34]. The biggest advantage of this scenario is the absence of investment in a new technology but maintaining two incinerators with relatively high capacity is the most expensive solution. The overall length of waste collection routes is medium, and it has corresponding environmental impact. However, all the transported waste is infectious, thus, pose a significant risk to human health. The rating for each priority is shown in the tab. 9.

Tab. 9 Rating of scenario 1.

Environmental impact	**Health risk**	**Budget burden**
D 13.397 t/a	E 23,099 km·t/a	F 450 million CZK/a

Scenario 2:

- Use of incinerator only in Hradec Králové (1,900 t/a).

The capacity of the incinerator in Hradec Králové is big enough to cover more than the entire infectious waste production in the whole region. For example, in 2019, 13.38 % of the incinerator's capacity would not have been utilised. Maintaining two incinerators can be considered as too expensive, especially when the only one is sufficient. However, the mentioned 13.38 % capacity reserve may be insufficient, especially if a sudden health-care crisis occurs.

The product of waste amount and overall transportation distance is 33,576 km·t, which is the highest value of all the scenarios [9], [34]. The transportation scheme is in fig. 13.

Fig. 13 Transportation scheme of scenario 2. [32]

Some routes can be optimised by adding stops along the journey, especially for serving small producers with the waste production less than 12 t/a like the route starting in Nová Paka. The cargo space of vehicles serving Nová Paka would only be used at 12 % of capacity because, despite low production, infectious waste cannot be stored for more than a month. It seems efficient to serve the municipality of Hořice too. The route along Hořice is even 4 km shorter than the fastest route losing just 10 minutes as displayed on the map in the fig. 14.

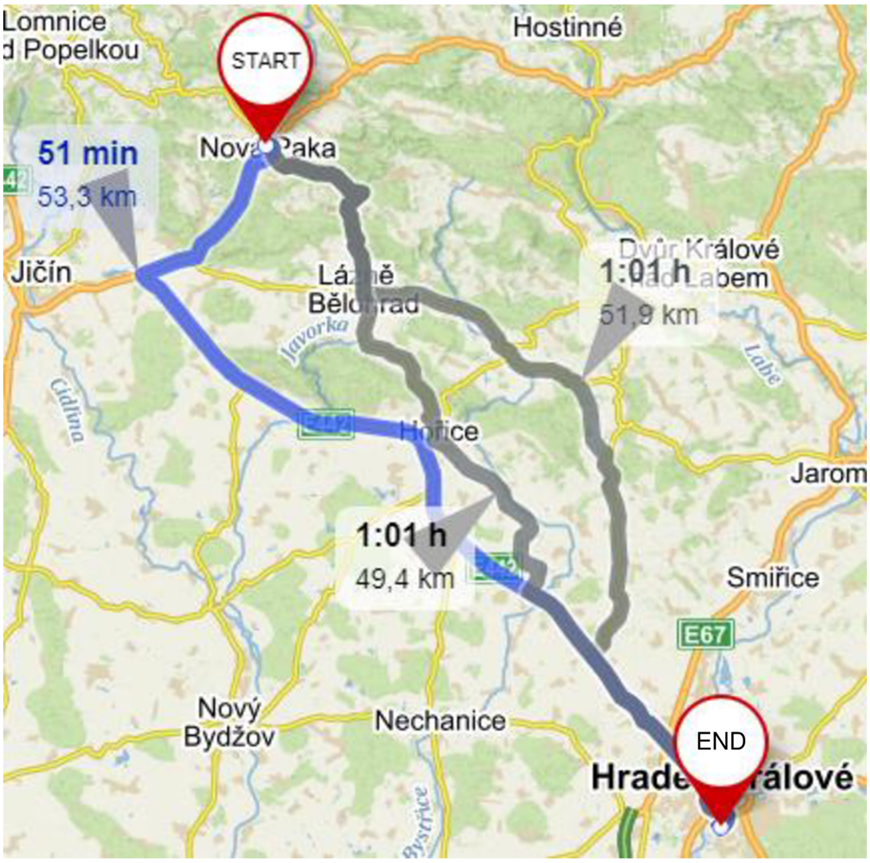

Fig. 14 Routes connecting Nová Paka and Hradec Králové. [35]

Alternatively, the route from Vrchlabí can be used in the same way. As shown on the map in the fig. 15, the fastest route between Vrchlabí and Hradec Králové is via Nová Paka.

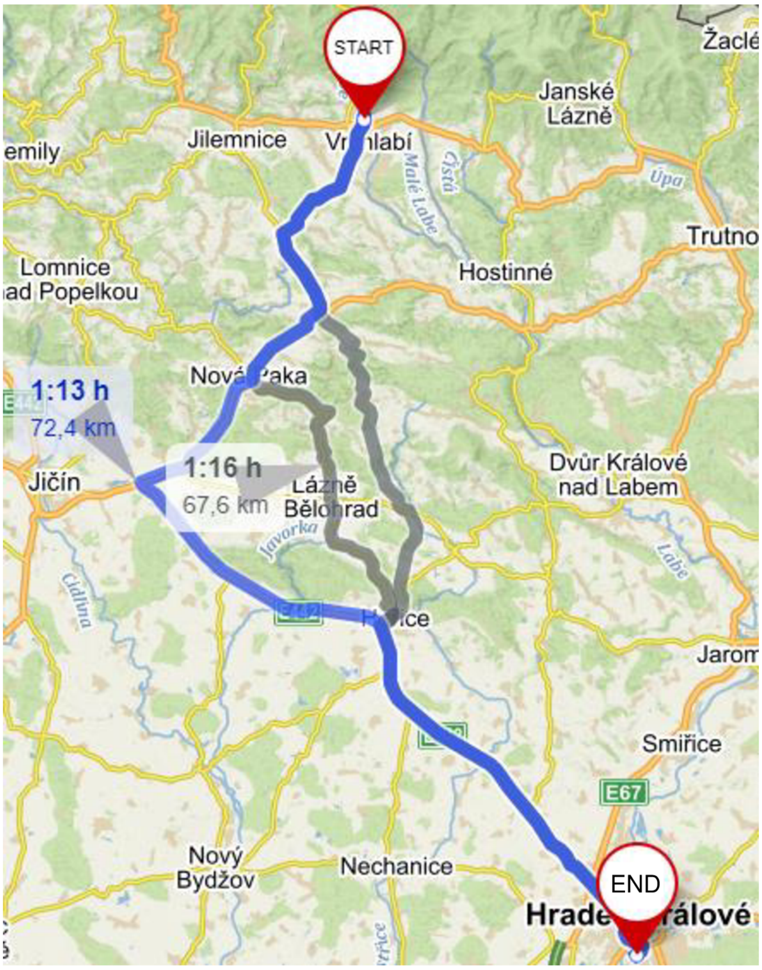

Fig. 15 Route connecting Vrchlabí and Hradec Králové. [35]

The adjustment slightly improves the fulfilment of all the priorities in those scenarios, where is only one incinerator – in Hradec Králové. The overall evaluation of the scenario 2 is in the tab. 10.

Tab. 10 Rating of scenario 2.

Environmental impact	**Health risk**	**Budget burden**
F 19.147 t/a	F 33,012 km·t/a	A 239 million CZK/a

The number of incineration plants has the major impact on costs. Therefore, the budget burden criterion has received the ‘A’ mark, even when the waste production rate was not decreased.

5.3 Scenarios with initial investment

Scenarios 3–9 include usage of advanced hot steam technology represented by the sterilisation crusher Converter. Its properties are described in the chapter 2.3. In each new scenario, the capacity of incineration plants is adjusted according to the new production rate affected by sterilisation crushers. In the scenarios in this chapter, the capacity of each incineration plant is equal to the projected new production rate increased by 25 % and rounded up to the higher whole hundreds.

