VYSOKÉ UČENÍ TECHNICKÉ V BRNĚ

BRNO UNIVERSITY OF TECHNOLOGY

FAKULTA STROJNÍHO INŽENÝRSTVÍ

FACULTY OF MECHANICAL ENGINEERING

ÚSTAV PROCESNÍHO INŽENÝRSTVÍ

INSTITUTE OF PROCESS ENGINEERING

Ing. Martin Pavlas, Ph.D.

MODERNÍ PŘÍSTUP PRO PODPORU ROZHODOVÁNÍ V OBLASTI ODPADOVÉHO HOSPODÁŘSTVÍ

UP-TO-DATE APPROACH FOR DECISION-MAKING IN WASTE MANAGEMENT

HABILITAČNÍ PRÁCE

HABILITATION THESIS

OBOR KONSTRUKČNÍ A PROCESNÍ INŽENÝRSTVÍ

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Abstrakt

Habilitační práce představuje komentovaný přehled publikovaných prací autora v oblasti koncepčního plánování zařízení pro energetické využití odpadů (EVO). Práce nejprve stručně shrnuje současný stav odpadového hospodářství v ČR a EU, důležité legislativní dokumenty, strategické cíle a komentuje míru jejich plnění. Dále zdůrazňuje fakt, že efektivní energetické využití odpadů reprezentuje důležitou součást systémů nakládání s odpady, a to i v rámci konceptu tzv. oběhového hospodářství. Stěžejní částí práce je představení komplexu unikátních výpočtových nástrojů pro podporu investičních rozhodnutí nakládání s odpady. Nástroje zahrnují hmotnostní, energetické a ekonomické bilance, které generují vstupy pro sofistikovanější modely operačního výzkumu. Klíčovým nástrojem je celočíselný lineární model NERUDA pro plánování kapacit zařízení EVO na vybraném území. Protože ekonomická udržitelnost i pozitivní dopad na životní prostředí zařízení EVO jsou úzce spjaty s dodávkou tepelné energie do systému centrálního zásobování teplem, je také řešena problematika integrace EVO s existujícími teplárenskými zdroji. V závěru práce jsou zmíněny perspektivní směry výzkumu v dané oblasti.

Klíčová slova

energetické využití odpadů, odpadové hospodářství, optimalizace, simulace, NERUDA

Abstract

The habilitation thesis is a commented overview of the author's published works in the field of conceptual planning of waste-to-energy facilities (WTE). The work first briefly summarises the current state of waste management in the Czech Republic and the EU, critical legislative documents and strategic objectives and comments on the degree of their fulfilment. It also emphasises the fact that efficient energy recovery of waste represents an integral part of waste management systems, even within the concept of the so-called circular economy. The central part of the work is the introduction of a complex of calculation tools to support investment decisions of waste management. Instruments include mass, energy and economic balances that generate inputs for more sophisticated operational research models. An essential tool is the NERUDA integer linear model for capacity planning of WTE equipment in a selected area. Since the economic sustainability and the positive environmental impact of WTE plants are closely linked to the supply of heat to the district heating system, the issue of integrating WTE with existing heating plants is also addressed. Perspective directions of research in this area are mentioned at the end of the thesis.

Keywords

Waste-to-energy plant, waste management, optimization, simulation, NERUDA

Poděkování

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Seznam obrázků

Seznam použitých zkratek

ARC – Arc routing problem

CEP – Balíček legislativních opatření pro podporu cirkulární ekonomiky (Circular economy package)

CZT – Centrální zásobování teplem

EVO – Energetické využití odpadů

GWP – Global warming potential

HDP – Hrubý domácí produkt

IRR – Vnitřní výnosové procento (Internal rate of return)

KO – Komunální odpad

MBÚ – Mechanicko biologická úprava

OH – Odpadové hospodářství

POH – Plán odpadového hospodářství

PAYT – Systém platby, kdy se platí za skutečně vyprodukované množství (Pay-as-you-throw)

RDF – Palivo z odpadů vyrobené v zařízeních MBÚ (Refuse-derived fuel)

SKO – Směsný komunální odpad – materiálově nevyužitelný komunální odpad vhodný pro EVO

ÚPI – Ústav procesního inženýrství, FSI VUT v Brně

ÚM – Ústav matematiky, FSI VUT v Brně

VRP – Vehicle routing problem

1 Cíl práce

Cílem práce je shrnout dlouhodobé zkušenosti a úspěchy výzkumu uplatnitelnosti unikátních výpočtových nástrojů pro klíčová rozhodnutí v oblasti odpadového hospodářství se zaměřením na energetické využití odpadů (EVO). Představený komplex prakticky aplikovatelných nástrojů vznikl činností širšího výzkumného týmu pod vedením autora na pracovišti Ústavu procesního inženýrství FSI VUT v Brně (ÚPI). Problematika je komentována v širších souvislostech, zahrnujících vývoj odpadového hospodářství (OH) v celoevropském kontextu a současný stav nakládání s odpady v ČR. Protože je pro řešenou problematiku klíčové využití tepla vyrobeného v EVO, předkládaná práce se dotýká také teplárenství.

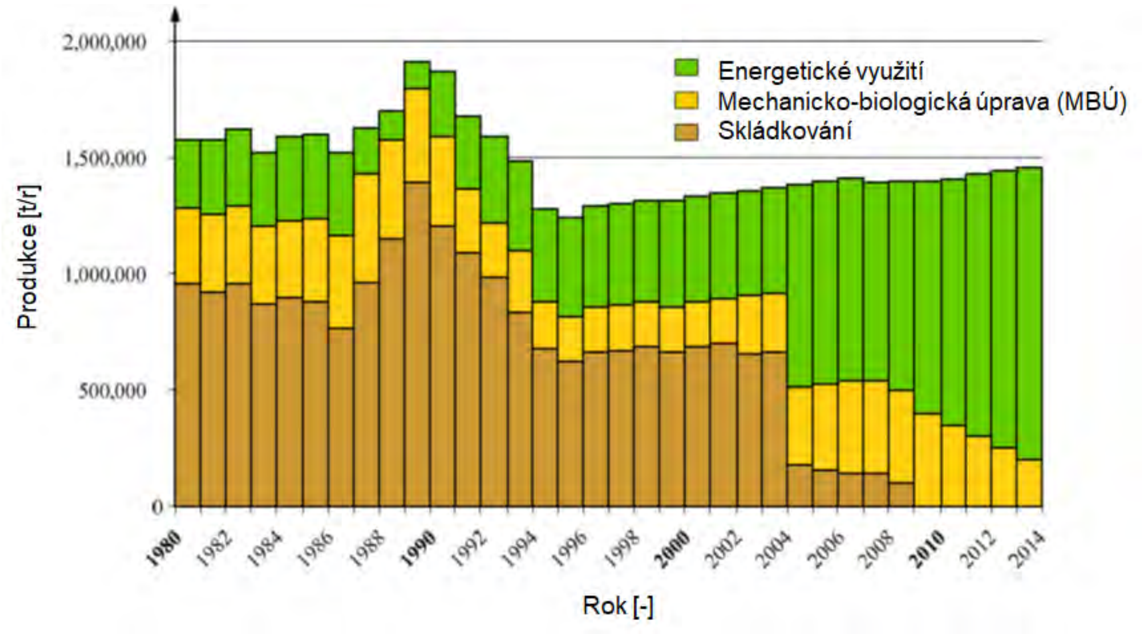
Předkládaná habilitační práce je v souladu s §72 zákona 111/1998 Sb., o vysokých školách, koncipována jako soubor uveřejněných vědeckých prací doplněný komentářem. Práce se opírá o články publikované autorem v mezinárodních impaktovaných časopisech (viz přehled literatury část A - Publikace autora citované v práci). Reprinty těchto článků jsou uvedeny v přílohách 1 až 11. Vzhledem k faktu, že postupná doba vydání těchto článků koresponduje s obsahovým řazením kapitol předkládané práce, lze ji rovněž považovat za chronologickou retrospektivu stěžejních oblastí výzkumných prací autora. Celkový obraz problematiky je doplněn celou řadou dalších odkazů na práce, na kterých se autor podílel jako spoluautor (viz další položky v přehledu literatury A), nebo na další související literaturu (viz B – Literatura ostatní).

K dosažení výsledků zmíněných v práci přispěly rovněž bakalářské a diplomové práce. Protože výsledky jsou založeny na efektivní kombinaci oborové znalosti procesního inženýrství (reprezentováno diplomovými a dizertačními pracemi na ÚPI) a matematiky (reprezentováno bakalářskými a diplomovými pracemi na Ústavu matematiky FSI VUT v Brně, ÚM), lze předloženou práci považovat za významný příspěvek nejen v oblasti vědy a výzkumu, ale i v oblasti pedagogické činnosti.

2 Úvod a motivace

Doprovodným jevem konzumní společnosti je produkce odpadů. Odpadem se rozumí každá movitá věc, které se osoba zbavuje nebo má úmysl nebo povinnost se jí zbavit [B1]. Tyto odpady mohou v zásadě vznikat při výrobě konkrétních produktů (průmyslové odpady), nebo v okamžiku spotřeby vyrobených produktů obyvateli (komunální odpady, KO) a nebo v souvislosti s využíváním poskytovaných služeb (živnostenské odpady). Celá řada prací (např. [B2] nebo [B3]) potvrdila, že v dlouhodobém horizontu existuje korelace mezi produkcí odpadů a ekonomickou sílou regionu. Ekonomická síla je vyjádřena např. pomocí hrubého domácího produktu (HDP). Cílem makroekonomického řízení je, aby HDP rostlo. V takovém případě bude narůstat také produkce odpadů měřená na jednoho obyvatele. Tento trend na příkladu vývoje v Rakousku ukazuje obr. 1. Mezi roky 1995 a 2014 reálný HDP v Rakousku vzrostl z 242 miliard EUR na 341 miliard EUR [B5]. Průměrný meziroční nárůst byl v tomto období přibližně 1,8 %.

Dlouhodobý a nevyhnutelný trend může být v jednotlivých regionech krátkodobě korigován legislativními opatřeními, jejichž snahou je postupně přecházet na environmentálně šetrnější formy nakládání s odpady. Jedná se např. o zákaz skládkování, podporu třídění konkrétních frakcí odpadů, podporu recyklace a s tím související implementaci ekonomických a sociologických nástrojů, které motivují producenty (občany) ke změně návyků.



Obr. 1 Vývoje produkce KO – příklad Rakousko, převzato a upraveno z [B4]

Tento či podobný trend byl a je patrný v celé řadě zemí EU. Vlastní OH jako odvětví ekonomiky, které řídí a zajišťuje nakládání s odpady, představuje obor relativně mladý a dynamicky se rozvíjející [B6].

V historickém kontextu lze sledovat několik fází vývoje OH, které jsou v zásadě totožné ve všech regionech světa. Rozdíl je pouze v tom, že nastávají v jiných časových okamžicích, s časovým posunem a jinou intenzitou. Jedná se o následující fáze:

Fáze č. 1 – **Produkce odpadů exponenciálně roste**. Pokud již neexistují relativně moderní a kontrolované skládky, dochází k přechodu od tzv. divokého skládkování k řízenému skládkování, kdy je odpad ukládán do technicky kvalitně zabezpečených skládek. Fáze je spojena s náklady na výstavbu potřebné infrastruktury a zajištění nakládání s odpadem. Na obr. 1 se jedná o období do roku 1990. V ČR tato fáze proběhla v období po přijetí prvního zákona o odpadech v roce 1991 (zákon č. 238/1991), který si vynutil přechod od tzv. obecných „smeťáků“ a černých skládek k výstavbě a provozu regulovaných, technicky zabezpečených skládek.

Fáze č. 2 – **Období osvěty, propagace a důrazu na environmentální smýšlení** obyvatel je charakteristické dílčí změnou chování obyvatel. Postupně se zintenzivňuje separace složek, je budována síť sběrných nádob. Nechtěné formy nakládání jsou zatíženy environmentální daní. Bonusy a daně se vztahují na subjekty odpovědné za nakládání s odpady (obce) a s rostoucími náklady na systém jsou pozvolna přenášeny na občany. Poplatek za službu, který platí občan, je roční a paušální, což předchází případnému vzniku černých skládek a odkládání odpadů v přírodě (tzv. littering). Potenciál opatření pro snižování množství odpadů se postupně vyčerpává a dochází k opětovnému nastolení trendu nárůstu celkového množství KO (mimo jiné i v důsledku vzniku nových odpadových proudů). V této fázi se nachází ČR.

Fáze č. 3 – **Legislativní omezování či úplný zákaz skládkování** neupravených komunálních odpadů vede k razantní změně infrastruktury a toků odpadů. Přechod je obvykle spojen s nepopulárním skokovým nárůstem celkových nákladů, protože nová řešení jsou dražší ve srovnání se skládkováním. Důraz je kladen na energetické využití odpadů.

Např. v Rakousku byl skládkovací poplatek v legislativě přijat v roce 1989, s tím, že od roku 2004, resp. 2008, platí zákaz skládkování neupravených odpadů. Německo uzákonilo zákaz skládkování nevyužitelných odpadů v roce 1993 s 12-letou lhůtou pro realizaci nezbytné infrastruktury. V ČR je skládkovací poplatek aktivní od roku 1992 a ČR tak byla jednou z prvních evropských zemí, kde byl tento mechanismus zaveden [B7]. Až do roku 2009 se skládkovací poplatek meziročně navyšoval. Od roku 2009 je jeho výše fixní na úrovni 500 Kč/t a při současných cenách a výši obecné inflace v poslední dekádě je neadekvátně nízký. Neumožňuje tak přesměrování toků z nechtěných skládek do jiných typů zařízení určených pro materiálové či energetické využití.

Zvýšené náklady motivují občany minimalizovat produkci odpadů. Jsou zaváděny systémy, kdy občan platí podle množství vyprodukovaných odpadů, tzv. PAYT systém (Pay-as-you-throw). Předpokladem úspěšnosti individuálního zpoplatnění služeb je jistá minimální úroveň environmentálního smýšlení, kdy je občan ochoten zvýšené náklady akceptovat a uvědomuje si smysl moderního OH ve vztahu k ochraně přírody (nedochází tak k tzv. odhazování odpadů do volné přírody). Sekundárním efektem PAYT je příprava pro materiálové využití. Celkové množství vyprodukovaných odpadů je pořád stejné, mění se jejich kategorizace a charakter.

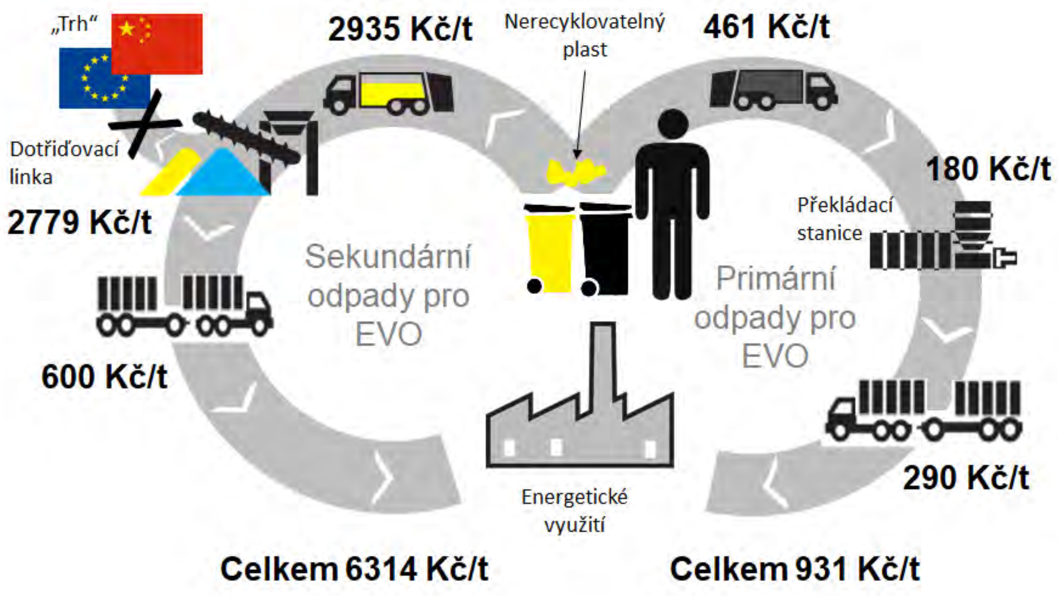
Fáze č. 4 – Důraz na materiálové využití a snižování významu energetického využití – této fázi je věnována samostatná kapitola 2.3.