The sterilisation shredder Converter from H-series for health-care waste applications is available in following models described in the tab. 11. The prices were provided by Ventos Energy Solutions, except for the smallest H25 model. The price of the model H25 was established based on the linear extrapolation of prices of models H50, H100 and H200. All dimensions are in the format of ‘length-width-height ‘.

Tab. 11 Converters of H-series [47], [50], [51].

Name	**Processing rate [kg/h]**	**Chamber volume [l]**	**Dimensions [m·m·m]**	**Dry weight [kg]**	**Total power [kW]**	**Price [million CZK]**
H25	4–6	25	0.6·0.7·0.9	110	2.8	1.5
H50	8–12	50	0.7·0.7·1.1	250	10	2.2
H100	15–20	100	1.5·1.1·1.4	1,000	55	5.2
H200	30–40	200	2.0·1.2·1.4	1,500	65	8.4
H400	60–80	400	2.3·1.5·1.8	2,200	100	12.2
H1000	150–200	1,000	6.7·2.5·5.9	12,000	260	21.9
H2000	250–350	2,000	6.7·2.5·6.5	14,000	360	30.4
H5000	500–600	5,000	8.0·2.5·6.5	16,000	520	41.0

Assuming 8,000 operating hours per year and one decontamination cycle taking 30 minutes, there are 14 efficient combinations of certain parameters summarised in the tab. 12. The first three sets are single crushers, because in case of a malfunction, untreated waste can be either stored for longer without the big demand on space or transported to the large capacity crushers in Trutnov or Hradec Králové. The rest of sets are always represented by crushers in pairs to avoid major issues in case of a malfunction. The amount of infectious waste produced in 2019 was multiplied by a factor of 1.25, then the set of the next higher processing rate was chosen. The prices are not part of the budget burden criteria.

Tab. 12 Sets of convertors [47], [50], [51].

Set No.	**Crushers**	**Processing rate [kg/h]**	**Processing rate [t/a]**	**Price [million CZK]**
I	H25	4–6	40	1.5
II	H50	8–12	80	2.2
III	H100	15–20	140	5.2
IV	H100 + H100	30–40	280	10.5
V	H200 + H100	45–60	420	13.7
VI	H200 + H200	60–80	560	16.8
VII	H400 + H200	90–120	840	20.6
VIII	H400 + H400	120–160	1,120	24.5
IX	H1000 + H400	210–280	1,960	34.1
X	H1000 + H1000	300–400	2,800	43.8
XI	H2000 + H1000	400–550	3,800	52.3
XII	H2000 + H2000	500–700	4,800	60.8
XIII	H5000 + H2000	750–950	6,800	71.4
XIV	H5000 + H5000	1,000–1,200	8,800	82.1

Scenario 3:

- Incinerators with decreased capacity in Hradec Králové (900 t/a) and in Trutnov (500 t/a).
- New crushers in Hradec Králové (set No. IX).

The university hospital in Hradec Králové is the biggest producer of infectious waste [9]. Shredding is the most efficient in this location because large-capacity crushers can work almost continuously. Continuous operation has a very high efficiency because the residual heat from previous shredding process is utilised [52]. This scenario reduces the amount of waste produced and burned in Hradec Králové by 50 % [24], however, it does not reduce the amount of transported waste, thus there is no improvement in rating compared to the scenario 1 as shown in the tab. 13.

Tab. 13 Rating of scenario 3.

Environmental impact	**Health risk**	**Budget burden**
D	E	F
13.397 t/a	23,099 km·t/a	426 million CZK/a

The budget is most affected by the number of incineration plants. Therefore, the rating does not significantly differ from the previous two scenarios. It was estimated that the incinerator in Hradec Králové with the decreased processing capacity of 900 t/a, would have operating cost of 211 million CZK per annum [30], [45], [46]. The incinerator in Trutnov, with the decreased capacity of 500 t/a, would cost 204 million CZK annually [30], [45], [46].

The University Hospital in Hradec Králové would be equipped with a set of Converter crushers H1000 and H400. Theoretically, if the crusher H1000 would have a malfunction, the remaining H400 crusher provides the period of 57 days to a solution. However, this considers a continuous H400 crusher operation 24 hours a day without any break, until the maximum allowed storage period for infectious waste of 30 days is broken (section 10, paragraph 5 of the Act No. 306/2012 Sb.). [47], [19]

Scenario 4:

- Incinerators with decreased capacity in Hradec Králové (1,000 t/a) and in Trutnov (250 t/a).
- New crushers in Hradec Králové (set No. IX) and Trutnov (set No. VI).

The scenario 4 shows that there is no significant difference (4 million CZK) in the budget burden between the state with thermal decontamination in Trutnov and without it. The major impact has the number of incinerator plants, not its capacity, because of the dominance of fixed costs.

Tab. 14 Rating of scenario 4.

Environmental impact	**Health risk**	**Budget burden**
D	E	F
13.397 t/a	23,099 km·t/a	422 million CZK/a

The Trutnov Regional Hospital would be equipped by the pair of H200 Converter crushers with total waste processing capacity of 560 t/a, which would have been 152 % of the utilised capacity in 2019 [9], [47]. The longest possible emergency continuous operation of only one crusher H200 is approximately 180 days.

Scenario 5:

- Incinerator with decreased capacity in Hradec Králové (1,100 t/a).
- New crushers in Hradec Králové (set No. IX) and Trutnov (set No. IV).

The conclusion from previous scenarios is that the major impact on the budget has the number of incinerators. In the scenario 2, there is only one incinerator in Hradec Králové. It is obvious that the best place for an incinerator is in Hradec Králové, because most of the waste is produced there [9]. It is also efficient to build up a crushing centre at the same place consisting of two Converter crushers, one H1000 and one H400, of the capacity of 1,960 t/a [47]. To decrease the health risk and environmental impact of transportation, it could be a good option to build up the set of sterilization crushers in the Trutnov Regional Hospital too. It would consist of the pair of H200 Converter crushers of the total capacity of 560 t/a [47]. The shredding centre in Trutnov would be also used for treating the waste from the two most remote municipalities Broumov (75.7 km to Hradec Králové [40]) and Vrchlabí (73.6 km to Hradec Králové [40]), where Trutnov is much closer as shown in the fig. 16, where the blue arrow represents the flow of contaminated waste.

Fig. 16 Transportation scheme of scenario 5. [32]

The results should be compared to the scenario 2, where is also only one incineration plant. Compare to the scenario 2, where both the environmental impact and the health risk criteria have the mark ‘F’, there is only a slight improvement to the mark ‘E’ in both, as summarized in the tab. 15. The budget criterion remains at the same mark. It is questionable whether it is worth investing extra 51 million CZK into sterilization crushers or not [50], [51].

Tab. 15 Rating of scenario 5.

Environmental impact	**Health risk**	**Budget burden**
E 17.052 t/a	E 22,696 km·t/a	A 225 million CZK/a

Scenario 6:

- Incinerators with decreased capacity in Hradec Králové (450 t/a) and in Trutnov (250 t/a).
- New crushers are where the production of infectious waste is greater than 3 t/a.

In this scenario, sterilization crushers are situated in main health-care facilities in the centres of those municipalities, where the production of infectious waste is greater than 3 t/a. This criterion of 3 t/a was set according to the fact, that the efficiency is higher when the crusher works continuously at least several cycles in a row [52]. The capacity of the smallest model 'H 25' of the Converter series is 4–6 kg/h [47]. When the waste flow is just 3 t/a and the crusher works 8,000 operating hours annually, the waste flow through the crusher would be equal to 0.375 kg/h on average, which is way less than its capacity. That means the crusher cannot work continuously, but should work at least once per 15 days in continuous operation all day long. The 15 days is the half of the maximum allowed storage period for infectious waste according to the Act No. 306/2012 Sb. [19]. The criterion is not met in two municipalities of the region: Nová Paka (1.4 t/a) and Kostelec nad Orlicí (1.8 t/a) [9]. The transportation scheme of this scenario is shown in the fig. 17.