2.1 Současný stav OH v Evropské unii

V současnosti akceptovaným kritériem hodnocení efektivity odpadového hospodářství v jednotlivých zemích EU je určení procentuálního podílu mezi hlavními způsoby nakládání s odpady, kterými jsou:

- odstranění,
- energetické využití,
- materiálové využití (recyklace),
- ostatní.

Data pro hodnocení jsou sbírána v jednotlivých zemích a shromažďuje je Eurostat. Přestože Eurostatem prezentovaná data představují alespoň nějaké srovnání mezi státy, mezi kritiky jsou diskutována slabá místa, nejednotnost a měření na vstupu do zařízení, které nerespektuje skutečné toky odpadů a vznik tzv. sekundárních odpadů [A1]. Obr. 2 ukazuje příklad vzniku sekundárního odpadu pro EVO. Nerecyklovatelný (na trhu neuplatnitelný) plastový odpad je občanem dle pokynů svozové společnosti odhozen do sběrné nádoby na plast, následně svezen a zpracován na dotřiďovací lince, aby byl v posledním kroku energeticky využit nebo v horším případě skládkován. Tento řetězec je významně dražší než v případě, že by absolvoval cestu primárního odpadu jako SKO, který je shromažďován v šedých (černých) sběrných nádobách.



Obr. 2 Primární a sekundární odpady pro energetické využití odpadů [A1]

Nedostatky v hodnocení má do budoucna snahu odstraňovat vznikající legislativa v rámci tzv. balíčku oběhového hospodářství (CEP, více kap. 2.3.). Podle procentuálního zastoupení jednotlivých způsobů lze rozlišit níže uvedené skupiny zemí. Vzhledem k úzké vazbě mezi toky odpadů a legislativou, jejíž úroveň byla využita při popisu fází OH v předchozí kapitole, skupiny zemí korespondují s fázemi rozvoje OH.

První skupina zahrnuje země s dobře vyvinutým OH, kde skládkování bylo téměř eliminováno a většina komunálního odpadu (KO) se materiálově využívá. Do druhé skupiny patří země, kde probíhají změny směrem k udržitelnějšímu OH. Příslušné legislativní kroky již byly provedeny, ale ještě nebylo zakázáno skládkování odpadů. Pro navýšení materiálového či energetického využívání KO, oproti skládkování, jsou však použity daňové nástroje. Země ve třetí skupině čekají na transformaci OH. Tyto země mají nedostatečnou kapacitu pro zpracování odpadů, skládkování není omezeno a jen malé množství odpadu se recykluje.

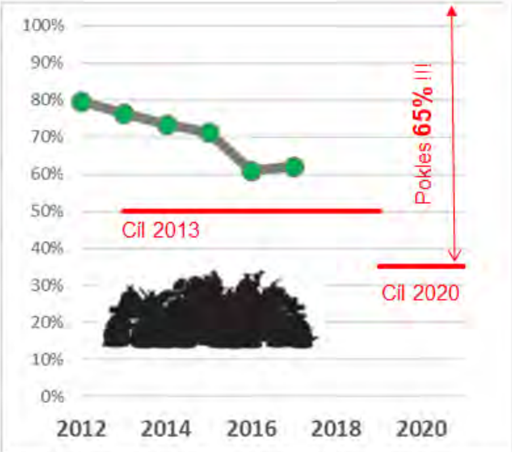
Rozmach EVO v zemích EU a potenciál výstavby dalších zařízení sumarizuje přehledový článek [B8]. Množství energeticky využitých odpadů se od roku 1995, kdy jsou data monitorována Eurostatem, zvyšuje. K nejprudšímu nárůstu došlo mezi lety 2001 a 2017. V souvislosti s implementací nové legislativy a zaměřením na materiálové využití je EVO v EU dále nepodporovanou technologií, přestože se jedná o recyklaci ve formě energie. Trh výstavby zařízení EVO se přesouvá do rozvíjejících se zemí zejména v asijském regionu.

2.2 Současný stav OH v České republice

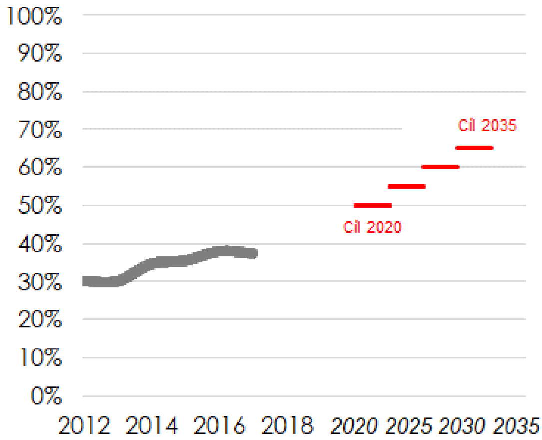
Klíčovým dokumentem v odpadovém hospodářství ČR je Plán odpadového hospodářství (POH) [B9], který představuje hlavní plánovací dokument v dané oblasti. Poslední verze POH cílí na období 2015 až 2024. Současný stav OH v ČR na základě dat 2017 hodnotí dokument [B10]. Publikované hodnoty tzv. indikátorů OH jsou porovnávány s tzv. cíli OH. Přestože legislativa EU, stanovující cíle pro následující období bude shrnuta až v kap. 2.3, jsou zde uvedeny tři konkrétní případy:

- Ze skládek v ČR bylo odkloněno v roce 2017 celkem 62 % biodegradabilních odpadů oproti stavu v roce 1995, cíl je odklonit 75 % do roku 2020 (obr. 3 a).

- Míra recyklace (resp. míra třídění jako přípravy k recyklaci) KO činila 38 %, má pozvolně stoupající trend, přičemž dlouhodobé cíle jsou 50 % v roce 2020 až 65 % v roce 2035 (obr. 3 b).
- Bylo skládkováno 45 % KO (2,5 mil. tun), přičemž cíl je max. 10 % v roce 2035 (bez ilustrace). V roce 2017 ČR skládkovala 45% KO, přičemž pokles míry skládkování je v posledních letech velmi pozvolný.



a) Podíl skládkovaného BRKO vůči roku 1995



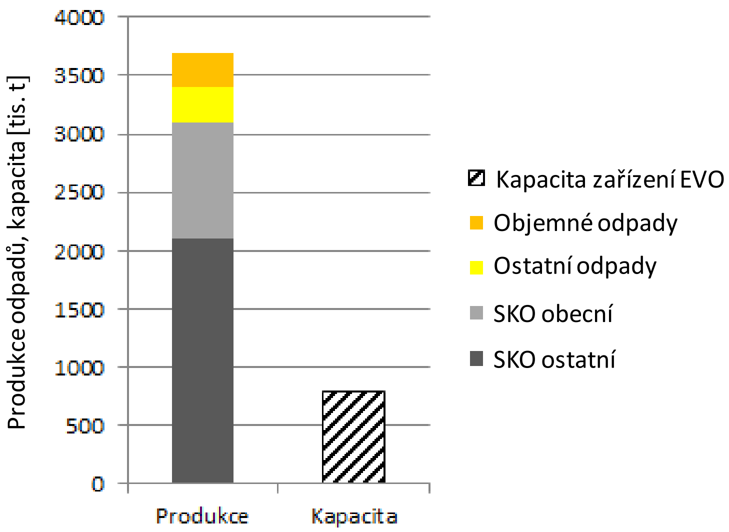
b) Komunální odpad – min. míra recyklace (příprava pro materiálové využití)

Obr. 3 Rekapitulace závazků ČR a současný stav jejich plnění

Je evidentní, že dosavadní trend a rychlost probíhajících změn nevede ke splnění stanovených cílů ani v případě obr. 3 a) ani b). Míra separace KO se pozvolna zvyšuje, ale trend není dostatečný pro splnění cílů.

V roce 2015 se autor výrazně podílel na řešení strategického projektu pro Ministerstvo životního prostředí [P1], jehož součástí bylo vyhodnocení současné sítě zařízení na území ČR a stanovení potřebných kapacit do budoucna. Při analýzách byly využity nástroje, které budou představeny dále. Revize vývoje probíhala následně v rámci aktivit projektu [P2]. Při bližší analýze bylo zjištěno, že klíčovým hmotnostním tokem z pohledu splnění závazků je SKO, který se z 90 % podílí na skládkovaném množství BRKO. SKO je rovněž důležitý z pohledu cílů v oblasti materiálově využitelných odpadů. Závěry analýz jsou následující:

- Byl nastartován separovaný sběr bioodpadu. Většina tohoto množství vzniká z údržby zahrad a veřejné zeleně a jedná se o nový odpadový proud. Množství odpadu odkloněného z SKO je minoritní a dochází k němu pouze v obcích či jejich částích, kde je realizován separovaný sběr bioodpadu z kuchyní.
- Klíčovým odpadovým tokem je směsný komunální odpad (SKO), který je ze 75 % skládkován.
- Kapacita EVO je nedostatečná (obr. 4). Pro dimenzování sítě je nutné započítat výše zmíněné sekundární odpady (obr. 2).
- Skládkovací poplatek je nízký.



Obr. 4 Produkce spalitelných materiálově nevyužitelných odpadů v roce 2015 a existující kapacita pro jejich zpracování (2015, včetně ZEVO Chotíkov před dokončením)

Lze konstatovat, že ČR v posledních dvou dekádách přeskočila fázi rozvoje výstavby zařízení EVO. V roce 1989 byl uveden do provozu první kotel v SAKO Brno, v roce 2000 byla uvedena do provozu zařízení TERMIZO Liberec a ZEVO Malešice a od té doby byl počet zařízení EVO na území ČR zafixován až do roku 2016, kdy bylo dokončeno ZEVO Chotíkov u Plzně. Celková kapacita 740 tis. t/r je nedostatečná (viz obr. 4). Přitom je nutné zdůraznit, že hlavní problematický proud OH ČR je SKO, tzn. zbytkový materiálově omezeně využitelný odpad vhodný pro energetické využití. Ten dnes dominantně končí na skládkách a je příčinou neplnění stanovených cílů OH (viz následující kapitola).

2.3 Vývoj v EU směřující k oběhovému hospodářství a budoucí význam zařízení EVO

V kontextu výše zmíněné hierarchie nakládání s odpady je dlouhodobou snahou EU preferovat recyklaci, znovupoužití odpadů, nahrazovat primární suroviny surovinami druhotnými (z odpadů) a současně minimalizovat množství odpadů, které jsou zpracovány bez využití, tzv. odstraněny. Nejrozšířenější způsobem odstraňování odpadů je skládkování.

Jedním ze zásadních počinů legislativy EU je příprava a postupná implementace tzv. „Circular economy (CE) package (CEP – balíčku oběhového hospodářství)". V rámci CE je vizí zavést koncepty s minimální produkcí odpadů, kdy v důsledku přechodu od lineárního schématu (těžba surovin -> vznik výrobků -> spotřeba -> odpad) dochází k uzavírání životního cyklu a opětovnému využívání druhotných zdrojů – recyklaci [B11]. Jako podpůrný legislativní nástroj přechodu k CE byla v EU v roce 2018 implementována:

- směrnice, která mění směrnici o skládkách odpadů – 2018/850/EU,
- směrnice, která mění směrnici o odpadech – 2018/851/EU,
- směrnice, která mění směrnici o obalech – 2018/852/EU.

Na schéma CE odkazuje také tzv. koncept ZERO Waste, který definuje cíle a strategie pro různé subjekty (města, instituce, podniky) s cílem uzavřít udržitelné přirozené cykly, ve kterých všechny nepotřebné materiály budou zdrojem pro další využití, všechen odpad se využije, žádný odpad nebude odstraněn ani spalován.

Dosažení takového stavu vyžaduje zásadní změny nejen na straně spotřebitelů (producentů odpadů), ale zejména výrobců zboží, kdy budou upřednostňovány výrobky z recyklovatelných materiálů nebo výrobky lehce recyklovatelné. Mluvíme o tzv. ecodesignu. Současné nakládání s odpady nejenom v ČR, ale i v EU a pomalé tempo změn ukazuje, že vize CE je dlouhodobý projekt a v daném časovém okamžiku má své limity a bariéry. Jednou z bariér mohou být budoucí náklady pro konečné uživatele.

V kontextu cirkulární ekonomiky se zařízení EVO zdají být zbytečnou součástí systému. Efektivnost je přitom nutné hodnotit s ohledem na všechny tří pilíře udržitelnosti: ekonomický, environmentální i sociální, a to vždy v širších souvislostech daného regionu. Do programu „ZERO Waste“ jsou dnes převážně zapojeny města jižní Evropy [B12]. Teplejší klimatické podnebí a neexistence nebo omezená existence systémů centrálního zásobování teplem (CZT) je jasnou překážkou pro implementaci dobře fungujících a smysluplných systémů EVO. Jak bude ukázáno dále, efektivnost EVO (ekonomická, ale také environmentální) je spojena s dodávkou tepla do CZT. Některé komentáře [B13], [B14] indikují nevýhodnost EVO i v zemích, kde má teplárenství dlouhou tradici, jako je např. Dánsko, a naznačují, že EVO spalující odpad s obsahem fosilního uhlíku je překážkou tzv. dekarbonizace energetického sektoru. Naproti tomu, rozsáhlá studie z Dánska [B15], ukazuje, že EVO má svůj význam i v energetice založené na vysokém podílu obnovitelných zdrojů.

Cílem práce autora je vytvořit výpočtové a optimalizační nástroje, které budou poskytovat relevantní výstupy a fakta pro seriózní diskusi nad potřebou, výhodami a nevýhodami procesu EVO, alternativních cestách v kontextu regionu a širších energeticko-environmentálních souvislostech. Podstatnou součástí řešeného problému je doprava odpadů ve všech fázích procesu. Tato dlouhodobá snaha je v souladu se závěry rešeršní práce [B16], která specifikuje následující výzkumné výzvy:

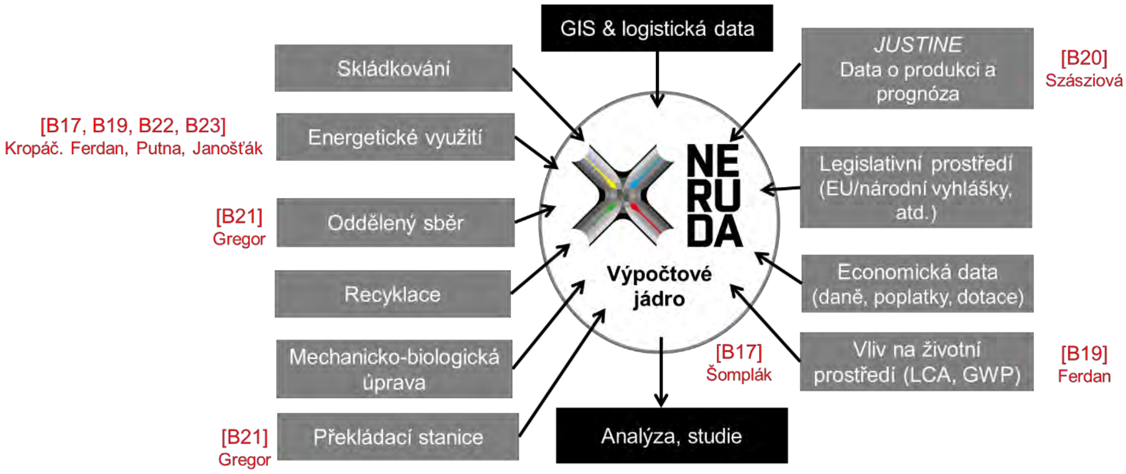
- **Vícerozměrnost:** Problém současných řešení, která se zaměřují pouze na určitý parametr, který je zvolen jako účelová funkce je, že vede k suboptimálnímu řešení. Autoři zdůrazňují potřebu integrovaného přístupu. Je evidentní, že takový přístup vede k výraznému rozsahu úloh (optimalizačních), nárůstů výpočtového času, potřeby disponovat výkonnými výpočtovými prostředky, které zaručí dosažení řešení v reálném čase.

- **Holistický přístup:** Potřeba hledat řešení v kontextu širšího geografického území. Optimální řešení z mikro pohledu nemusí být optimální v kontextu více provozovatelů, obcí, států.

- **Na míru šitá řešení:** Zohlednění specifických aspektů, univerzálnost a modulárnost výpočtových nástrojů, robustnost navržených metodik. V práci budou představeny výpočtové nástroje různé složitosti: simulační a optimalizační vícestupňové modely a komplexní síťová úloha.

Přestože výsledky výzkumu jsou přenositelné do libovolného území, regionem zájmu práce je prioritně Česká republika. Dlouhodobě vytvářená datová základna v rámci týmu autora práce je využívána pro vývoj a testování vytvořených nástrojů a prověření jejich praktické uplatnitelnosti. Datová základna je poskytována pro zpracování závěrečných prací. Výpočtové nástroje jsou vyvíjeny na základě reálných dat, což je zejména důležité a motivační pro návrh matematických modelů v rámci studentských prací vypisovaných na ÚM.

Hlavní výsledek dosavadní dlouhodobé systematické činnosti přehledně sumarizuje obr. 5. Jedná se o výpočtový nástroj NERUDA – síťovou úlohu pro podporu klíčových rozhodnutí v odpadovém hospodářství a jeho součásti (více viz kap. 4.1).



Obr. 5 Moduly komplexní síťové úlohy NERUDA a jejich vazba na řešené či ukončené dizertační práce

Obr. 5 současně ukazuje, jak ukončené či rozpracované dizertační práce, kde se autor práce podílel či podílí jako školitel specialista a nositel hlavních myšlenek a konceptu jednotlivých prací, přispívají k hlavnímu výsledku – nástroji NERUDA. Jedná se o dokončené práce [B17], [B18], [B19], [B20], [B21] a rozpracované dizertační práce [B22] a [B23].

Jednotlivé práce obsahují rešeršní části, které ukazují na přínos výsledků v celosvětovém kontextu. Výsledky rešerše lze shrnout následovně:

Dosud:

- V literatuře bylo popsáno velké množství matematických modelů. Přestože jsou velmi často inspirativní, jsou většinou prezentovány na školských a smyšlených úlohách. V lepším případě jsou řešeny velmi jednoduché případové studie.

Vlastní přínos:

- Původní práce na ÚPI je charakteristická aplikovatelností v praktickém měřítku.
- Implementuje dílčí výsledky do komplexu ucelených nástrojů.
    - Např. NERUDA dle [B24] reprezentuje celočíselný lineární stochastický vícekriteriální model pro plánování umístění koncových a pomocných zařízení pro zpracování odpadů, který zohledňuje vliv kapacity zařízení na ekonomiku a pracuje s více typy komodit.
- Dosavadní výzkum autora přináší zcela nové poznatky a přístupy, které dosud nebyly publikovány a řešeny. Jako příklady lze uvést:
    - cena dopravy závislá na množství přepravovaných odpadů a ujeté vzdálenosti ve struktuře vhodné pro implementaci do síťových úloh ([B21], [A2], [A3]),
    - mezioborovost – provázání problematiky odpadového hospodářství s teplárenstvím, které se projevuje na charakteristickém tvaru tzv. křivky ceny za zpracování odpadů (více kap. 3.4); zde je nutné zmínit poměrně ojedinělou pozici ČR díky existenci velkého množství sítí CZT [B22],
    - prognózování produkce komodity ve všech uzlech síťové úlohy s využitím algoritmů na bázi vyrovnání dat [B20] (více viz kap. 4.3).

Jak je patrné, dílčí části nástroje NERUDA, zde označené jako moduly, zahrnují různé technologie a oblasti, které se mohou na první pohled zdát vzdálené technologickému konceptu EVO, kterým se práce dominantně zabývá. Zvolený postup je však nezbytný z následujících důvodů:

- EVO je preferovanou formou pro jinak materiálově nevyužitelné odpady – proto je nutné řešit produkci odpadů jako takovou (činnosti popsané v [B20] a dále v kap. 4.3) a stanovit reálný potenciál materiálového využití (modul separace).
- EVO je součástí teplárenství – uplatnění tepla představuje rozhodující aspekt jeho realizovatelnosti a udržitelnosti.
- Doprava odpadů stejně jako doprava obecně je velmi citlivé téma. Navíc doprava odpadů je realizována v tzv. konvergentní síti [B24] s největší intenzitou v blízkosti zpracovatelského zařízení.
- Je nutné posuzovat alternativní technologie (model mechanicko-biologické úpravy, MBÚ) a provádět srovnání s EVO.

Klíčové pro úspěch celého komplexu nástrojů jsou ovšem znalosti vlastního technologického procesu EVO, jeho specifických aspektů, bilance apod. Tomuto byla věnována hlavní pozornost práce autora zejména v první fázi vědecké kariéry a klíčové výsledky uvádí kap. 3. Dobře popsaná technologie EVO pak mohla být posuzovaná v komplexu dalších technologií a specifických aspektů. Tomuto tématu se věnuje kap. 4.

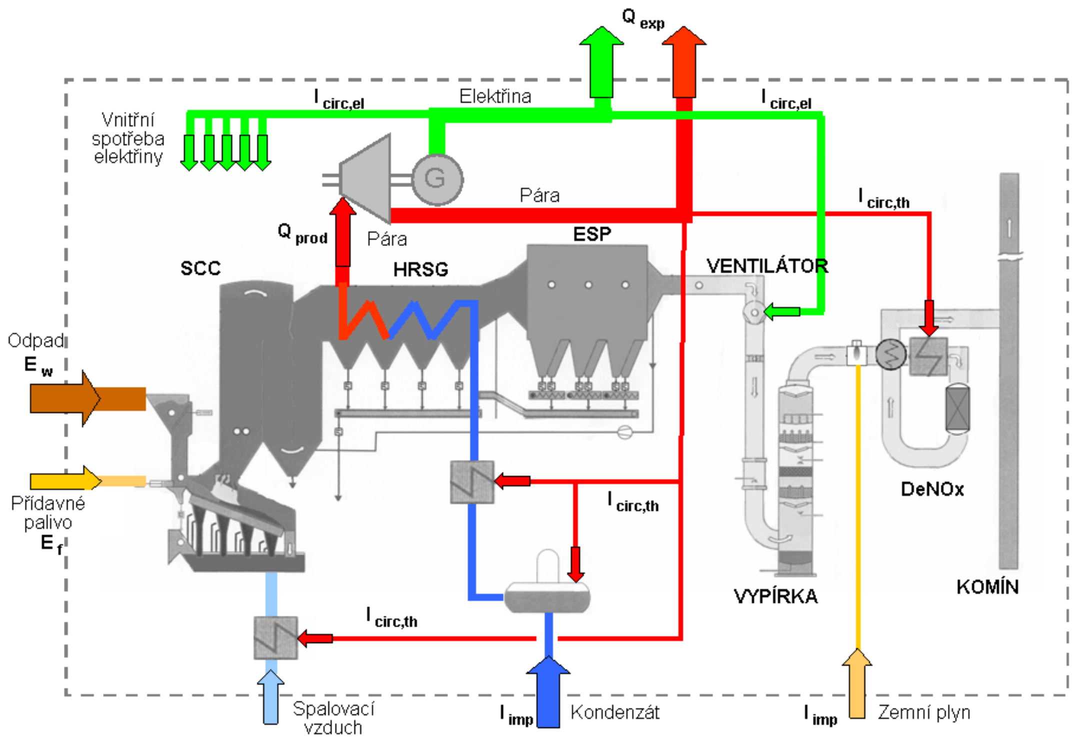
3 Zařízení EVO

3.1 Definice EVO

Zařízením EVO je obecně označováno zařízení pro termický rozklad odpadů s následným využitím uvolněné energie. V zásadě se rozlišuje několik typů technologických konceptů, jako jsou pyrolýzní, zplyňovací a oxidační zařízení, která se liší podílem přívodu vzduchu k jeho stechiometrickému množství (tj. teoretickému množství daného oxidačními reakcemi hořlavých složek paliva).

V podmínkách EU je nejrozšířenější koncept oxidační spalovny (tepelný rozklad probíhá při přebytku vzduchu) vybavené obvykle pohyblivým roštem. Tento koncept lze považovat za dlouhodobě provozně ověřené a robustní řešení. Koncept s omezeným přívodem vzduchu, tj. technologie zplyňování a pyrolýzy, je dlouhodobě známý a využívaný. Pro specifické aplikace, kdy vstupním materiálem jsou komunální odpady a jejich frakce, je ale považován za „emerging technology“. Podrobně se tomuto problému věnovala práce [A4] zpracovaná v rámci projektu [P1]. Pyrolýzní a zplyňovací technologie jsou provozovány pro specifické typy odpadů, jejichž společným znakem jsou relativně homogenní vlastnosti a složení (např. drcené pneumatiky, jednodruhové průmyslové odpady apod.). Jejich aplikace na zbytkové komunální odpady (SKO jako celek) je ale problematická. V dlouhodobějším horizontu může být přínosem výroba biopaliv druhé generace, kdy namísto tepla jako energetického toku z kogenerace je produkován metanol nebo bioetanol, tzn. výrobky s vyšší přidanou hodnotou. Jako příklad lze uvést [B25].

Současná úroveň poznání a technologická vyspělost EVO je ve větším detailu popsána v obsáhlém referenčním dokument BREF, který popisuje tzv. nejlepší dostupné technologie (BAT) [B26]. Pro účely této práce bude dále za EVO považována technologie roštové oxidační spalovny. Jak bylo uvedeno výše, jedná se provozně dlouhodobě ověřenou technologii. Množství aplikací v EU a také v ČR zaručuje dostatek relevantních vstupů pro výpočty a modely pospané dále v této práci. Zařízení vyrábí páru o tlaku 4 až 6 MPa, která je následně expandována v parní turbíně, přičemž se vyrábí tepelná a elektrická energie. Polutanty, vznikající při termickém rozkladu vstupního odpadu, jsou z proudu spalin odstraňovány ve vícestupňovém systému čištění spalin. Stručné schéma takové technologie je uvedeno na obr. *6*.



Obr. 6 Hlavní toky energie roštové oxidační spalovny s využitím energie [A5]

V kontextu evropské legislativy [B27], implementované do legislativy ČR v rámci přílohy č. 12 zákona č. 185/2001 Sb., o odpadech a změně některých dalších zákonů, [B1] může být jako zařízení EVO kategorizováno zařízení, které splňuje určitou minimální energetickou efektivitu. Legislativa pro kategorizaci zavádí parametr *R1 Energy Efficiency*, který je dán vztahem:

$$R1 = \frac{E_p - (E_f + E_i)}{0{,}97 * (E_w + E_i)}, \quad (1)$$

kde hlavní proudy vstupující do výpočtu jsou zřejmé z obr. 6 a mají následující význam:

- E_p se rozumí roční množství vyrobené energie ve formě tepla nebo elektřiny. Vypočítá se tak, že se energie ve formě elektřiny vynásobí hodnotou 2,6 a teplo vyrobené pro komerční využití hodnotou 1,1 [GJ/r].
- E_f se rozumí roční energetický vstup do systému z paliv přispívajících k výrobě páry [GJ/r].
- E_W se rozumí roční množství energie obsažené ve zpracovávaných odpadech vypočítané za použití výhřevnosti odpadů [GJ/r].
- E_i se rozumí roční dodaná energie bez E_w a E_f [GJ/r] a řadí se sem např. zemní plyn nutný pro ohřev proudu spalin před aparáty snižování oxidů dusíků ($DeNO_x$).
- 0,97 je činitelem energetických ztrát v důsledku vzniklého popela a vyzařování.

V této souvislosti je nutné poznamenat, že volba názvu parametru, který obsahuje termín „účinnost“, lze považovat za nešťastný a nepřesný. Vzhledem ke specifickému postupu výpočtu, který je dán metodikou [B28], může parametr významným způsobem přesahovat hodnotu 1. Toto potvrzuje rozsáhlá analýza dat z provozu evropských spaloven [B29]. Maximální hodnota činila 1,45. Nejvyšší hodnoty jsou přitom dosaženy u kogeneračních zařízení (dodávka tepla a elektřiny) provozovaných v severských zemích, kde klimatické podmínky umožňují plně využít potenciál uvolněné energie k dodávce tepla. Výrazně nižších hodnot je dosaženo u zařízení, která vyrábějí pouze elektrickou energii (max. 0,85, průměrně 0,55). Přitom legislativa stanovuje, že prahová hodnota *R1* je 0,65. Zařízení, která tuto hodnotu nedosáhnou, představují pouhé odstranění odpadů.

Skutečný význam *R1* odpovídá výpočtu tzv. měrné úspory primární energie (primary energy savings, *pes*) [A5]. Koncept výpočtu *pes* je zcela běžný při hodnocení kogeneračních systémů (bez rozlišení typu paliva) a je zakotvený ve směrnici [B30]. Toto zjištění, prezentované nejprve v [A6], autor práce rozpracoval v příspěvku [A7] (viz Příloha 1) a [A8] (viz Příloha 2). Prvně zmíněná práce využívá termín *pes* pro srovnání efektu úspor primární energie z EVO s dalšími typy energetických zdrojů. Příspěvek byl velmi kladně přijat vědeckou komunitou a představuje nejcitovanější výstup činností autora (v 9/2019 celkem 46 citací). Metodika vyčíslení *R1* a *pes* byla dále rozpracována v druhém zmíněném článku. Byl nově definován pojem „vysoceúčinné energetické využití odpadů“.

Analýza parametru *pes* a potažmo *R1* ukazuje na zásadní význam efektivní integrace EVO v rámci existujících teplárenských zařízení. Nesprávný odhad reálné dodávky a budoucích provozních režimů může vést k horším provozním parametrům a nedosažení očekávaných efektů. Přesnější určení budoucích provozních režimů a roční bilance skutečně dodaného tepla z EVO je možná pouze na základě detailního posouzení spolupráce a integrace EVO s existujícím teplárenským zařízením. Tato problematika je předmětem dizertační práce [B22]. Základní poznatky jsou shrnuty v kap. 5.1.

3.2 Hmotnostní a energetické bilance zařízení EVO

Analýzy zmíněné v předchozí kapitole jsou založeny na znalosti klíčových energetických toků v rámci zařízení EVO a jeho subsystémů. Autor práce se dlouhodobě věnuje modelování procesu EVO ve smyslu vyčíslení hmotnostních a energetických bilancí pro různé provozní stavy a konfigurace technologie.