Fig. 17 Transportation scheme of scenario 6. [32]

This solution improves environmental impact and health risk to the best level marked 'A'. The only health risk is posed from the small amount of transported infectious waste from Nová Paka and Kostelec and Orlicí. The rate of 829 km·t/a is in fact fictional. Despite the small waste production in both municipalities, there must be at least 24 journeys (12 there and 12 back again) per year, to respect the Act No. 306/2012 Sb. [19]. In case of the waste transport from Nová Paka and Kostelec nad Orlicí, the fictional waste production of 12 t/a is considered as the amount of the transported waste. It is considered that the number of journeys is more important for the health risk criteria than the transported mass itself.

Sterilization crushers used in this scenario are showed in the tab. 16. Most of them are the models H100 and H25 (six per each model), three H50 and only one H1000. The total initial investment is 80 million CZK.

Tab. 16 Sets of sterilization crushers in scenario 6 [9], [50], [51].

Municipality	Set No.	Models	Processing rate [t/a]	Processing capacity [t/a]	Utilisation [%]	Price [million CZK]
Broumov	I	H25	24.4	40	61 %	1.5
Dobruška	I	H25	30.7	40	77 %	1.5
Dvůr Králové nad Labem	I	H25	31.4	40	79 %	1.5
Hořice	II	H50	50.4	80	63 %	2.2
Hradec Králové	IX	H1000 + H400	931.6	1,960	48 %	34.1
Jaroměř	I	H25	27.5	40	69 %	1.5
Jičín	III	H100	100.7	140	72 %	5.2
Náchod	IV	H100 + H100	140.5	280	50 %	10.5
Nové Město nad Metují	I	H25	13.4	40	34 %	1.5
Nový Bydžov	II	H50	49.3	80	62 %	2.2
Rychnov nad Kněžnou	III	H100	74.5	140	53 %	5.2
Trutnov	IV	H100 + H100	125.4	280	45 %	10.5
Vrchlabí	II	H50	45.1	80	56 %	2.2
Total	–	–	1,644.9	3,240	51 %	79.6

The scenario is well comparable to the scenario 1, because there are 2 incineration plants in both scenarios. As shown in the tab. 12, the budget burden was slightly improved to the mark 'E', despite the major impact on the budget has the number of incinerators and this number remained the same. The environmental impact was improved from the mark 'D' to the best 'A', similarly the health risk criteria from 'E' to 'A'.

Tab. 17 Rating of scenario 6.

Environmental impact	Health risk	Budget burden
A 6.939 t/a	A 829 km·t/a	E 403 million CZK/a

Scenario 7:

- Incinerator with decreased capacity in Hradec Králové (1,100 t/a)
- New crushers are where the production of infectious waste is greater than 3 t/a.

The only difference between scenarios 6 and 7 is in the number of incineration plants. In this scenario, there is only one incinerator, located in Hradec Králové. The transportation scheme is shown in the fig. 18.

Fig. 18 Transportation scheme of scenario 7. [32]

Compared to the scenario 6, the budget burden criterion receives the best mark 'A'. However, there is a mild deterioration in environmental impact criterion to the mark 'B', because of the longer distances from northern municipalities to the incinerator in Hradec Králové. The health risk does not significantly differ, remains at the best mark 'A'.

Tab. 18 Rating of scenario 7.

Environmental impact	Health risk	Budget burden
B 10.036 t/a	A 1,032 km·t/a	A 221 million CZK/a

Scenario 8:

- Incinerators with decreased capacity in Hradec Králové (1,000 t/a), and in Trutnov (250 t/a).
- New crushers at all nine hospitals.

It is projected that it would be easier to handle infectious waste treatment in a hospital than elsewhere. There are nine hospitals in the region in the centre of following municipalities: Broumov, Dvůr Králové and Labem, Hradec Králové, Jaroměř, Jičín, Náchod, Nové Město nad Metují, Trutnov, and Vrchlabí [34]. The transportation scheme is shown in the fig. 19.

Fig. 19 Transportation scheme of scenario 8. [32]

The aim of this scenario is determining whether it is necessary to strictly follow the scenario 6 or building up new sets of crushers in remaining four municipalities (Dobruška, Hořice, Nový Bydžov, and Rychnov nad Kněžnou) should be avoided. Criteria's marks are shown in the tab. 19.

Tab. 19 Rating of scenario 8.

Environmental impact	**Health risk**	**Budget burden**
B 9.141 t/a	B 8,424 km·t/a	F 414 million CZK/a

The rating of scenario 8 shows a single-level decrease in every criterion compared to the criteria of the scenario 6.

Scenario 9:

- Incinerator with decreased capacity in Hradec Králové (1,300 t/a).
- New crushers at all nine hospitals.

Similarly like in the previous scenario 8, the aim is identifying the difference between building up shredders in each one municipality with the waste production higher than 3 t/a, or only there, where a hospital is already presented. The transportation scheme is shown in the fig. 20 and the scenario's rating in the tab. 20.

Fig. 20 Transportation scheme of scenario 9. [32]

Tab. 20 Rating of scenario 9.

Environmental impact	Health risk	Budget burden
A 6.002 t/a	B 8,005 km·t/a	A 220 million CZK/a

This solution moves the mark 'B' from the environmental impact in the scenario 7 to the health risk in this variant.

5.4 Evaluation

All the scenarios are briefly evaluated in the tab. 21 showing all the criteria and the potential investment in sterilization crushers.

Tab. 21 Evaluation of scenarios [50], [51].

Scenario No.	Environmental impact	Health risk	Budget burden	Investment in crushers [million CZK]
1	D	E	F	–
2	F	F	A	–
3	D	E	F	34.1
4	D	E	F	50.9
5	E	E	A	44.6
6	A	A	E	79.7
7	B	A	A	79.7
8	B	B	F	68.6
9	A	B	A	68.6

The number of incineration plants plays an important role in the budget burden, separating scenarios into only nearly two options, either the 'A' mark for one incineration plant or 'F' mark for two. The only exception is the scenario 6 receiving the 'E' mark for the smallest possible amount of incinerated waste, because of the application of sterilization crushers in those municipalities with extended powers, where the infectious waste production is above 3 t/a. Those were 13 municipalities out of 15.

The environmental impact and health risk criteria give similar results for all scenarios, differing in no more than one level of a mark. The environmental impact criterion is affected by the amount of transported waste no matter whether it is hazardous (infectious) or not, because only the amount of emitted CO_2 matters. Conversely, the health risk criterion is affected only by infectious waste transportation. Those two criteria are related, because of the way of the sterilization by crushers, which compress the output waste by roughly 50 % [24], resulting in the smaller total amount of transported waste.

Sterilization crushers proved they can decrease the CO_2 footprint from transportation in Hradec Králové Region by roughly 6–10 t/a if they are used in each municipality where the production rate of infectious waste is above 3 t/a. However, it is still a lot less than the carbon footprint from the electricity consumption of sterilization shredders, according to the current ways of power generation in the Czech Republic. The equivalent emission of CO_2 from the current way of power generation is 0.52 kg/kWh in the Czech Republic [53]. The quantity of CO_2 indirectly produced by sterilization shredders is for each scenario viewed in the tab. 22, showing that the argument of environmental impact is invalid under current conditions in the Czech Republic. However, the power generation in the Czech Republic is projected to reduce the carbon equivalent to zero between years 2033–2038 with the ban of coal-fired power stations [54].

Tab. 22 Indirect carbon footprint of sterilization crushers.