Jako zásadní výstup v této oblasti lze jmenovat softwarový nástroj s názvem W2E (Waste-to-Energy). Počátek vývoje tohoto nástroje je prezentován diplomovou prací autora [A9], ve které byl sestaven koncept a teoretický základ celého systému. Současně byla provedena první softwarové implementace v prostředí Delphi. Ta se vyznačovala velmi jednoduchým uživatelských rozhraním. V rámci řešení autorovy dizertační práce [A10] a výzkumných projektů [P3] a [P4] byl koordinován další vývoj bilančního modelu až do formy nástroje W2E ve verzi 2.0, která odpovídá současnému stavu. Nástroj získal moderní uživatelské rozhraní, grafický editor. Byla využita technologie Java. Výpočtové jádro je plně odděleno od grafického rozhraní. Architektura je navržena tak, aby umožnila další doplňování modulů. Toho bylo plně využito v dizertační práci [B17], který definovala a následně implementovala modely bloků systémů čištění spalin.

Nástroj W2E je využíván především jako podpůrný nástroj výzkumně-vývojových aktivit na pracovišti autora (bilancování procesu EVO) a při řešení projektů s průmyslovou sférou. Konkrétně lze uvést studie:

- Dosažitelné výrobní ukazatele provozu EVO Most, Komořany, zpracováno pro United Energy, a.s. (2010),
- komplexní studie (3 na sebe navazující etapy) v rámci přípravné fáze nového zařízení EVO pro významnou energetickou společnost působící v ČR (2012-2013),

- Modelování dopadů podpory energetického využití odpadů na konečného spotřebitele za podmínek zákazu skládkování, studie zpracovaná pro Ministerstvo průmyslu a obchodu ČR v rámci projektu MPO-Efekt (2013).

Kromě toho byla k využití W2E v roce 2014 udělena licence pro výzkumné pracoviště KISR – Kuwait Institute for Scientific Research, Safat, Kuvajt. Součástí prodeje licence bylo rovněž týdenní školení uživatelů systému.

Nástroj W2E je také využíván ve výuce předmětu Energie a emise (FSI-KEE-A), obor M-PRI, 2. stupeň, 1. ročník, letní semestr. Zjednodušená bilance zařízení EVO je navíc centrálním tématem semestrální práce v tomto předmětu.

Nástroj W2E svým charakterem představuje tzv. „white-box model“, tzn. model, kde je transformace vstupních parametrů na výstupní popsána systémem algebraických rovnic (příklad viz [A5] a [B17]). Použitý model je dlouhodobě testován vůči skutečným provozním datům. Probíhá spolupráce se dvěma provozy EVO v ČR, a to konkrétně s TERMIZO Liberec, a.s. a ZEVO Malešice Praha. Data z reálných provozů pak umožňují vytvářet tzv. „grey-box“ a „black-box“ modely. Ty jsou vytvořeny na základě aplikace metod popisné statistiky, kdy se hledá regresní funkce popisující vztah mezi výstupními a vstupními veličinami [A11] (viz Příloha 3), [B31]. Rovněž se využívají složitější modely založené na neuronových sítích:

- V roce 2010 byl vytvořen model zařízení TERMIZO Liberec (grey-model).
- V roce 2010 byl vytvořen white-box model ZEVO Malešice pro základní výpočet bilance procesu a výpočet ekonomiky.
- V období 2014-2017 byl vytvořen v rámci rozsáhlého projektu grey-box model ZEVO Malešice, jehož účelem je predikovat výrobu elektřiny v následujících 40 hodinách. Model byl v roce 2017 po dlouhodobém testování nasazen do rutinního provozu. Dílčí výsledky a metodika byla publikována v článku [A12] (viz Příloha 4).

Obdobná metodika pak byla aplikována při řešení průmyslového případu a zakázky ve zcela jiné oblasti. Jednalo se o simulační a následně optimalizační model zdrojové části energetického systému Národního divadla v Praze. Výsledky byly opět publikovány v impaktovaném časopise [A11] (viz Příloha 3).

3.3 Environmentální dopady

Prosazení a následná realizace projektu EVO je problematická. Téma je velmi citlivě vnímáno obyvateli, kdy jedním z argumentů proti je nepříznivý dopad na životní prostředí v bezprostředním okolí chystaného zařízení. Přestože emise jsou velmi nízké (viz kap. 5.2), u některých parametrů na hranici měřitelnosti (viz [B26]), u občanů přetrvává v důsledku neinformovanosti a desinformacím nedůvěra k této technologii a projevuje se tzv. NIMBY efektem (not-in-my backyard).

Velmi přísné emisní limity a vyspělá technologie, která plnění takových limitů umožňuje, vede k celkově nízkým emisním tokům a sekundárně i minimálnímu imisnímu zatížení v lokalitě. Problematice modelování emisí a jejich rozptylu se věnovala diplomová práce [B32]. Přestože práce byla motivována snahou rozšířit nástroj NERUDA o zohlednění lokálních emisí (viz kap. 5.2), výsledky získané pro modelovou technologii 100 kt/r ukazují reálně zanedbatelný příspěvek technologie EVO ke znečištění ovzduší. Jako příklad jsou uvedeny oxidy dusíku NO_2. V zájmové oblasti se roční průměrné pozaďové imisní koncentrace NO_2 v době zpracování práce pohybovaly v rozmezí přibližně od 11 do 20 μg/m3 [B33]. Legislativou stanovený imisní limit pro roční průměr NO_2 činí 40 μg/m^3 [B34]. Maximální dosahované roční přírůstky průměrné koncentrace NO_2 vlivem provozu EVO byly vyčísleny na úrovni 0,0250 μg·m^{-3}. Na první pohled je tedy zřejmé, že příspěvek ke stávajícím imisním koncentracím v oblasti i k imisnímu limitu je zanedbatelný. Řádově obdobné závěry byly potvrzeny i pro další polutanty v práci [B32] či v rozptylových studiích jako nezbytné součásti povolovacího procesu záměru EVO [B35]. Obava obyvatel o škodlivost EVO a jeho vlivu vychází z neinformovanosti či šíření nerelevantních informací.

Z odborného hlediska je akceptovatelný citlivý argument nárůstu intenzity dopravy v blízkosti zařízení a podél hlavních svozových tras či související hlukové zatížení. K jeho objektivnímu hodnocení přispívá nástroj NERUDA tím, že se vedle lokalizace zpracovatelských zařízení zabývá tokem odpadu po jednotlivých hranách. Z celkového množství převážených odpadů lze s využitím poznatků [B21] stanovit potřebný počet jízd nákladních vozidel a jejich počet srovnat se současnou intenzitou dopravy v daném místě. Přístup byl využit v rozsáhlé studii pro region Táborsko [B36].

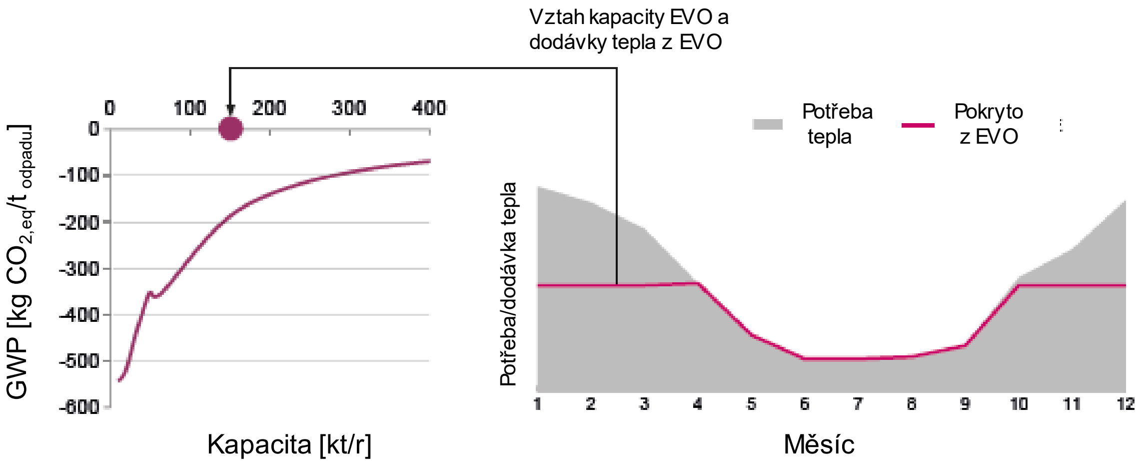
Hodnocení environmentálních dopadů úzce souvisí s výpočtem hmotnostních a energetických bilancí. Hmotnostní bilance přímo či nepřímo určuje hmotnostní toky sledovaných polutantů vyprodukovaných zařízením. Pak mluvíme o tzv. lokálních emisích (tzn. emisích vyprodukovaných v daném zařízení). Pohled lze více rozšířit a do hodnocení zahrnout také emisní toky ovlivněné provozem EVO sekundárně. Typicky se jedná o úsporu emisí v konvenčních energetických zdrojích, které nemusí vyrobit energii dodanou zařízením EVO, nebo emise související s dopravou odpadu do konkrétního zařízení EVO. Zařízení EVO vyrábí teplo a elektřinu, která by jinak musela být dodána z konvenčního zařízení spalováním např. fosilních paliv. Tento přístup se nazývá „globální“ pohled. Hodnocení lokálních a globálních emisí z EVO bylo provedeno v dříve zmíněném příspěvku [A7] (viz Příloha 1).

Mnohem komplexnější a dnes odborně uznávanou metodou pro hodnocení evironmentálních dopadů procesů technologií a produktů je tzv. metoda LCA (Life cycle assessment), která je standardizovaná normou ISO 14040:2006. V obecné rovině metoda LCA hodnotí nejenom vlastní provoz zařízení, ale také životní fáze, které uvedení do provozu předcházely (výstavba, výroba materiálu a různých forem energie nezbytných pro realizaci zařízení) a které budou nezbytné po ukončení provozu. Dává tedy ucelenější pohled. Nedílnou součástí LCA je tzv. inventarizace, která v zásadě představuje analogii hmotnostní a energetické bilance, kdy se vyhodnocují toky na hranici hodnoceného systému.

Z pohledu LCA sledovaných parametrů existuje celá řada kategorií ekologických zátěží. Mezi nejvíce zmiňované kategorie patří například globální oteplování (GWP z anglického Global warming potential), humánní toxicita (HTP), acidifikace (AP), úbytek stratosférického ozónu (ODP), tvorba fotooxidačních látek (POCP) a další [B37]. Konkrétní skladba kritérií se volí dle účelu studie a zahrnutých technologií. Z porovnání výsledků některých studií (např. [B38], [B39] a [B40]) vyplývá, že parametr GWP je jedním z nejvýraznějších vlivů na životní prostředí v rámci odpadového hospodářství a zejména pak v souvislosti s provozem zařízení EVO. Nevýhodou metody LCA je její časová náročnost.

Autor práce v roce 2016 v rámci projektu [P2] koordinoval spolupráci s německou společností bifa, Gmbh s cílem vyhodnotit GWP různých konfigurací EVO. V potaz byla brána pouze fáze provozu. Studie ověřila, že v případě EVO lze majoritní GWP vysvětlit na základě zjednodušeného přístupu, kdy nejvýznamnější jsou toky, které lze popsat výše zmíněnými bilancemi. Studie tak potvrdila dříve prezentovanou metodiku v [A7].

Detailním hodnocením navázala práce [B19], jejíž cílem v této konkrétní oblasti bylo sestavit bilanční model, který bude umět pro libovolnou lokalitu, technologický koncept, parametry vstupujícího odpadů a množství využitého tepla odhadnout parametr GWP. Výsledky práce byly publikovány v příspěvcích [A13] a [A14] a následně v impaktovaném časopise [A15] (Příloha 5). Jako ilustrativní příklad výsledku je na obr. 7 uvedena závislost GWP na kapacitě zařízení EVO.



Obr. 7 GWP jako funkce kapacity EVO, resp. dodávky tepla z EVO do CZT

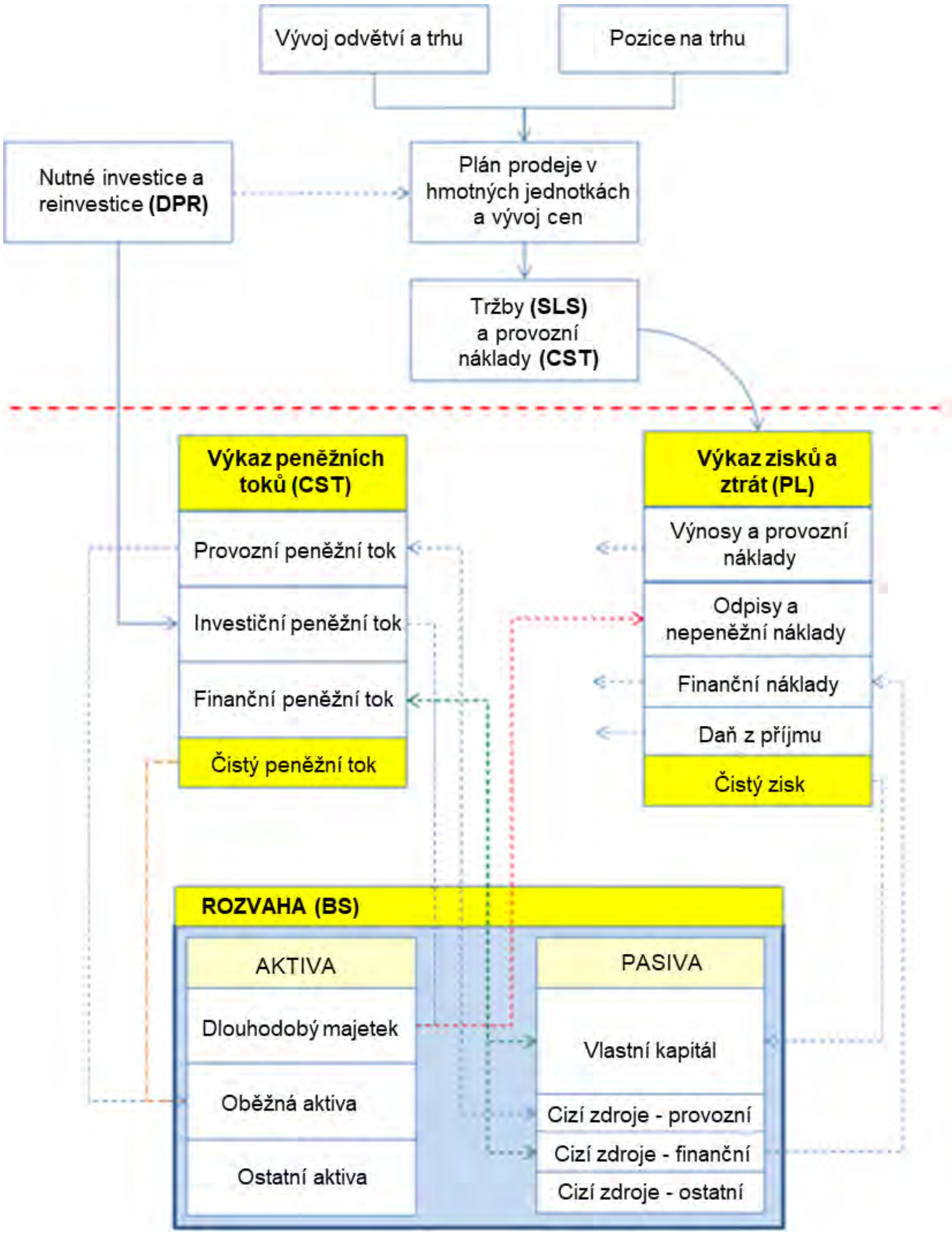
Obr. 7 ukazuje, jak klesá pozitivní efekt výroby tepla z EVO s jeho rostoucí kapacitou. Přestože zvyšující se kapacita znamená, že EVO v rámci konkrétní sítě (obr. 7 vpravo) dodá v souhrnu více tepla (plocha pod profilem spotřeby tepla se zvyšuje), měrná dodávka tepla vztažená na tunu zpracovaného odpadu klesá, kvůli propadu spotřeby v letních měsících. Tím klesá také měrná úspora paliva v konvenčním zdroji a tedy i úspora CO_2. Uvedený příklad předpokládá, že je upřednostněna dodávka tepla z EVO. Detailnější analýzy zpracované v rámci [B22] ukazují, že v některých případech se musí EVO podřídit provozu ostatních zdrojů. Jedná se zejména o případy předimenzovaných uhelných kotlů s vysokým minimálním výkonem, požadavek na zajištění nezbytné zálohy nebo poskytování podpůrných služeb elektrizační soustavě [A16].

Analýza v [B19] zahrnovala také emise z dopravy odpadů do EVO. Lze konstatovat, že z pohledu zpracování zbytkových odpadů (SKO) je příspěvek dopravy k emisím zanedbatelný. Z pohledu GWP je tedy zásadní se zabývat maximálním využitím vyrobeného tepla při respektování vzájemné spolupráce všech zdrojů dodávajících teplo do jednoho CZT, viz kap. 4.

3.4 Investiční náročnost, ekonomická bilance

V rámci projektu [P5] byla v roce 2011 navázána úzká spolupráce se specialistou, ekonomem Dr. Michalem Marešem. Cílem bylo rozšířit hmotnostní a energetické bilance o ekonomický modul tak, aby bylo možné posuzovat ekonomickou udržitelnost různých technologických variant EVO v jednotlivých lokalitách. Navržený ekonomický modul vychází ze standardních nástrojů ekonomické analýzy projektů a zahrnuje výkaz zisků a ztrát (profit and loss), rozvahu (balance sheet) a analýzu toku hotovosti (cash flow). Modul zahrnuje všechny podstatné aspekty a vazby mezi jeho jednotlivými částmi jsou patrné z obr. *8*.

Technologický návrh a hmotnostní a energetická bilance definuje tržby (SLS) a provozní náklady (CST). Ty vstupují do výkazu zisků a ztrát (PL), kde společně s dalšími položkami (odpisy, úroky, daně apod.) formují čistý zisk. Druhá větev modelu sleduje investice a reinvestice související s nákupem technologie a jejím udržováním (DPR). Obě větve se promítají do výkazu peněžních toků (CF).



Obr. 8 Struktura ekonomického modelu použitého pro hodnocení zařízení EVO

Na základě znalostí hlavních parametrů je stanoven čistý, resp. volný, peněžní tok. Ten se následně diskontuje (zohledňuje se časová hodnota peněz v budoucnosti [B41]) a dopočítávají se základní charakteristiky projektu, jako je prostá míra návratnosti, čistá současná hodnota projektu nebo vnitřní výnosové procento (*IRR*) [B41]. Ekonomický model byl následně konfrontován s požadavky jednotlivých investorů (např. ČEZ jako spoluřešitele projektu [P2] a dalšími privátními subjekty v rámci zpracování studií pro různé lokality).

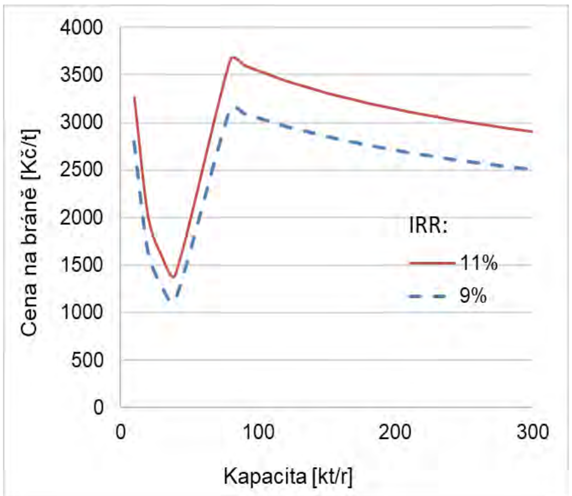
Problematika hodnocení projektů z pohledu ekonomiky je ve zjednodušené formě zařazena do výuky předmětu Bilancování procesních a energetických systémů (FSI-KBP), obor M-PRI, 2. stupeň, 1. ročník, zimní semestr. Získané znalosti pak studenti využijí v semestrální práci předmětu Energie a emise (FSI-KEE-A).

Typ budoucího investora a jeho požadavek na výnosnost, vyjádřený nejčastěji pomocí vnitřního výnosového procenta (IRR), popř. WACC (Weighted average cost of capital) v případě složeného financování, kdy se na investici podílí také další subjekt (typicky banka), má výrazný vliv na udržitelnost vlastního projektu. Bližší informace o způsobu výpočtu míry rizika, která se následně projeví do výše požadovaného IRR, uvádí [B18], kde je zmíněn ukazatel oceňování kapitálových aktiv (Capital asset pricing model – CAMP [B42]). Ten bere v úvahu míru rizikovosti investice vůči možnosti bezrizikového investování. ČR je bezpečnou lokalitou pro investování. V našem konkrétním případě se jedná o průnik energetického průmyslu a OH. Obě odvětví vykazují dlouhodobě malou rizikovost. Po dosazení všech parametrů do modelu CAMP se požadované IRR z pohledu privátního investora pohybuje okolo 10 % za podmínky stabilního legislativního prostředí a nízkého rizika vzniku konkurenčního projektu, který by udržitelnost sledovaného projektu mohl zásadním způsobem ovlivnit.

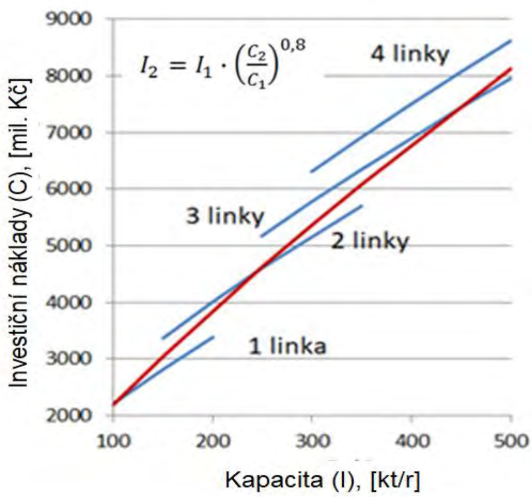
Příklad výsledku modelování ekonomiky EVO ukazuje obr. 9. Pro dvě konkrétní hodnoty IRR 9 a 11 % jsou zobrazeny průběhy očekávané ceny odpadu na bráně v závislosti na kapacitě projektovaného zařízení EVO (obr. 9 a)). Cena na bráně reprezentuje platbu producenta odpadu za zpracování jedné tuny odpadu. Pro budoucího provozovatele se tedy jedná o příjmovou položku. SKO reprezentuje palivo s negativní cenou. Analogicky jako v případě GPW, průběh ceny na bráně ovlivňuje dodávka tepla a zejména pak také klesající měrné investiční náklady. Investiční náklady EVO nerostou s kapacitou lineárně, ale dle exponenciálního modelu s hodnotou exponentu menší než 1. Pro technologii EVO byl v rámci projektu [P2] ověřen koeficient 0,8. (viz obr. 9 b). Se vzrůstající kapacitou je technologie realizována ve více linkách. Vybrané provozní soubory (spalovací zařízení a kotel, systém čištění spalin) se opakují. Jiné zůstávají společné (příjem odpadu a bunkr, energocentrum s turbinovým systémem).

Analýzy rovněž potvrdily, že v některých lokalitách může být výhodné uvažovat o EVO s kapacitou do 40 kt/r. Tato idea byla poprvé představena v [B43] a detailněji rozpracována v rámci řešení projektu [P2]. Nižší investiční náročnost v kombinaci s vysokým podílem uplatněného tepla v CZT představují kombinaci, která zejména v lokalitách, kde je nahrazován zemní plyn, vede k cenám za zpracování na bráně srovnatelnými s dnešní úrovní ceny za skládkování.

Vytvořené technicko-ekonomické modely byly použity pro řešení celé řady studií, kdy objednatelem byla města jako dominantní producenti SKO nebo provozovatelé existujících zdrojů jako potenciální investoři do zařízení EVO. Komplexní studie byly zpracovány pro následující lokality: Písek, Tábor, Opava, Mělník, Dětmarovice.



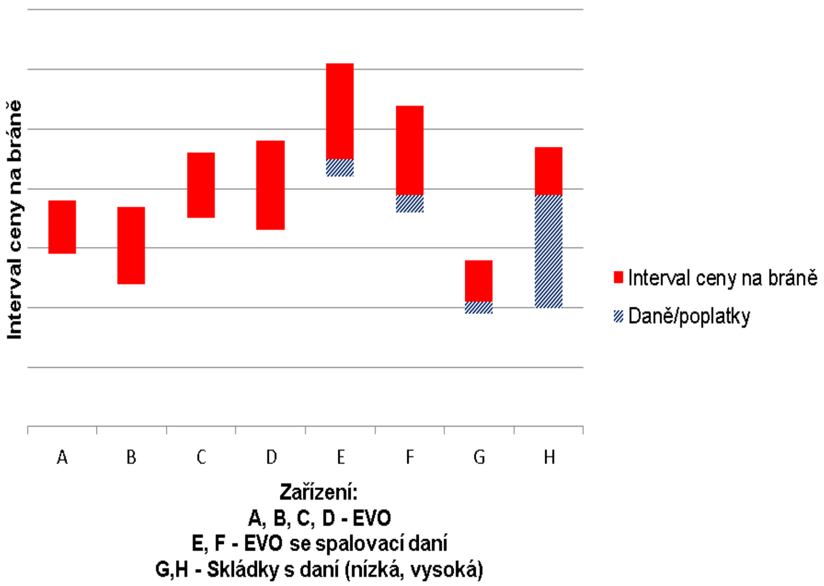
a)



b)

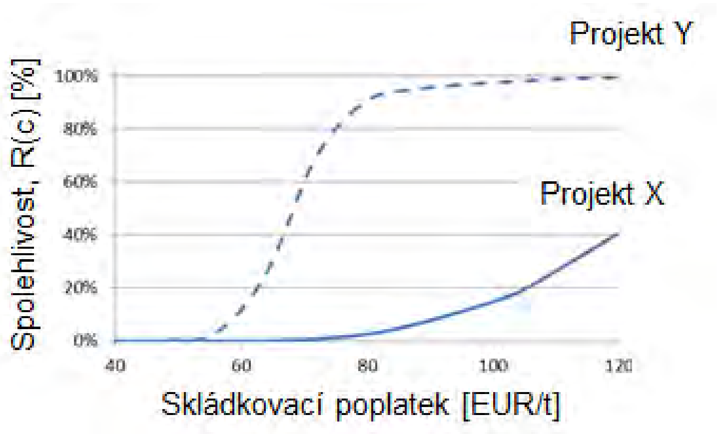
Obr. 9 Výpočet ceny odpadu na bráně jako výsledek aplikace technicko-ekonomických modelů (a) a použitý model investičních nákladů (b)

Není překvapením, že podmínky, ovlivňující ekonomiku plánovaných EVO, se v jednotlivých lokalitách budou lišit. Výsledkem bude, že se budou lišit také křivky pro jednotlivé lokality (analogické k obr. 9). Jednotlivé projekty lze z pohledu ceny odpadu na bráně vzájemně porovnávat. Porovnávat je lze i třeba se současnou cenou skládkování nebo budoucí cenou skládkování v případě uzákonění vyššího skládkovacího poplatku (obr. 10). Uvedený postup představuje možnost prvotního hrubého rozlišení mezi levnými (konkurenceschopnými) či drahými (nekonkurenceschopnými) projekty.



Obr. 10 Interval cen odpadu na bráně pro různá zařízení a poplatky/daně

Analýza ceny na bráně, popř. GWP dle kap. 4.2, se současně stala základem detailních analýz vedoucích k doporučení, kde a s jakou kapacitou projekty realizovat tak, aby vznikla kvalitní infrastrukturní síť s celkově nízkými dopady na budoucí cenu zpracování a životní prostředí. V takovém případě je nutné zohlednit prostorové rozdělení produkce odpadů a dopravu odpadů do zařízení různých kapacit. Problematice nadregionálního pohledu na plánování kapacit zařízení EVO se věnuje kap. 4. Současně lze testovat citlivost navrženého řešení na změnu významných parametrů. Příklad je uveden na obr. 11. Projekt X nebude udržitelný ani při vysokém skládkovacím poplatku. Projektu Y potřebuje skládkovací poplatek na úrovni 80 EUR/t (dnešní výše je cca 20 EUR/t). Parametr *Spolehlivost*, použitý na svislé ose, bude vysvětlen v kap. 4.1.



Obr. 11 Vliv skládkovacího poplatku na udržitelnost projektů ve dvou odlišných lokalitách

4 EVO v kontextu regionu, alternativní možnosti a teplárenství

V předchozích kapitolách práce byl diskutován význam EVO a stručně představeny jeho charakteristické rysy. Obr. 4 ukazuje propastný rozdíl mezi současnou instalovanou kapacitou zařízení EVO a potřebnou kapacitou, vyjádřenou množstvím materiálově nevyužitelných odpadů. Kap. 3.4 pak představila postupy vedoucí k odhadu ceny odpadu na bráně konkrétních projektů v dané lokalitě. Zásadní otázkou je, jak by měla být potřebná kapacita rozprostřena v rámci území ČR. Přitom je nutné sledovat ekonomické hledisko (zajištění cenově přijatelného způsobu nakládání s odpady pro všechny producenty nebo alespoň většinu producentů) a environmentální hledisko.

POH ČR, schválený v roce 2014 jako vrcholový plánovací dokument ČR v oblasti OH, vyhodnocuje potřebnou kapacitu EVO z pohledu nakládání s komunálními odpady při zohlednění budoucí míry separace. Doporučená kapacita pro rok 2024 činí 1,47 mil. tun a je agregovaná za celou ČR. Rozprostření kapacity v rámci území ČR a jednotlivých krajů není v POH ČR řešeno.

První pokus o vyhodnocení rozložení potřebné kapacity EVO ve větším detailu územního členění ČR byl proveden v rámci projektu [P5]. Základní územní jednotkou byly kraje. Původní myšlenkou bylo analyzovat jednotlivé kraje separátně, tzn. nebyla uvažována mezikrajová spolupráce. Předpokladem bylo, že jednotlivé kraje jsou víceméně soběstačné.

Bilanční výpočet bez asistence pokročilého nástroje v rámci projektu MPO-Efekt uvažoval:

- projekty EVO s roční zpracovatelskou kapacitou nad 100 kt/r,
- se 100% předností dodávky tepla z EVO do existující sítě CZT.

Na první pohled bylo z výsledků zřejmé, že rozdílnost produkce, existence či neexistence sítí tepla v městech jednotlivých krajů nemusí v případě takového přístupu vést k efektivním výsledkům. Klíčovým pojítkem byla logistika a odpověď na otázku, za jakých podmínek je výhodné odpady převážet i na delší vzdálenosti do zařízení nadregionálního významu (centrálních zařízení). Současně byl diskutován význam nového konceptu EVO s malou kapacitou (viz výše a [B43]). Otázkou bylo, zda není lepší vytvořit sít více menších mikro-regionálních zařízení.