Scenario No.	Electric energy consumption of crushers [MWh/a]	CO_2 Equivalent [t/a]	CO_2 saved by lower transportation rate [t/a]
1	–	–	–
2	–	–	–
3	319	166	13
4	411	214	13
5	411	214	17
6	411	214	7
7	411	214	10
8	360	187	9
9	360	187	6

It is still questionable, whether the environmental impact is going to be improved after 2035 by lowing the amount of waste transported compared to the increase in the consumption of electrical energy. By that time, it is uncertain whether vehicles are still going to be powered by combustion engines that exhausts CO_2. In that case, the quantifier of the environmental impact would need to be updated.

Identifying the best-case scenario

The list of scenarios which were given an A from the respective criterion:

- Environmental impact: Scenarios 6 and 9.
- Health risk: Scenarios 6 and 7.
- Budget burden: Scenarios 2, 5, 7 and 9.

The scenarios with at least two A marks are scenarios 6, 7 and 9. The scenario 6 should be eliminated, because it was given mark E from budget burden.

The scenario 7 simulates the situation, in which sterilization crushers are situated in every single municipality with waste production above the limit of 3 t/a. The scenario 9 is almost the same as the scenario 7, but sterilization crushers are located just in hospitals, therefore it should be easier to find suitable premises and staff. The initial investment for the scenario 9 is lower by 11 million CZK. **The resulting best-case scenario is the scenario 9, where is only one incineration plant as part of the largest hospital of the region and there are different sets of sterilization shredders operating in each of total nine hospitals.**

If there would be no willingness to invest into sterilization shredders, there are only two available scenarios. Either combusting the waste in two incineration plants (the current state) or utilization of only the one in Hradec Králové. The number of incineration plants is the main impact factor on the budget. Two incineration plants give the 'budget burden' criterion the mark 'F', meanwhile only one incinerator improves it to the best mark 'A'. On the other hand, the other criteria have better marks for the scenario with two incineration plants (scenario 1), which is the current state, but the gap is not so significant as the one affecting budget.

5.5 Discussion and comparison with other studies

The approach presented in this thesis shows a good effort-to-achievement ratio. It should represent the golden mean between usual and complex mathematical approaches. The usual approach analyses just already existing solutions, in this case, only the shortest or quickest possible way to the nearest incinerator, creating only one option (presented as the scenario 1).

On the other hand, the complex mathematical approach is always coming from a vast number of inputs and multiple different experts must cooperate on it and there is a special software involved. One example of a special computing software is the tool NERUDA, which simulates waste flows on regional or international level [55]. The necessary inputs are economic and environmental priorities, treatment technologies and production data [55]. The accuracy of the software is affected by the quality of inputs because the algorithm divides a region *'in hundreds of nodes.' [55]* In this study, there are only 14 nodes presented as the centres of 'municipalities with extended powers.' To gain more nodes, it would be necessary to gain access to the data of waste production of single health-care facilities, which are currently unavailable for public.

Waste production data

The most exact way of gaining production data is obtaining them from each one health-care facility. There are roughly 4,500 health-care facilities in Hradec Králové Region [26]. Even if their production data were published, it would be time-consuming to process them, especially the dataset with distances between each facility and incineration plants.

On the other hand, the simplest approach (basic) would only reflect the number of beds in each hospital and the production rate would be obtained by multiplying for example the number of beds or the number of doctor's offices by a certain factor. Various expert sources report annual infectious waste production rates:

- 36 kg/bed – a study from the United Kingdom [56],
- 69–321 kg/bed – a study from Taiwan [57],
- 88 kg/bed – a study from Uganda [58],
- 91–165 kg/bed – a study from Iran [59],
- 110 kg/bed – a study from Pakistan [60],
- 120 kg/bed – a study from Greece [61].
- 172 kg/bed – a study from Bangladesh [62].

However, the resulting production calculated from whatever production rate mentioned in the previous paragraph can match with the official Czech data of waste production in municipalities. For example, the University Hospital in Hradec Králové had 1,375 beds in 2019 [63] and the long-term care hospital in the same city has currently 94 beds [64], while the production rate of the infectious waste in the whole municipality of Hradec Králové was 929.8 t in 2019 [9]. If those facilities were the only two facilities in the municipality, it would result in the production rate of 633 kg per bed. In conclusion, considering the number of beds, the multiplication factor is naturally very inaccurate way of estimating a waste generation rate.

A different approach was used in another study from the Czech Republic, which was focused on the Zlín Region. The production data in that study were obtained directly from those four hospitals and consulted with a waste disposal company, which means, that the data must be exact [28]. The study was focused only on the medical waste transportation from four main hospitals of the region to an incineration plant [28]. The amount of waste per bed was not mentioned in the study, but the infectious waste production factor, based on the waste production in those four hospitals (946.3 t/a [28]) and the sum of beds in each one of them (2,236 beds [65], [66], [67], [68]) can be estimated at 423 kg/bed.

The case-study in this thesis did not use any factor of waste generation per bed nor official production waste disposal data from each health-care facility. The waste production data were obtained from the public database of the Ministry of the Environment of the Czech Republic [9]. The database shows production rates of infectious waste in 14 'municipalities with extended powers' located in the studied region. The centre of a municipality or a dominant health-care facility of a municipality were considered as the place where all the waste is produced, because there are roughly 4,500 health-care facilities in the region [33], and it would not be efficient to obtain production data of all of them. Therefore, the approach presented in this thesis seems to be the most efficient one.

Different region application and generalization

The method can be algorithmized and applied on every region of the Czech Republic, including the capital city. An algorithm of scenarios can be even applied on the entire country, because the whole country is divided into defined number of municipalities and the capital city districts. There are more than 200 'municipalities with extended powers' in the Czech Republic and 22 Prague city districts. However, in case of the whole country, there would be a lot of possible options, therefore the definition of possible scenarios should also be algorithmized.

The production rates of any kind of waste of each municipality or district are published by the Ministry of the Environment and the dataset is publicly available [9]. Processing capacity of 22 incineration plants, that burn medical waste in the Czech Republic, are publicly available at Czech Hydrometeorological Institute [7]. In other countries, the limitation is in the presence of input data in required format and several changes would need to be made in costs, especially in payroll costs, but the classification of environmental impact and health risk criteria can remain the same as for the Czech Republic. In other surrounding countries of the Czech Republic – Austria, Germany, Poland, and Slovakia, no such database, that displays production of medical waste in small districts, was found.

Waste transportation

This thesis does not cover the waste transportation inside each one of 14 municipalities, but the waste collection problem is simplified, thus, assumed that there are only 14 waste producers and no more than 2 incineration plants. Solving more complex transportation problems requires usage of special software algorithms, waste production data and waste producers' locations. The similar study of the Zlín Region deals with only four producers and only one incineration plant, creating only two possible scenarios [28]. The purpose of the scenarios in the mentioned study is deciding whether each one hospital should have its own vehicle for the waste transportation, or it would be more efficient to use only two common vehicles [28]. Additionally, the comparison of four different vehicles was made considering several factors like: price, weight, fuel consumption, cargo space capacity, tire type, amortization, toll, and other fees [28]. The study presented in this thesis does not solve the problem of vehicle election or the number of vehicles required. The transportation costs are calculated in general, based on the price list of one selected transportation company, when referring to non-infectious waste transport. When referring to infectious waste transport, only one vehicle is assumed, and costs are calculated according to the data from the case-study of the Zlín Region [28].