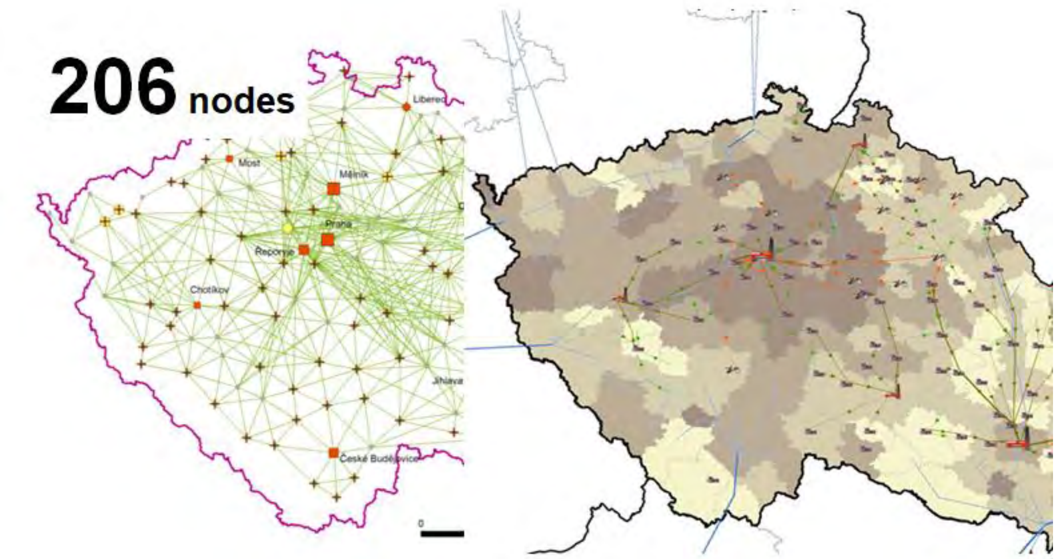
Z výše uvedeného lze vyvodit závěr, že na takto položené otázky nelze odpovědět bez efektivní podpory výpočtových nástrojů. Je nutné vzájemně posuzovat rozsáhlé území (ČR) a mnoho potenciálních projektů (řádově 20 až 30 lokalit, kde jsou dnes provozovány systémy CZT), přičemž produkce odpadů je územně distribuovaná a liší se v různých částech území zejména s ohledem na počet obyvatel, ekonomickou sílu regionu, procentuální zastoupení různých typů bydlení a míru třídění KO, popř. existenci a charakter průmyslové výroby (průmyslové odpady).

Podstatným aspektem pro naplnění plánované kapacity je dostupnost odpadu a jeho doprava od producentů do konkrétního zařízení. Proto vznikla myšlenka vytvořit pro účel plánování kapacit zařízení EVO v ČR optimalizační síťovou úlohu. Vývoj nástroje od prvotní myšlenky po finální produkt, použitelný v praktickém měřítku, je příkladem spolupráce mezi ÚPI a ÚM. První koncept byl navržen v bakalářské práci [B44]. Úloha později dostala propagačně-marketingový název NERUDA. Inspirací byla nerudovská otázka „Kam s ním?“.

4.1 Výpočtový nástroj NERUDA

NERUDA je nástroj pro logistické dopravní úlohy. Analyzované území je rozděleno do tzv. uzlů, které reprezentují produkci v daném územním celku. Základní úroveň detailu pro území ČR je obec s rozšířenou působností (ORP), kterých je v ČR 206. Součástí úlohy je model infrastruktury, který popisuje silniční a železniční síť mezi jednotlivými uzly. Jednotlivé hrany jsou v souladu s teorií grafů ohodnoceny maticí parametrů, které popisují specifické aspekty jednotlivých systémů (vzdálenost, zpoplatnění mýtem, druh komunikace, dopravní omezení apod). Nad touto sítí probíhá optimalizační výpočet, kdy jsou minimalizovány celkové náklady na dopravu a zpracování odpadů, popř. je úloha řešena jako vícekriteriální optimalizace. Jako neznámé veličiny (a tedy výstupy) jsou kapacity zařízení v jednotlivých lokalitách a toky po jednotlivých hranách.

Výsledek výpočtu je pak viditelný na obr. 12 v pravé polovině. Obrázek ukazuje doporučené rozmístění zařízení EVO, jejich optimální kapacitu (čím větší symbol, tím větší kapacita), svozové trasy do jednotlivých zařízení, použitý systém dopravy (silniční, železniční – v obrázku odlišeno barvou) a umístění překladišť odpadů.

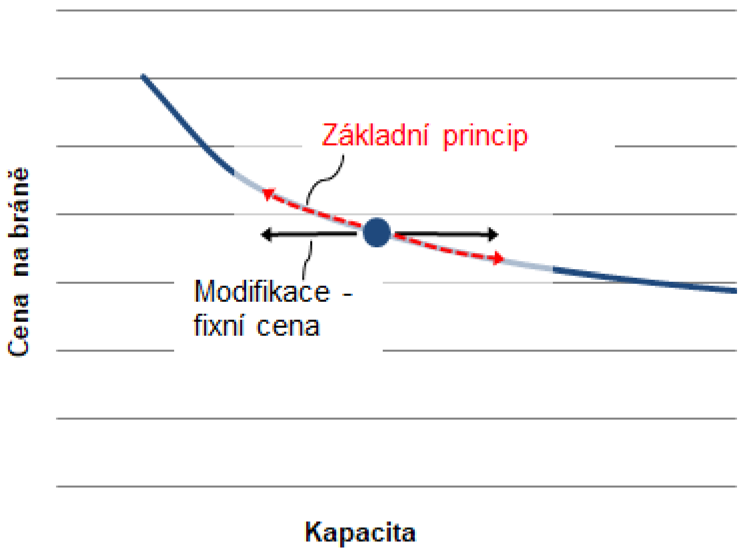


Obr. 12 Infrastrukturní model a příklad vizualizace výsledků výpočtu pomocí nástroje NERUDA

Ihned po dokončení práce [B44] následovala první aplikace nástroje v rámci studie pro Skupinu ČEZ, a.s. Úkolem byl prvotní screening vhodných lokalit pro výstavbu zařízení EVO. Zpětná vazba z reálné zakázky a diskuse s potenciálními investory vedla ke kontinuálnímu rozvoji nástroje, který je detailně popsán v dizertační práci [B18]. Rozsáhlost úlohy a nutný požadavek na její aplikační schůdnost si vyžádaly vývojové práce, zaměřující se na širokou oblast od rozvoje matematického modelu po hodnocení reálné aplikovatelnosti a dosažení výsledků v přijatelném čase. Jako příklad dílčího vývojového kroku lze jmenovat bakalářskou práci [B45] (vypracováno na ÚM), která umožnila testovat výpočtovou náročnost modelu při vzrůstající velikosti sítě a různé implementaci modelu infrastruktury ve formě grafu, nad nímž výpočet probíhá (úplný graf, bipartitní graf apod.). Navržený algoritmus, který využil heuristický přístup ke generování virtuální sítě, byl natolik inspirativní, že byl později prezentován v příspěvku [A17].

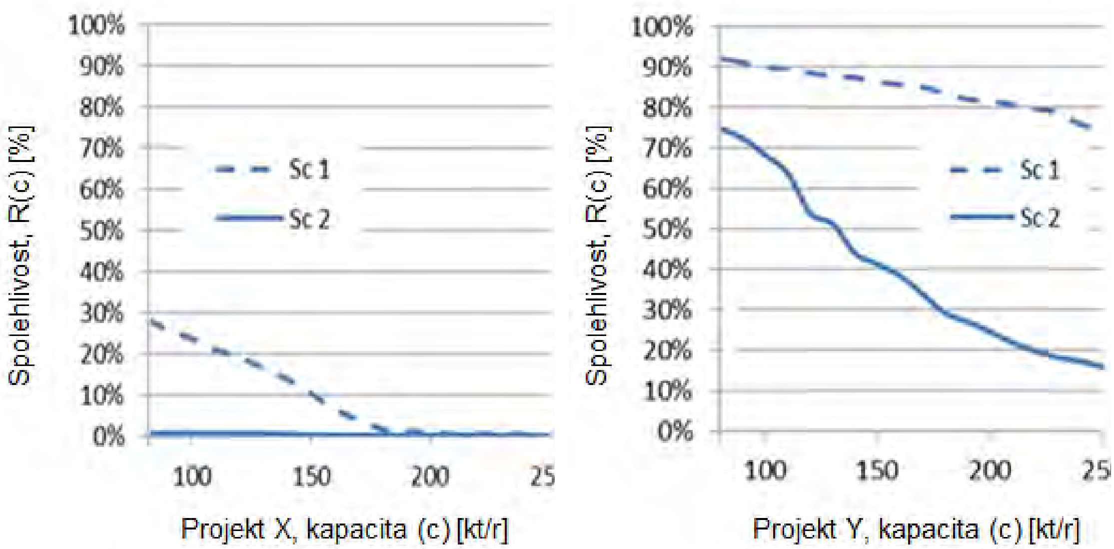
Na národní úrovni byl nástroj NERUDA využit při řešení projektu [P6], kde se již plně ukázaly jeho přednosti, založené vesměs na systematickém kontinuálním vývoji tohoto nástroje. Dále byl NERUDA použit při řešení studií v oblasti návrhu systému zpracování zbytkových materiálově nevyužitelných odpadů na nižších územních celcích, konkrétně dvakrát na krajské úrovni (2015) a dvakrát na mikroregionální úrovni (2015 a 2016). V roce 2015 pak byla na nástroji NERUDA postavena metodika řešení rozsáhlého projektu [P1]. Úkolem týmu vedeného autorem této práce bylo provést návrh optimální sítě nakládání s odpady pro celou řadu skupin odpadů zahrnujících jak komunální, tak průmyslové odpady.

Různé aplikace a modifikace nástroje NERUDA byly publikovány v impaktovaných časopisech. Práce [A18] (viz Příloha 6) sumarizovala princip nástroje NERUDA a jeho funkčnost byla demonstrována na případové studii, založené na datech získaných v rámci výše zmíněného projektu [P6]. Základní případ využití nástroje NERUDA je založen na znalosti křivky ceny odpadu na bráně, získanou postupy popsanými v kap. 3.4. Křivka představuje vstup do optimalizačního modelu a hledá se taková kapacita, které současně vyhovuje ceně na bráně. V obr. 13 je tento přístup označen šipkou s popisem (NERUDA – základní princip). Výsledek úlohy tedy leží na křivce ceny na bráně.



Obr. 13 Princip přístupu k ceně odpadu na bráně při různých aplikacích nástroje NERUDA

Úloha, řešená nástrojem NERUDA je koncipována jako stochastická, tzn. některý ze vstupních parametrů je brán jako neurčitý. Typicky se jedná o cenu na bráně, kdy je křivka, zobrazená na obr. 13, posouvána ve směru osy y, čímž vznikne pás ceny na bráně, ze kterého je vstupní cena pro jednotlivé scénáře volena náhodně. Stochastický přístup umožňoval definovat tzv. Survival function (R(c) v obr. 14). Funkce reprezentuje úspěšnost konkrétního projektu a jedná se o podíl počtu scénářů, kdy byl projekt s určitou kapacitou doporučen, vůči celkovému počtu scénářů. Na základě tvaru funkce lze identifikovat projekt jako rizikový (a) nebo málo rizikový (b).



a) Projekt s vysokou mírou rizika   b) Udržitelný projekt

Obr. 14 Příklady výsledků pro hodnocení rizikovosti projektu EVO s kapacitou nad 80 kt/r ve dvou různých lokalitách X a Y a dva scénáře Sc1 a Sc2 (upraveno na základě [A18])

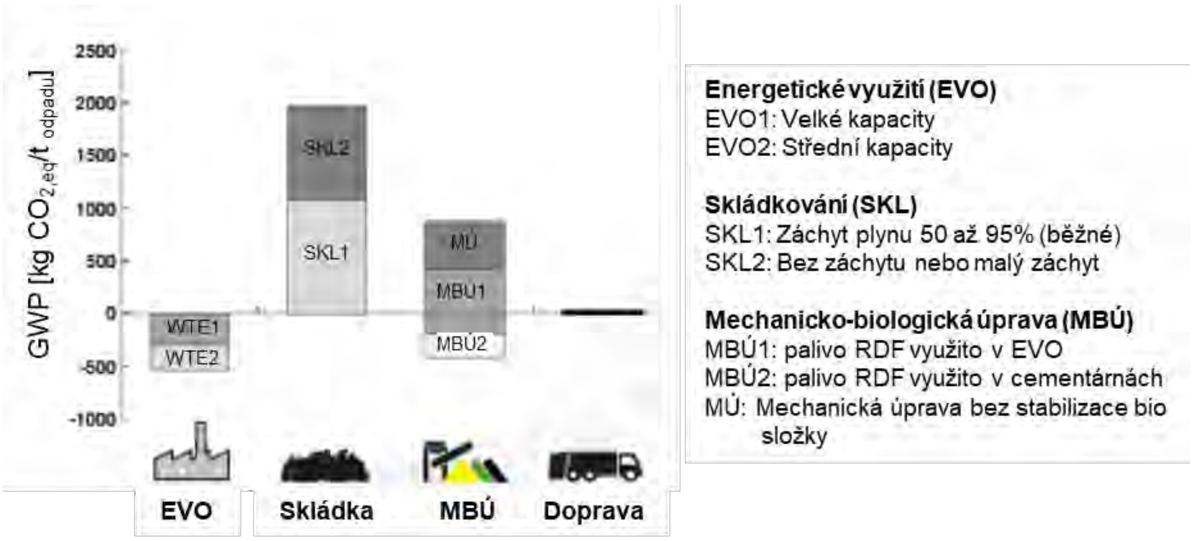
Rizikovost projektů EVO byla dále rozpracována v článku [A19] (viz Příloha 7). Je nutné zmínit, že např. v příspěvku [B46], [B47] a [B48] je dostupnost odpadu zmíněna jako jeden z rizikových faktorů výstavby projektu EVO. Provedená rešerše odhalila, že dosud publikované práce neuváděly metodiku, jak dostupnost odpadu vyčíslit. Toto bylo provedeno v příspěvku [A19], kde byl definován pojem „waste availability“ a waste availability factor - WAF“. Dostupnost odpadu v tomto kontextu není chápaná pouze jako množství vyprodukovaných odpadů v konkrétním vymezeném regionu, ale dostupnost je ovlivněna cenou za zpracování. Extrémně vysoká cena na bráně (gate-fee), vyžadovaná budoucím provozovatelem (např. jako důsledek vyšší očekávané výnosnosti), může znamenat malou ochotu producentů využít toto zařízení, pokud naleznou jiné výhodnější (levnější) řešení. Dostupnost odpadu bude nízká. Naopak nízká cena za zpracování může způsobit, že i producenti ze vzdálenějších míst budou ochotní odpad dopravovat do zařízení. I přes zvýšené náklady na transport nízká cena na bráně povede k atraktivním celkovým nákladům. Dostupnost odpadu v takovém případě bude velká. Dostupnost odpadu tedy bude záviset na ceně na bráně. Podstatné je, že závislost dostupnosti odpadu na ceně lze vypočítat s využitím nástroje NERUDA, resp. analýzou výsledků mírně modifikované úlohy. Úprava je znázorněna v obr. 13 vodorovnou čarou. Cena za zpracování je fixní, a tedy nezávisí na kapacitě. Kapacita se uvolní a hledá se takové množství odpadu, které se vyplatí do zařízení s danou cenou na bráně svážet. Při měnící se ceně je výsledkem křivka dostupnosti odpadu. Jedná se tedy o alternativní využití síťové úlohy.

4.2 Environmentální aspekty v účelové funkci nástroje NERUDA

Dosud prezentované aplikace nástroje NERUDA se zaměřily na ekonomickou optimalizaci. Účelovou funkci lze rozšířit také o ekologické hledisko. Globální oteplování, přičítané produkci antropogenního CO_2, představuje silně diskutované téma. Jedním z odvětví, které významně přispívá k produkci skleníkových plynů, je odpadové hospodářství. Příklady hodnot GWP jako indikátoru tvorby skleníkových plynů pro zařízení EVO byly uvedeny v kap. 3.3. Pro srovnání jsou v obr. 15 uvedeny typické rozsahy GWP pro zpracování zbytkových odpadů v různých zařízeních. Ze srovnání je zřejmé, že v ČR dnes nejrozšířenější metoda skládkování produkuje významné množství GHG, a to ve formě tzv. skládkových plynů, které jsou zastoupeny zejména metanem.

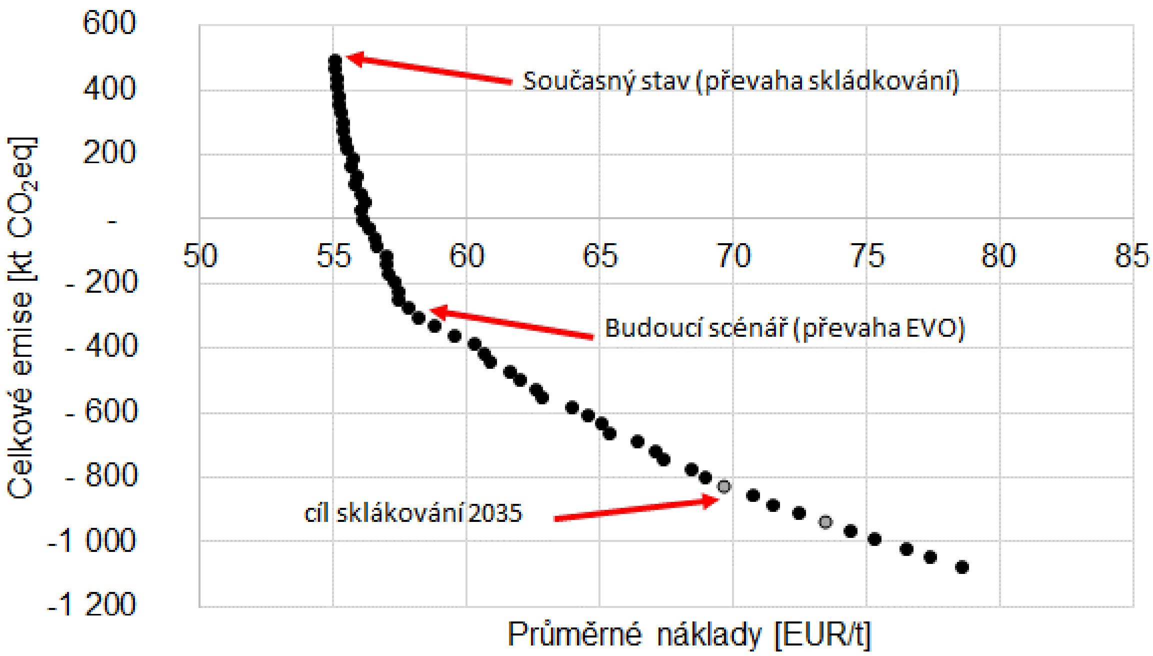
GWP je významné i pro skládky, které jsou vybaveny systémem odplynění. Zdroj [B49] uvádí, že lze dosáhnout účinnosti záchytu cca 75 %.

Z technického hlediska však nelze skládku zabezpečit dokonale. Analogicky jako pro EVO (viz kap. 3) lze zpracovat analýzu GWP pro technologii MBÚ, která je považována za alternativu EVO. MBÚ představuje zařízení pro mechanicko-biologickou úpravu odpadů. Nejedná se o cílové zařízení, ale pouze mezistupeň zpracování, který má za úkol vstupní tok rozdělit na několik frakcí, se kterými je nakládáno samostatně. Jedním z výstupů je tzv. palivo z odpadů (RDF). Obr. 15 v třetím sloupci zobrazuje celkový dopad různých variant zpracování odpadů na bázi paliva (tzv. RDF) v rámci celkového řetězce zpracování SKO v MBÚ s následným využitím kalorických produktů (RDF).



Obr. 15 Uhlíková stopa vyjádřená pomocí GWP různých technologií zpracování SKO (upraveno na základě [A15]

Informace o GWP různých zpracovatelských systémů SKO byly využity pro vytvoření vícekriteriálního optimalizačního modelu, který byl popsán v [A20] a dále rozpracován v [A21]. Environmentální část účelové funkce byla využita jako omezení pro ekonomickou úlohu NERUDA. Postupně bylo snižováno množství dovolených GHG emisí ze zpracování SKO ve všech zařízeních a byl sledován dopad na skladbu zařízení. Současný systém s celkovou produkcí 495 tis. t CO_2eq (220 kg CO_2eq/t), který je založen na skládkování SKO, se měnil. Obr. 16 zobrazuje jeden z výsledků výpočtu. Jedná se o tzv. Paretovu frontu, což je typický příklad výsledků vícekriteriální optimalizace, která dává do vztahu průměrné náklady na zpracování jedné tuny SKO s měrnými emisemi. Výpočet potvrdil, že přechod na nízkouhlíkové odpadové hospodářství, spojený s dosažením cílů EU o max. množství skládkovaných komunálních odpadů (kap. 2.3), bude spojen s vyššími náklady. Doporučené řešení s celkovou úsporou emisí GHG 770 tis. t/r oproti současnému stavu předpokládá kapacitu EVO 1,3 mil. t/r (současná činí 740 tis. t/r, viz obr. 4) a bude znamenat pouze minimální zvýšení nákladů. Emise CO_2 jsou dnes obchodovány v rámci (ETS z anglického Emissions Trading System). Sektor odpadového hospodářství do ETS není zahrnut. Jeho zahrnutí však nelze do budoucna vyloučit. Znamenalo by to jasnou hnací sílu a ekonomickou podporu pro přechod od skládek k šetrnějším formám nakládání s odpady.



Obr. 16 Vztah mezi budoucími náklady na zpracování SKO v ČR a uhlíkovou stopou (upraveno na základě [A21])

Obr. 16 ukazuje agregovaný výsledek za celé řešené území, tzn. ČR. Pozornost současně byla věnována také detailní analýze, jak jednotliví producenti odpadů přispějí k tvorbě či úspoře GHG podle toho, jakou variantu zpracování SKO v budoucnu využijí. Bližší rozklíčování těchto vztahů však vyžaduje specializovaný model, který se nasadí na výše prezentované výsledky tzv. globání úlohy. Problematika je řešena v [A22] (viz Příloha 8).

4.3 Kvantitativní hodnocení uzlů síťové úlohy – prognóza množství odpadů

Rozvoj a následné aplikace nástroje NERUDA, který optimalizuje nakládání s odpady pro síť producentů, zahrnující stovky uzlů (producentů), vyžaduje znalost kvantitativního parametru (produkce) ve všech uzlech sítě. Navíc je „výpočet NERUDA“ obvykle situován do budoucnosti – např. do roku, ke kterému je vázána určitá změna (2024 zákaz skládkování v ČR). Modeluje se budoucí systém infrastruktury, jejíž výstavba je časové náročná.

Nástroj NERUDA lze zařadit do skupiny tzv. „supply-chain models“ a ještě přesněji mezi tzv. reverzní úlohy, kde se výsledný produkt (většinou nechtěný, jako např. odpad, popř. nevyužité zboží nebo zboží reklamované) vrací od producentů do menšího počtu centrálních bodů [B16]. Byla provedena rešerše, jak autoři publikací, věnující se „supply-chain modelům“, pracují s parametry pro ohodnocení uzlů. Závěr je takový, že většina článků v této oblasti se zaměřuje na prezentování vlastností modelů. Analýza vstupních dat pro následné reálné výpočty publikována není. Ve většině případů detaily uvedeny nejsou. Výsledky rešerše společně s výsledky podrobné analýzy dostupnosti a systému zpracování dat v OH v ČR vedla autora práce k nutnosti iniciovat výzkumné aktivity v oblasti prognózování prostorově distribuovaných hierarchicky uspořádaných dat. Výsledky výzkumu jsou shrnuty v dizertační práci [B20] a v článcích v impaktovaných časopisech [A23] (viz Příloha 9). Výpočtový nástroj dostal označení Justine a je opět výsledkem spolupráce ÚPI a ÚM. Případová studie v [A23] vycházela z projektu [P1] a zabývala se prognózou nebezpečných odpadů. Specifickým rysem bylo, že se celkem zabývala 380 typy odpadů (katalogových čísel), které byly sdruženy do 6 skupin. Podstatné je, že skupiny byly disjunktní a jednotlivé skupiny se neovlivňovaly. Prognózu proto bylo možné řešit šesti paralelními výpočty. Tento případ lze označit jako prognózu bez interakce komponent.

Mnohem složitější případ, který byl zmíněn v příspěvku [A24] a [A25] a nedávno rovněž publikován v [A26] (viz Příloha 10), je prognóza množství a složení komunálních odpadů. Tento případ byl opět poprvé řešen v rámci studie [P1] a dále byl rozpracován v projektu [P2]. Jak nepřímo vyplývá z kap. 2, existuje závislost mezi množstvím separovaných odpadů, jako je papír, plast a sklo, a obsahem těchto komodit ve zbytkových odpadech, jejichž součet tvoří produkci zbytkového SKO. Pokud je vytříděno více plastů, musí jích méně zůstat v SKO. Takový systém byl označen jako systém s interakcí [A23] (viz Příloha 9) a kromě „územní podmínky“, která vyžaduje zachování hmoty ve stromové struktuře, musí v takovém systému ještě platit zákon zachování hmoty jednotlivých komponent vyjádřený tzv. „podmínkou složení“ [A26]. Počet omezení v modelu Justine vzrůstá. Problematika prognózování a další rozvoj nástroje Justine je řešen v rámci probíhajícího projektu [P7], jehož je autor hlavním řešitelem.

5 Shrnutí a další směry vývoje

Dosavadní výzkum autora v předmětné oblasti se snahou o úzkou spolupráci s aplikačním sektorem generuje další výzkumné výzvy. Jako příklad jsou uvedeny dva tematické okruhy, které jsou rozpracovány, ale dosud nebyly publikovány. Společným znakem je využití moderních matematických modelů pro řešení praktických úloh. Rozvoj těchto nástrojů (po teoretické stránce) probíhá v rámci dvou řešených projektů [P8] a [P9].

5.1 Komplexní posouzení integrovaného systému EVO - teplárna

Výše bylo zmíněno, že zásadní pro ekonomiku a enviromentální dopad je uplatnění tepla z EVO v síti CZT. Doposud provedené analýzy vycházely ze znalosti potřeby tepla v dané síti CZT, která byla nejčastěji definována ve formě křivky tvořené spotřebou tepla během 12 měsíců (viz obr. 7). Při analýzách se dále předpokládalo, že EVO bude preferovanou technologií, tzn. že teplo z EVO bude využito přednostně. Tato situace byla znázorněna na obr. 7, kde dodávka tepla z EVO pokrývá spodní část diagramu a je limitována pouze celkovou spotřebou tepla v síti.

Dosavadní analýzy, prezentované v [B22] a zejména pak v příspěvcích [A27] (viz Příloha 11), [A16] a [A28], ukazují, že pro zpřesnění odhadu dodávky tepla a tím i celé ekonomiky EVO je nutné zohlednit také další aspekty:

- Posouzení budoucího systému, kde integrované EVO spolupracuje s existující teplárnou, je významné z pohledu využití jednotlivých zdrojů
- Analýza v kratším časovém intervalu vede k přesnějším výsledkům. Jako vhodný kompromis mezi přesností a výpočtovou náročností se jeví denní průměry. Hodinové průměry již znatelně prodlužují výpočtový čas a jejich přínos k přesnosti je zanedbatelný.
- Zohlednění reálného využití jednotlivých zařízení, ze kterých se systém skládá, rovněž ovlivňuje výsledky. Teplo z EVO nemusí být vždy prioritně využito. Příčinnou mohou být technická omezení – výkonový rozsah kotlů, poskytování podpůrných služeb elektrizační soustavě, zálohování zdrojů. O využití jednotlivých kotlů a turbin rozhoduje ekonomika, doplněná o omezující podmínky (jako např. maximální. produkce CO_2) [A28].
- Přímá akumulace energie ve formě vyrobeného tepla nebo využití odpadní tepla pro zvyšování energetické hodnoty vstupních paliv (sušení kalů z čistíren odpadních vod a následná příprava palivového mixu s materiálově nevyužitelnými plasty) zlepšuje ekonomiku celého systému.
- Cena tepla z EVO, která vstupuje do technicko-ekonomického modelu, popsaného v kap. 3.1, by měla být předmětem výpočtu. Princip byl prezentován v [A16]. Dílčí analýzy ukazují, že cena tepla a také skutečné množství dodaného tepla výrazně závisí na budoucím provozním režimu existujících zařízení, resp. možností jejich odstavení a tím získání úspor variabilních nákladů (palivo, emisní povolenky apod.).

V tomto kontextu je přínosné pokračovat ve vývoji nástroje dle [B22].

5.2 Rozšíření nástroje NERUDA o kritéria související s emisní stopou

Kap. 4.2 ukázala, jak síťový model může kombinovat ekonomické a ekologické aspekty. Indikátor GWP, na kterém byl dopad na životní prostředí dosud představen, lze považovat za indikátor příspěvku ke globálnímu jevu, v tomto případě globálnímu oteplování. V souvislosti s realizací budoucí infrastruktury OH a zejména pak EVO je odborná i laická debata vedena spíše ohledně lokálních dopadů. Patří sem produkce škodlivých emisí a v mnoha případech také hluková zátěž. Přestože rozptylové studie, které mají za úkol posoudit dopad záměrů na změnu kvality ovzduší, jsou součástí povolovacích procesů a jsou tedy vyžadovány legislativou, lokální dopady při plánování umístění a kapacity nejsou v současných simulačních a optimalizačních nástrojích zahrnuty. Nástroj označený jako holistický by toto měl ovšem umět. V článku [A29] byla představena idea takového nástroje. V současné době probíhá vývoj nástroje jako celku. Nástroj by měl při plánování zpracovatelských kapacit zohledňovat:

- ekonomickou stránku – náklady na dopravu a zpracování, náklady na zpracování v průběžných zařízeních a zpracování v koncových zařízeních,
- globální environmentální dopady vyjádřené GWP,
- hustotu osídlení,
- současnou úroveň znečištění ovzduší,
- intenzitu a směr šíření emisí z nově plánovaných zdrojů a související dopravou,
- úspory emisí ze současných zdrojů v důsledku náhrady tepla, popř. elektřiny.

Jedná se o vícekriteriální optimalizaci, na kterou lze nahlížet z více úhlů pohledu. Pro minimální cenu je podstatná co nejužší synergie s teplárenským zdrojem – co možná nejvyšší využití tepla ale také sdílení existující infrastruktury, nakupovaných služeb i zaměstnanců. Vzhledem k poloze areálů teplárenských zdrojů v blízkosti spotřebitelů tepla bude EVO lokalizováno přímo v hustě obydlených oblastech či v jejich blízkosti. Takové řešení dává ekonomický i environmentální smysl z pohledu minimalizace dopravy odpadů. Na druhou stranu, koncentrace dopravy v blízkosti EVO a zvýšená lokální emisní zátěž je zřejmý důvod protestů obyvatel. Druhé extrémní řešení je lokalizace EVO mimo obydlené oblasti. V takovém případě musí být realizován odvoz odpadů do tohoto zařízení. Takové EVO bude mít často omezenou nebo žádnou možnost dodávky tepla a s tím související nižší úsporu GHG. Dopad vyprodukovaných emisí na okolní obyvatelstvo bude nízký. Nedojde ale k úspoře emisí v důsledku náhrady fosilních paliv. Holistický nástroj může takové externality identifikovat a modelovat, jak přísnější požadavky na snižování lokálních environmentálních dopadů ovlivňují náklady na zpracování. Na základě ceny za „ekologii" lze stanovit omezení projektu.

Je evidentní, že popsaný výpočtový model bude náročný na vstupní data. Jako příklad lze jmenovat:

- aktuální emisní mapy a meteorologické informace,
- rozložení pohybu obyvatel v městské infrastruktuře v čase,
- současný energetický mix v modelovaných lokalitách a emise související s dodávkou elektřiny a tepla.