If the presented method is applied on the entire country, not on separate regions, the dataset would be too big, and an advanced tool needs to be applied [69]. However, the problem is not as complicated as the optimalization for municipal solid waste collection, because there are much less producers. Generally, it would be necessary to perform rigorous pre-processing [69]. After that, it is possible to use a heuristic approach, for example utilizing the Adaptive Large Neighbourhood Search algorithm [69], [70]. For a traffic model, several options could be assumed. One study dealing with this problem is the study from the United Kingdom, which focuses particularly on infectious waste from pharmacies that treat waste from patients in homecare [70]. There are 3 general scenarios specified in the mentioned study:

- The scenario of 85 %: The pharmacy calls a waste-transport operator whenever 85 % of their storage capacity is reached. [70]
- The scenario of threshold: Similarly like at the previous scenario, but high reactivity of a waste-transport operator is required. [70]
- The scenario of the rolling horizon: Solutions are revised every day according to actual data. [70]

Another study from the Czech Republic shows a complex methodology of municipal waste transportation, which is a little different, because the certification of the Agreement of concerning the International Carriage of Dangerous Goods by Road (ADR) is not needed and there are more possible nodes. The methodology begins with the analysis of the relation between the gate fee in an incineration plant and its capacity [55]. Then the NERUDA optimalisation software tool is utilised to show the best-case scenario of transportation [55]. A studied area is also divided into municipalities (sub-regions), it also utilises a traffic network between those nodes (road and rail network) [55]. The software tool bypasses the heuristic approach of creating possible scenarios, presented in this thesis, by a complex mathematical model [55]. However, the study admits inaccuracies, when dealing with hardly predictable input parameters [55].

Evaluation

Scenarios were evaluated according to the marks which the criteria received according to the methodology. However, the weightage of each criterion was not considered. In case of practical utilisation of the presented methodology, it would be necessary to assign a relative weightage to each criterion. After that, one solution would be using the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). The technique relies on a simple mathematical model, which utilises the Euclidean distance. According to the TOPSIS, the best case-scenario is the one with the longest Euclidean distance between the ideal best solution and the ideal worst solution. [71]

6 Conclusion

The aim of the concept of infectious waste management at the regional level is showing what results can be achieved by a heuristic approach of creating several possible scenarios without the utilization of any advanced software algorithms. The aim was fulfilled by using methodology which was set up with knowledge and relatively simple calculation formulas from many different expert sources.

The concept development was aimed at determining the level of environmental impact, health risk and budget burden of each scenario. These three criteria were evaluated according to the methodology, which was defined in the theoretical part of the thesis. The evaluation showed that:

- **The environmental impact** represented by the carbon footprint was mostly affected by the amount of waste that is processed by sterilization crushers. Sterilisation crushers reduce waste mass and volume and thus the number of journeys required for waste shipping is lowered along with the carbon footprint. The positive effect might be questioned in some countries because it also depends on the carbon equivalent of the electricity consumed by the shredders. However, most of the electrical energy in the European Union is produced from renewable sources and the share of fossil fuels rapidly decreases over time [72].
- **The health risk** was quantified according to the amount infectious waste shipment. This criterion was also mostly affected by the utilisation of sterilisation shredders, as well as the environmental impact. The number of incineration plants also had an influence on both environmental impact and health risk criteria, but the effect of sterilization crushers was greater.
- **The budget burden** was roughly estimated considering many variables. During calculations, the number of hazardous waste incinerators was found to have virtually the only effect on the outcome. Using one incineration plant instead of two proved to be a cheaper solution. The second largest impact was the capacity of these incinerators.

In the evaluation, the Scenario 9 was chosen as the best-case scenario, because it is most in line with the criteria mentioned above. In the scenario, there was only one incineration plant as a part of the largest hospital of the region in the city of Hradec Králové and different sets of sterilization shredders operating in each of all nine hospitals in the region. Only one incineration plant caused low budget burden and the high rate of sterilization meant a good result in both environment impact and health risk criteria. However, there were other scenarios with even better results, but those were eliminated because the operation of the crushers in other health-care facility than a hospital seems to be problematic. Hospitals probably already employ staff in charge of waste management and introducing new procedures would certainly not be as complicated for them as for other health establishments. This was not included in the methodology, but it was clear that the result needed to be adjusted based on practical considerations.

Many of the ideas presented in the methodology and the thesis itself would have been worth exploring further. For example, the qualification of the environmental impact. It is questionable whether the CO_2 production is the best environmental impact indicator because in fact, the only disadvantage of the CO_2 emissions is that the CO_2 causes the greenhouse effect in the atmosphere. For example, the decontamination by wet steam is for sure a source of sewage water that somehow needs to be cleaned. The total amount of pollutants released with the sewage water can possibly be another quantifier of the environmental impact.

Another topic that could be furtherly studied is the idea of separate regions that are self-sufficient in waste management. The methodology presented in the chapter 3 of this thesis cannot compare the state of interregional waste management (the current state) with the presented idea of waste management within separate regions due to the lack of publicly available data regarding waste transportation. Therefore, it is still not clear whether it is the right idea or not.

List of sources

[1] Risks associated with health-care waste. CHARTIER, Yves, Jorge EMMANUEL, Ute PIEPER, et al. Safe management of wastes from health-care activities. [online]. Second edition. Geneva: World Health Organization, 2014, s. 25–41 [cit. 2021-5-1]. ISBN 978-92-4-154856-4. Avalaible at: https://apps.who.int/iris/bitstream/handle/10665/85349/9789241548564_eng.pdf;jsessionid=A9A4316BD44ED607E8EC359D68F5B0C6?sequence=1

[2] EUROPEAN UNION. Commission Decision of 18 December 2014 amending Decision 2000/532/EC on the list of waste pursuant to Directive 2008/98/EC of the European Parliament and of the Council. In: Official Journal of the European Union. Brussels: EUR-Lex, 2014, 2014/955/EU. Available also at: https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:32014D0955

[3] EUROPEAN UNION. Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives. In: Official Journal of the European Union. Strasbourg: EUR-Lex, 2008. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02008L0098-20180705

[4] Metodika pro nakládání s odpady ze zdravotnických, veterinárních a jim podobných zařízení [online]. Praha: Státní zdravotní ústav, 2016 [cit. 2020-11-20]. Available at: https://www.mzp.cz/C1257458002F0DC7/cz/nakladani_s_odpady_zdravotnictvi/$FILE/OODP-metodika_zdravotnicke_odpady-20170424.pdf

[5] Informace o spalovně: Fakultní nemocnice v Motole. Czech Hydrometeorological Institute [online]. Prague: Ministry of the Enviroment of the Czech Republic, c2020, 15.10.2020 [cit. 2020-12-29]. Avalaible at: https://www.chmi.cz/files/portal/docs/uoco/web_generator/incinerators/728951001_CZ.html

[6] Informace o spalovně: SUEZ CZ a.s. – Spalovna NO Ostrava. Czech Hydrometeorological Institute [online]. Prague: Ministry of the Enviroment of the Czech Republic, c2020, 15.10.2020 [cit. 2021-01-11]. Avalaible at: https://www.chmi.cz/files/portal/docs/uoco/web_generator/incinerators/713838061_CZ.html

[7] Podklady pro oblast podpory odpadového a oběhového hospodářství OPŽP 2021 – 2027: Nakládání s nebezpečnými odpady – odpady ze zdravotní péče [online]. London: Ernst and Young, 2020 [cit. 2021-04-16]. Avalaible at: https://www.mzp.cz/C1257458002F0DC7/cz/odpadove_obehove_hospodarstvi/$FILE/OODP-7_Zdravotnicke_odpady-20200529.pdf

[8] Abfallentsorgung: Fachserie 19 Reihe 1 – 2017. In: Destatis: Statistisches Bundesamt [online]. Wiesbaden: Statistisches Bundesamt (Destatis), c2020, 24.06.2019 [cit. 2020-11-20]. Available at: https://www.destatis.de/DE/Themen/Gesellschaft-Umwelt/Umwelt/Abfallwirtschaft/Publikationen/Downloads-Abfallwirtschaft/abfallentsorgung-2190100177005.xlsx?__blob=publicationFile

[9] Veřejné informace o produkci a nakládání s odpady. Informační systém odpadového hospodářství [online]. Praha: Inisoft [cit. 2020-11-20]. Available at: https://isoh.mzp.cz/VISOH/

[10] BJÖRNBERG, Arne and Ann Y. PHANG. Euro Health Consumer Index 2018: Report [online]. Marseillan: Health Consumer Powerhouse, 2019 [cit. 2020-11-20]. ISBN 9789198068757. Available at: https://healthpowerhouse.com/media/EHCI-2018/EHCI-2018-report.pdf

[11] GARWIN, Michael L. Infectious waste management: a practical guide. Boca Raton: CRC Press, February 24, 1995, s. 5–15. ISBN 9780873716376.

[12] TYPLTOVÁ, Jolana. Hospitals in the Czech Republic in 2013 [online]. 5/2014. Praha: ÚZIS ČR, 2014 [cit. 2021-5-8]. Avalaible at: https://www.uzis.cz/sites/default/files/knihovna/ai_2014_05.pdf

[13] Spalovny NO, Energetické využití. BURSA, Karel, Jitka KLUZOVÁ, Zuzana STEHLÍKOVÁ, Lukáš TOMAN, Jana TRACHTOVÁ, Gabriela ČERNÁ and Vlastimil BOHÁČ. Plán odpadového hospodářství Královéhradeckého kraje 2016-2025 [online]. Prague: ISES, 2015, s. 153 [cit. 2020-12-29]. Avalaible at: http://www.kr-kralovehradecky.cz/assets/krajsky-urad/ziv-prostredi-zemedelstvi/aktuality/EIA/POH-HK_final.pdf

[14] Definition and characterization of health-care waste. PRÜSS, A., E. GIROULT and P. RUSHBROOK. Safe management of wastes from health-care activities [online]. Geneva: World Health Organization, 1999, s. 3–23 [cit. 2020-11-28]. ISBN 9241545259. Avalaible at: https://www.who.int/water_sanitation_health/medicalwaste/077to112.pdf?ua=1

[15] EUROPEAN UNION. Commission notice on technical guidance on the classification of waste. In: Official Journal of the European Union. Brussels: Publications Office of the European Union, 2018, C/2018/1447. Available also at: https://op.europa.eu/en/publication-detail/-/publication/6009e0ad-3b81-11e8-b5fe-01aa75ed71a1

[16] LoW_EWC Stat Conversion. In: European Comission [online]. Brussels: European Union, c1995–2020, 16.06.2020 [cit. 2020-11-19]. Available at: https://ec.europa.eu/eurostat/documents/342366/0/LoW_EWC-Stat+Conversion/0d019dec-3454-47f7-910d-41c6df657aa6

[17] CZECH REPUBLIC. Zákon o odpadech. In: Sbírka zákonů. Zlín: Zákony pro lidi, 2020, Částka 222/2020, 541/2020. Avalaible at: https://www.zakonyprolidi.cz/cs/2020-541/zneni-20210101#p158_p158-1

[18] CZECH REPUBLIC. Vyhláška o Katalogu odpadů a posuzování vlastností odpadů (Katalog odpadů). In: Sbírka zákonů. Zlín: AION, 2021, 5/2021, 8/2021. Avalaible at: https://www.zakonyprolidi.cz/cs/2021-8

[19] CZECH REPUBLIC. Vyhláška o podmínkách předcházení vzniku a šíření infekčních onemocnění a o hygienických požadavcích na provoz zdravotnických zařízení a ústavů sociální péče. In: Sbírka zákonů. Zlín: Základy pro lidi, 2012, 109/2012, 306/2012. Available at: https://www.zakonyprolidi.cz/cs/2012-306

[20] Generation of waste by waste category, hazardousness and NACE Rev. 2 activity. European Comission [online]. Brussels: European Union, c1995–2020, 22/10/2020 [cit. 2020-11-30]. Available at: https://ec.europa.eu/eurostat/databrowser/view/env_wasgen/default/table?lang=en

[21] Population on 1 January by age and sex. European Comission [online]. Brussels: European Union, c1995–2020, 03/07/2020 [cit. 2020-11-30]. Available at: https://ec.europa.eu/eurostat/databrowser/view/demo_pjan/default/table?lang=en

[22] Treatment and disposal methods. PRÜSS, A., E. GIROULT and P. RUSHBROOK. Safe management of wastes from health-care activities [online]. Geneva: World Health Organization, 1999, s. 107–116 [cit. 2020-11-28]. ISBN 9241545259. Avalaible at: https://www.who.int/water_sanitation_health/medicalwaste/077to112.pdf?ua=1

[23] VERONESI, Paolo, Cristina LEONELLI, Umberto MOSCATO, Angelo CAPPI and Ornella FIGURELLI. Non-incineration Microwave Assisted Sterilization of Medical Waste. Journal of Microwave Power and Electromagnetic Energy [online]. Mechanicsville: International Microwave Power Institute, 2016, 40(4), 211-218 [cit. 2021-02-05]. ISSN 0832-7823. doi: 10.1080/08327823.2005.11688546

[24] Converter [online]. Torino: Ompeco, 2017 [cit. 2021-02-14]. Avalaible at: https://www.ompeco.com/ompeco/downloads/Converter_EN_web.pdf

[25] KOVÁŘ, Lukáš. Methods of Infectious Waste Management from Hospital Operations [online]. Brno, 2018 [cit. 2021-02-16]. Avalaible at: https://www.vutbr.cz/www_base/zav_prace_soubor_verejne.php?file_id=174067. Bachelor's thesis. Brno University of Technology, Faculty of Mechanical Engineering. Supervisor Eva Konečná.

[26] Wet and dry thermal treatment. PRÜSS, A., E. GIROULT and P. RUSHBROOK. Safe management of wastes from health-care activities [online]. Geneva: World Health Organization, 1999, s. 98–105 [cit. 2020-11-28]. ISBN 9241545259. Available at: https://www.who.int/water_sanitation_health/medicalwaste/077to112.pdf?ua=1

[27] SURYAWAN, Wayan, Gita PRAJATI and Anshah AFIFAH. Bottom and fly ash treatment of medical waste incinerator from community health centres with solidification/stabilization. In: Exploring Resources, Process and Design for Sustainable Urban Development: Proceedings of the 5th International Conference on Engineering, Technology, and Industrial Application (ICETIA) 2018 [online]. College Park: AIP Conference Proceedings, 2019, 26 June 2019, s. 2–6 [cit. 2021-01-11]. ISBN 978-0-7354-1850-9. doi: https://doi.org/10.1063/1.5112467

[28] GREGOR, Jiří. Logistika nemocničních odpadů ve Zlínském kraji: Případová studie. Brno, duben 2019.

[29] Module 1: Definition, Sources and Characteristics of Healthcare Waste. In: Training modules in health-care waste management [online]. Geneva: World Health Organization, 2013 [cit. 2021-03-08]. Avalaible at: https://www.who.int/water_sanitation_health/facilities/waste/module1.pdf?ua=1

[30] UCEKAJ, Vladimír. Analysis of municipal solid waste treatment possibilities in microregion [online]. Brno, 2010 [cit. 2021-03-05]. Avalaible at: https://www.vutbr.cz/www_base/zav_prace_soubor_verejne.php?file_id=33298. PhD Thesis. Brno University of Technology, Faculty of Mechanical Engineering. Supervisor Ladislav Bébar.

[31] HUSTOLES. Map of municipalities with extended powers in the Czech Republic. In: Wikipedia: the free encyclopedia [online]. San Francisco (CA): Wikimedia Foundation, 2021, 3 January 2016 [cit. 2021-04-11]. Edited. Avalaible at: https://commons.wikimedia.org/wiki/File:ORP.PNG

[32] Správní obvody. In: Czech Statistical Office [online]. Prague, 2021, 22.12.2020 [cit. 2021-02-06]. Avalaible at: https://www.czso.cz/csu/xh/spravni_obvody

[33] Celkový přehled zdravotnických zařízení. Regionální zpravodajství NZIS: Královéhradecký kraj [online]. Prague: ÚZIS ČR, 2016, 2017 [cit. 2021-04-06]. Avalaible at: https://reporting.uzis.cz/hkk/index.php?pg=statisticke-vystupy--infrastruktura-zdravotni-pece--prehled-zdravotnickych-zarizeni--celkovy-prehled-zdravotnickych-zarizeni

[34] Mapy.cz [online]. Prague: Seznam.cz, c2020 [cit. 2020-03-15]. Avalaible at: en.mapy.cz

[35] Královéhradecký kraj. Population of administrative territories of municipalities with extended powers, 1 January 2020 [online]. Prague: Czech Statistical Office, 2020, p. 2 [cit. 2020-12-29]. Avalaible at: https://www.czso.cz/documents/10180/121739326/1300722002.pdf/aee54b9c-afaf-4d58-8532-270d3fa4d40d?version=1.1

[36] University Hospital Hradec Králové. University Hospital Hradec Králové [online]. Hradec Králové: FN HK, c2020 [cit. 2020-12-29]. Avalaible at: http://eng.fnhk.cz/about-hospital/about-us

[37] Informace o spalovně: Fakultní nemocnice Hradec Králové – Spalovna NO, kotelna + kotel CERTUS. Czech Hydrometeorological Institute [online]. Prague: Ministry of Health of the Czech Republic, c2020, 15.10.2020 [cit. 2020-12-29]. Avalaible at: https://www.chmi.cz/files/portal/docs/uoco/web_generator/incinerators/646870171_CZ.html

[38] Informace o spalovně: Oblastní nemocnice Trutnov a.s. – Spalovací zařízení spalující plynná paliva, Spalovna nemocničního odpadu. Czech Hydrometeorological Institute [online]. Prague: Ministry of Health of the Czech Republic, c2020, 15.10.2020 [cit. 2020-12-29]. Avalaible at: https://www.chmi.cz/files/portal/docs/uoco/web_generator/incinerators/769020371_CZ.html

[39] Informace o spalovnách za rok 2019: Seznam zařízení pro tepelné zpracovávání odpadu. Czech Hydrometeorological Institute [online]. Prague: Ministry of Health of the Czech Republic, c2020 [cit. 2020-12-29]. Avalaible at: https://www.chmi.cz/files/portal/docs/uoco/web_generator/incinerators/index_CZ.html

[40] Mapy.cz [online]. Prague: Seznam.cz, c2020 [cit. 2020-12-29]. Avalaible at: https://en.mapy.cz/s/cozadojese

[41] Spalovny NO. BURSA, Karel, Jitka KLUZOVÁ, Zuzana STEHLÍKOVÁ, Lukáš TOMAN, Jana TRACHTOVÁ, Gabriela ČERNÁ and Vlastimil BOHÁČ. Plán odpadového hospodářství Královéhradeckého kraje 2016-2025 [online]. Prague: ISES, 2015, s. 57 [cit. 2020-12-30]. Avalaible at: http://www.kr-kralovehradecky.cz/assets/krajsky-urad/ziv-prostredi-zemedelstvi/aktuality/EIA/POH-HK_final.pdf

[42] HAQUE, Sazzadul, Shariar UDDIN, Sayed SAYEM and Kazi MOHIB, XIWANG, Zhang, ed. Coronavirus disease 2019 (COVID-19) induced waste scenario: A short overview. Journal of Environmental Chemical Engineering [online]. Amsterdam: Elsevier, 7 November 2020, [cit. 2021-01-07]. ISSN 2213-3437. doi: https://doi.org/10.1016/j.jece.2020.104660

[43] Spočítejte si, kolik emisí CO2 vyprodukuje Vaše auto. Ekoblog: technologie a životní prostředí [online]. Brandýs nad Labem – Stará Boleslav: Chamanne, c2007–2014 [cit. 2021-03-11]. ISSN 1803-6252. Avalaible at: http://www.ekoblog.cz/?q=emise

[44] BUSTA, Michal. Test: Renault Master – valník s plachtou [online]. Prague: BusinessCar, c2020, 24 June, 2018 [cit. 2021-03-11]. Avalaible at: https://www.business-car.cz/uzitkove-vozy/test-renault-master-valnik-s-plachtou

[45] Průměrná mzda: vývoj průměrné mzdy. Kurzycz [online]. Prague: Kurzy.cz, c2000–2021, 04.12.2020 [cit. 2021-03-10]. Avalaible at: https://www.kurzy.cz/makroekonomika/mzdy/

[46] Inflace: míra inflace a její vývoj v ČR. Kurzycz [online]. Prague: Kurzy.cz, c2000–2021, 12.02.2021 [cit. 2021-03-10]. Avalaible at: https://www.kurzy.cz/makroekonomika/inflace/

[47] Technical Specifications: Converter Serie H Models. Ompeco [online]. Torino: Ompeco, c2021 [cit. 2021-03-09]. Avalaible at: https://www.ompeco.com/h-serie-2/

[48] Ceny elektrické energie 2021. TZB-info [online]. Prague: Topinfo, c2001-2020 [cit. 2021-03-09]. Avalaible at: https://www.tzb-info.cz/ceny-paliv-a-energii/14-prehled-cen-elektricke-energie

[49] Ceník. Multitrans CZ: Mezinárodní a vnitrostátní kamionová doprava [online]. Pardubice: Multitrans CZ, c2016 [cit. 2021-03-03]. Avalaible at: https://www.multitrans.cz/cenik/

[50] Kurz Eura. Kurzycz [online]. Prague: AliaWeb, c2000–2021, 25.03.2021 [cit. 2021-03-25]. Avalaible at: https://www.kurzy.cz/kurzy-men/nejlepsi-kurzy/EUR-euro/

[51] GRELICH, Leoš. Infected waste prices and technical data. Prague, 2020.

[52] KONEČNÁ, Eva and Michal TOUŠ. Analýza aktuálního stavu nakládání s infekčním odpadem v ČR. Brno, 8.12. 2017

[53] NOVOTNÝ, Jiří and Tomáš MATUŠKA. Emise CO2 a jejich dopad na hodnocení zdrojů v budovách. TZB-info [online]. Prague: Topinfo, c2001–2021, 19.03.2018 [cit. 2021-03-29]. ISSN 1801-4399. Avalaible at: https://vytapeni.tzb-info.cz/provoz-a-udrzba-vytapeni/17112-emise-co2-a-jejich-dopad-na-hodnoceni-zdroju-v-budovach

[54] PETŘÍČEK, Martin. Konec uhlí štěpí českou vládu. Prodloužení odchodu se ale může prodražit. Idnes.cz [online]. Prague: MAFRA, c1999–2021, 24.03.2021 [cit. 2021-03-29]. Avalaible at: https://www.idnes.cz/ekonomika/domaci/uhli-ekologie-konec-politika.A210323_202507_ekonomika_kou

[55] PAVLAS, Martin. NERUDA: tool for simulation of waste flows at regional and/or international level. Process Engineering [online]. Brno: Brno University of Technology, c2021 [cit. 2021-04-03]. Avalaible at: https://upi.fme.vutbr.cz/veda-vyzkum/neruda/

[56] TUDOR, Terry L., Margaret P. BATES, Anne C. WOOLRIDGE, Margaret P. BATES, Sharon PHILLIPS and Keith JONES. Utilizing a 'systems' approach to improve the management of waste from healthcare facilities: best practice case studies from England and Wales. Waste Management and Research [online]. Thousand Oaks: SAGE Publishing, 2008, 21 May 2007, 26, 233–240 [cit. 2021-04-06]. ISSN 0734–242X. Avalaible at: https://journals.sagepub.com/doi/pdf/10.1177/0734242X07081482

[57] CHENG, Y.W., F.C. SUNG, Y. YANG, Y.H. LO, Y.T. CHUNG and K.C. LI. Medical waste production at hospitals and associated factors. Waste Management [online]. Amsterdam: Elsevier, 2008, 17 January 2008, 29(1), 440-444 [cit. 2021-04-06]. ISSN 0956-053X. Avalaible at: doi: https://doi.org/10.1016/j.wasman.2008.01.014

[58] MUGAMBE, Richard, John SSEMPEBWA, Nazarius TUMWESIGYE, Bas VAN VLIET and Adebola ADEDIMEJI. Healthcare waste management in Uganda: management and generation rates in public and private hospitals in Kampala. Journal of Public Health [online]. Heidelberg: Springer Nature B.V, 2012, 20(3), 245-251 [cit. 2021-04-06]. ISSN 2198-1833. Avalaible at: doi:10.1007/s10389-011-0459-6

[59] HADIPOUR, Marzieh, Shabnam SAFFARIAN, Mohsen SHAFIEE and Soode TAHMASEBI. Measurement and management of hospital waste in southern Iran: a case study. Journal of Material Cycles and Waste Management [online]. Tokyo: Springer Japan, 2014, 16(4), 747-752 [cit. 2021-5-8]. ISSN 1438-4957. Doi: 10.1007/s10163-013-0214-x

[60] ULLAH, Junaid Habib, Khurshed AHMAD and M. Amanullah KHAN. Managing the healthcare solid waste in selected Districts of Punjab, Pakistan. Pakistan Journal of Medical Sciences [online]. Karachi: Professional Medical Publications, 2010, Oct 2010, 26(4), 795-799 [cit. 2021-04-06]. ISSN 1682-024X. Avalaible at: https://www.pjms.org.pk/index.php/pjms

[61] KOMILIS, Dimitrios, Nikolaos KATSAFAROS and Panagiotis VASSILOPOULOS. Hazardous medical waste generation in Greece: case studies from medical facilities in Attica and from a small insular hospital. Waste management & research [online]. London, England: SAGE Publications, 2011, 29(8), 807-814 [cit. 2021-04-06]. ISSN 0734-242X. doi: 10.1177/0734242X10388684

[62] ALAM, Md Maksud, Mohammad SUJAUDDIN, Gazi Mohammed Asif IQBAL and Syed Mohammed Shamsul HUDA. Waste Management and Research [online]. Thousand Oaks: SAGE Publishing, 2008, June 1, 2008, 26(3), 291–296 [cit. 2021-04-06]. ISSN 1096-3669. Avalaible at: doi: 10.1177/0734242X07087661

[63] Základní kapacitní a výkonové ukazatele FN. Výroční zpráva za rok 2019 [online]. Hradec Králové: Fakultní nemocnice Hradec Králové, 2020, s. 16 [cit. 2021-04-06]. Avalaible at: https://www.fnhk.cz/fs3075/vz-2019-web.pdf

[64] Léčebna pro dlouhodobě nemocné v Hradci Králové [online]. Hradec Králové: Petr Bláha, c2021 [cit. 2021-04-06]. Avalaible at: https://www.ldnhk.cz/

[65] Nemocnice. Krajská nemocnice Tomáše Bati ve Zlíně [online]. Zlín: Krajská nemocnice Tomáše Bati ve Zlíně, c2012 [cit. 2021-04-10]. Avalaible at: https://www.kntb.cz/nemocnice

[66] Základní ukazatele jednotlivých oddělení nemocnice. Kroměřížská nemocnice: Výroční zpráva za rok 2019 [online]. Kroměříž, 2020, s. 10 [cit. 2021-04-10]. Avalaible at: https://www.nem-km.cz/webfiles/soubory-ke-stazeni/kmn_vyrocni_zprava_2019.pdf

[67] Jednotlivá oddělení nemocnice. Výroční zpráva: Uherskohradišťské nemocnice za rok 2019 [online]. Zlín, 2020, s. 21 [cit. 2021-04-10]. Avalaible at: https://www.nemuh.cz/doc/00864a38-3bb5-11eb-a10f-525400006c3f/@@download

[68] Základní ukazatele jednotlivých oddělení nemocnice. PROUSKOVÁ, Věra, Lenka PLAČKOVÁ, Martin PAVLICA, Libor CZEFFER, Martin RAIS, Ladislav KAŠPAR, Ivana MIKULOVÁ a Barbora ZIENTEK. Výroční zpráva 2019 [online]. Vsetín: Vsetínská nemocnice, 2020, s. 34 [cit. 2021-04-10]. Avalaible at: https://nemocnice-vs.cz/wp-content/uploads/2020/07/12_38_V%C3%9DRO%C4%8CN%C3%8D_ZPR%C3%81VA_VN_2019_2_%C4%8CERVNA_2020_IMP.pdf

[69] NEVRLÝ, Vlastimír, Radovan ŠOMPLÁK and Pavel POPELA. Heuristics for Waste Collection Arc Routing Problem. Mendel [online]. Institute of Automation and Computer Science, Brno University of Technology, 25(1), 15-22 [cit. 2021-04-11]. ISSN 2571-3701. doi: 10.13164/mendel.2019.1.015

[70] NOLZ, Pamela C., Nabil ABSI and Dominique FEILLET. A stochastic inventory routing problem for infectious medical waste collection. Networks [online]. New York City: Wiley Periodicals, 2014, 01 October 2013, 63(1), 82-95 [cit. 2021-04-11]. ISSN 0028-3045. doi: https://doi.org/10.1002/net.21523

[71] PAVIĆ, Zlatko a Vedran NOVOSELAC. Notes on TOPSIS Method. International Journal of Research in Engineering and Science [online]. June 2013, 1(2), 05-12 [cit. 2021-5-14]. ISSN 2320-9364. Avalaible at: https://www.researchgate.net/publication/285886027_Notes_on_TOPSIS_Method

[72] REDL, Christian, Fabian HEIN, Matthias BUCK, Patrick GRAICHEN and Dave JONES. The European Power Sector in 2020: Up-to-Date Analysis on the Electricity Transition [online]. Berlin: Agora Energiewende, 2021 [cit. 2021-5-7]. Avalaible at: https://ember-climate.org/wp-content/uploads/2021/01/Report-European-Power-Sector-in-2020.pdf

List of shortcuts

ADR	Agreement concerning the International Carriage of Dangerous Goods by Road
CO_2	carbon dioxide
CZK	Czech Koruna
dCi	direct Common-rail injection
EU	European Union
HP	Hazardous Property
LHV	lower heating value
PVC	polyvinyl chloride
STAATT	The State and Territorial Association on Alternate Treatment Technologies
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
WHO	World Health Organisation

List of symbols

symbol	**meaning**	**unit**
C_e	unit price of electricity	[CZK/kWh]
C_{mr}	maintenance and reinvestment costs	[CZK]
C_o	overall costs	[CZK]
C_p	payroll costs	[CZK]
C_s	shredding costs	[CZK]
C_{ti}	costs of infectious waste transportation	[CZK]
C_{wt}	waste treatment costs	[CZK]
D_a	distance that vehicles travel annually	[km]
d_i	distance between certain facilities	[km]
e	Euler's number	[–]
E_e	electric energy consumption per ton of waste	[kWh/t]
i_{CZK}	inflation rate of Czech koruna	[CZK]
LHV	lower heating value	[MJ/kg]
m	mass	[kg], [t]
m_i	mass of produced waste	[t]
T	temperature	[°C]
W_a	annually processed waste	[kt]
w_g	wage growth	[%]
W_s	annually shredded waste	[t]
w_{tr}	annual waste transportation rate	[km·t]