Uvedené datové soubory jsou dostupné a získatelné. Za předpokladu, že je cílem výpočtu určení místa budoucího záměru a jeho kapacity, je pro určení dopadu nutné modelovat rozptyl emisí z bodového zdroje (zařízení EVO) a současně liniového zdroje – doprava odpadů po hranách grafu. Jedná se o výpočtově náročnou úlohu. Z dosavadního výzkumu [A29] se zdá být realistické, že lze provést rozsáhlý pre-processing, který poskytne náhradní vstupy a udrží vlastní optimalizační úlohu řešitelnou.

5.3 Routingové algoritmy a „otevřená data" - optimalizace svozu odpadů

Dalším atraktivním směrem výzkumu, který je zmíněn v této práci, je myšlenka vývoje výpočtového nástroje pro zefektivnění systému svozu odpadů pro následné materiálové a energetické využití. Svoz frakcí komunálního odpadu představuje nákladnou aktivitu, která zatěžuje každoroční rozpočet obcí. Náklady se liší podle typu odpadu, velikosti svážené aglomerace a dle systému, prostřednictvím kterého je sběr a svoz realizován. Mezi klíčové parametry patří sypná hmotnost a hustota produkce, tj. reálné přejezdové vzdálenosti mezi kontejnery. Například průměrné náklady v ČR na svoz a odstranění či využití směsného komunálního odpadu činily v roce 2017 cca 2700 Kč/t. Za svoz separovaného plastu, jeho dotřídění to v průměru bylo 7500 Kč/t [B50].

Do budoucna lze ze strany EU a vyvíjející se legislativy ČR očekávat rostoucí tlak na množství separovaně sbíraných složek (papír, plast, biologicky rozložitelný odpad a další). S výše uvedeným lze očekávat vzrůstající náklady na svoz a využití nezbytné infrastruktury, která má směřovat k naplňování principů cirkulární ekonomiky.

Cílem je vytvořit nástroj, který pomůže pro dané město, aglomeraci, popř. přilehlé obce, v horizontu cca 5 let nastavit efektivní systém svozu potenciálně materiálově využitelných složek, který bude založen na následujících atributech:

- dosažení cílových hodnot výtěžnosti, minimálně dle požadavků daných legislativou ČR, popř. vyšších, pokud to bude výhodné,
- ekonomická přijatelnost,
- aplikace „SMART“ řešení (dlouhodobé sledování výtěžnosti a nákladů jako nutná podmínka pro hodnocení reálného potenciálu budoucích změn),
- důsledné hodnocení získaných dat a vyvození závěrů, návrh opatření.

Z provedené rešerše [B51] vyplývá potřeba disponovat optimalizačním nástrojem na bázi routingových algoritmů (ARC nebo VRP). Byla představena celá řada teoretických konceptů a matematických modelů pro takovou úlohu. Praktická aplikovatelnost však vyžaduje vedle robustního matematického řešení zohledňovat reálné situace, které svoz ovlivňuji. Jedná se o:

- kolísající produkci svážených odpadů,
- uzavírky a dopravní omezení na svozových trasách,
- měnící se intenzitu dopravy v kritických místech městské infrastruktury.

Nezbytné tedy bude využívání otevřených dat, jejichž množství se bude v prostředí SMART Cities zvyšovat a jejich dostupnost bude narůstat.

Následující text přináší zamyšlení nad tím, jak by mohl fungovat takový systém optimalizace svozu odpadů.

Sběrné nádoby (kontejnery, popř. popelnice) jsou sledovány za pomoci snímačů naplněnosti kontejnerů. V případě nádob s malým objemem není nutné sledovat všechny, ale analýzou jsou stanoveny reprezentanti. Po dosažení stanovené míry naplnění jsou sváženy. Každý snímač disponuje základními informacemi o nádobě (ID, poloha, velikost, druh komodity). Obsluha kontejnerů je realizována pomocí svozových vozidel (KUKA vozů). Každá svozová trasa vozidla je plánována na základě aktuálního stavu naplnění nádob. Současně mohou být svezeny i nádoby s nižší naplněností, pokud systém vyhodnotí, že je to ekonomické a levnější, než kdyby tato nádoba měla být svážena později. V okamžiku výsypu se automaticky snímají základní informace o dané nádobě. Odpad je naložen na KUKA vůz a odvážen do koncového zařízení, kterým může být dotřiďovací linka, kompostárna, zařízení pro energetické využití (v případě SKO) či jiné zařízení. Svozový vůz je možné průběžně vážit. Typicky se toto provádí při svozu více obcí jedním vozem na začátku a konci obce. Analogicky lze sledovat výtěžnost a produkci v různých částech města, městských čtvrtích, různých typech zástavby a tím zpřesňovat modely prognózování produkce.

Svozový automobil po naplnění (v důsledku optimalizace svozových tras je maximálně využita kapacita) přijíždí na dotřiďovací linku. Automobil je identifikován (komodita, svozová trasa, jednotlivý producenti apod.) a přesně zvážen. V tuto chvíli je svezené množství odpadu rozpočítáno mezi producenty na základě verifikovaného algoritmu, který mimo jiné využívá dílčí informace o naplněnosti všech svezených nádob a průběžných vážení celého automobilu.

Svezená frakce je dotříděna a rozdělena na jednotlivé komodity, které jsou recyklovatelné a obchodovatelné na trhu druhotných surovin (skutečné materiálové využití) a materiálově nevyužitelný zbytek (sekundární odpad, viz obr. 2), který bude skládkován (výhledově energeticky využíván). Jednotlivé frakce jsou shromažďovány ve velkoobjemových kontejnerech. Při vývozu je kontejner identifikován a zvážen. Získaná data jsou zpracována sofistikovanými algoritmy s cílem:

- určit výtěžnost skutečně využitelných složek, které se uplatní na trhu,
- provést výpočet skutečných nákladů na produkci jednotlivých komodit při zohlednění celého řetězce (svoz, dotřidění – cena na trhu) nejen souhrnně za sledované období a území, ale také individuálně pro jednotlivé producenty (ulice, obce, apod.) v různých časových obdobích
- optimalizovat celý řetězec.

6 Závěr

Odpadové hospodářství je relativně mladý a dynamický obor. V rozvinutých zemích světa lze pozorovat trend směřující k nakládání s odpady environmentálně šetrným způsobem, kdy je snaha maximálně redukovat spotřebu primárních surovin. Tento trend se označuje jako cirkulární ekonomika a zejména EU je velmi aktivní na poli přípravy a schvalování legislativy, podporující cirkulární principy v odpadovém hospodářství.

Vybrané legislativní předpisy jsou v práci shrnuty a zdůrazněny dlouhodobé cíle, které z nich pro ČR vyplývají. Na základě volně dostupných dat o produkci komunálních odpadů byl ukázán vývoj klíčových indikátorů v posledních letech. Současný trend pozvolna klesajícího množství skládkovaných biologicky rozložitelných i všech komunálních odpadů je nedostatečný. Nedostatečná je rovněž příprava komunálních odpadů pro materiálové využití. Jako hlavní problematický proud byl identifikován směsný komunální odpad – materiálově obtížně využitelný zbytkový odpad. Jeho preferovaným způsobem využití je energetické využití. Instalovaná kapacita zařízení EVO je v ČR 740 tis. tun/r a je nedostatečná. Přestože v kontextu EU není energetické využití příliš podporovanou technologií, její kapacitu je nutné do budoucna zvednout na dvoj– až trojnásobek současné hodnoty.

Práce se zaměřila na sumarizace pokroku ve vývoji sofistikovaných výpočtových nástrojů pro podporu koncepčního plánování zpracovatelských kapacit. Jako příklad výsledku výzkumných aktivit byl uveden celočíselný lineární stochastický model síťové úlohy s názvem NERUDA a jeho doplňkové moduly. Výsledek je ukázkou efektivní mezioborové spolupráce založené na využití možností aplikace metod z oblastí matematiky v průmyslové i komunální sféře (opět založeno na úzké spolupráci mezi Ústavem procesního inženýrství a Ústavem matematiky FSI VUT v Brně při zadávání a vedení závěrečných prací).

Na základě autorem publikovaných prací zejména v impaktovaných časopisech byl ukázán přínos existence takového modelu pro další výzkumné aktivity i aplikace v komerční sféře. Zpětná vazba z průmyslové sféry je pak hnací silou pro další výzkumné aktivity a současně představuje zdroj námětů pro přípravu témat závěrečných (bakalářských i magisterských) a doktorských prací. Lze konstatovat, že vytvořený komplex výstupů, související s nástrojem NERUDA, odpovídá současnému trendu vývoje takových nástrojů mimo jiné tím, že je holistický.

V první části práce byly sumarizovány poznatky, týkající se vlastní technologie energetického využití odpadů. Byla zmíněna problematika hmotnostní a energetické bilance, která je úzce spojena s hodnocením energetické účinnosti a vyčíslením produkce emisí v lokálním i globálním měřítku. Jako konkrétní výsledek výzkumu byl uveden software W2E, který je kromě řešení reálných úloh využíván i ve výuce na pracovišti autora. Důležitým bodem je využití tepla, uvolněného termickými procesy v rámci systémů CZT.

Byly zmíněny aktivity a současné výpočtové možnosti, vedoucí ke zpřesnění dodávky tepla detailním modelováním integrace zařízení EVO s existujícím teplárenským provozem. Dodávka tepla má také zásadní vliv na ekonomiku zařízení. S využitím technicko-ekonomického modelu byla ukázána konstrukce důležitého vstupu pro optimalizační výpočty – závislosti nákladů na zpracování jedné tuny odpadů na kapacitě zařízení EVO. Vzhledem k tomu, že se křivka liší pro jednotlivé lokality, lze provést optimalizační výpočet s cílem alokovat kapacity zařízení EVO na území ČR, což je prováděno právě pomocí nástroje NERUDA.

Vedle ekonomiky lze účelovou funkci doplnit rovněž environmentálními kritérii. Analogicky k ekonomickému vstupu byla vysvětlena konstrukce křivky, hodnotící dopad zařízení EVO na produkci skleníkových plynů. Jako indikátor byl využit GWP. Pro hodnocení lokálního znečištění ovzduší v blízkosti uvažovaných zařízení EVO byl ukázán směr budoucího vývoje nástroje. Nástroj NERUDA dnes pracuje v detailu větších územních celků (typicky 206 obcí s rozšířenou působností). V závěru práce byla diskutována potřeba řešení logistiky odpadů v rámci jednotlivých obcí. Pro tento účel byl doporučen vývoj routingového algoritmu, který by silně využíval data zpřístupněná městskou samosprávou a veřejnými subjekty. Jejich význam a dostupnost bude narůstat.

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Waste to energy – An evaluation of the environmental impact

Martin Pavlas*, Michal Touš, Ladislav Bébar, Petr Stehlík

Brno University of Technology, Institute of Process and Environmental Engineering – VUT, ÚPEI, Technická 2896/2, 616 69 Brno, Czech Republic

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ABSTRACT

The thermal treatment of waste with the heat recovery (Waste to Energy – WTE) provides us with clean and reliable energy in the form of heat as well as power. This has contributed to primary energy savings in conventional utility systems. Impact of WTE regarding the environmental issue is quantified in this paper. The evaluation focuses on the calculation of primary energy savings. A novel methodology is proposed. Then an assessment of the emission rate is made and results discussed. Real up-to-date municipal solid waste incinerator with nominal capacity 100 kt/y is involved in a case study. Benefit of its operation has been compared with other up-to-date utility concepts.

1. Introduction

Quantity of waste produced either by inhabitants or by industrial companies is considered to be one of the most serious environmental problems. Annual production of municipal waste in EU undergoes significant grown at the end of millennium as documented on Fig. 1 and it reached 522 kg per capita in 2007 [1]. Landfilling of waste, which has not been pre-treated to decrease their organic matter content, is limited. This represents a driving force for development of new, more effective methods of waste processing. Thermal treatment with heat recovery is one of the preferred options not only within the EU [2,3]. In comparison with other processes it has a number of advantages [4,5]: (i) short time of treatment; (ii) possibility of treating extremely dangerous and/or hazardous waste; (iii) possibility of off-gas control; (iv) possibility of utilizing heat released by the oxidation process usefully.

On the other hand, several problems related to human health coming out from its operation are discussed [6]. The requirements on the quality of side products from the incineration process regardless of its state of matter (flue gas, waste water, solid residues) set by environmental legislation constantly raise. Originally simple incineration facilities have developed into complex processes [7]. In order to meet strict emission limits (see Fig. 2 [8,9]) each new generation of incineration plants involve newer and more effective air pollution control devices. This development trend is demonstrated for example by Porteous [10]. Comparison of emissions into air from two generations of plants is presented. It is shown that the discharge rate of pollutants (including extremely hazardous dioxins) is several order lower in up-to-date facilities. A general review of information concerning dioxin formation and minimisation issues from waste incineration can be found in [11]. A comparison of the most efficient technologies for this type of emissions reduction convenient for municipal solid waste (MSW) incineration is presented by Pařízek [12]. However, numerous other arrangements of flue gas cleaning system are available. Their performance is influenced by many specific aspects (properties of waste, legislation, etc.) and the presented results cannot be generalized. The present research and development activities concentrate on waste streams in solid state as well. For example, the questions of bottom ash utilization and safe disposal of gas cleaning residues is discussed [13,14].

With development of the processes the requirement on effective recovery of heat released is constantly growing. Today we therefore speak about WTE. Efficiency of energy production from waste is much lower than efficiency of energy generation in conventional plants utilizing fossil fuels. This is caused by several constraints given by specific properties of waste used as a fuel (reduction of maximum output steam pressure due to corrosion risk, higher flue gas temperature leaving the boiler, etc.).

Due to more and more sweeping legislation related to the WTE plant operation, it provides us with one of the cleanest and reliable energy in the form of heat as well as power (see Fig. 2). However, this trend also has an important side effect. The overall energy

* Corresponding author. Tel.: +420 541 142 367; fax: +420 541 142 177.
E-mail address: pavlas@fme.vutbr.cz (M. Pavlas).

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Nomenclature

A	activity rate, t/y or MJ/y
CEF	controlled emission factor, kg/t or kg/MJ
E	emissions production rate, kg/y
E_{Alt}	energy released by combustion of an alternative fuel, GJ/y
E_f	imported energy to the combustion process (e.g. supplementary fuel), GJ/y
ER	overall emission reduction efficiency, –
E_{W}	energy released by waste combustion process, GJ/y
I_{imp}	imported energy not used for heat production, GJ/y
LCA	life cycle assessment
MSW	municipal solid waste
PE^{Ref}	primary energy consumed in the reference utility system, GJ/y
PE^{WTE}	primary energy consumed within the WTE plant, GJ/y
PES	primary energy savings, GJ/y
pes	specific primary energy savings, –
Q_{exp}	total amount of exported energy (thermal and electrical), GJ/y
UEF	uncontrolled emission factor, kg/t or kg/MJ
$\eta_{\text{th}}^{\text{Ref}}$	efficiency of heat generation in a reference heating plant, –
$\eta_{\text{el}}^{\text{Ref}}$	efficiency of power generation in a reference power plant, –
WTE	waste to energy

demand of the process is increasing. The more complex and effective the systems are, the higher is the energy demand for electrical appliances driving and higher consumption of heat for maintaining optimal operational regime. This decreases heat delivery to the consumers and plant power generation and subsequently it results in lower efficiencies of energy production. Regarding different waste heat utilization strategies WTE plants are classified as [15]: (i) those producing heat only; (ii) power plants without heat delivery; (iii) cogeneration systems where heat and electricity are produced simultaneously. The average net heat production efficiency addressed to the first group is 63%. Net

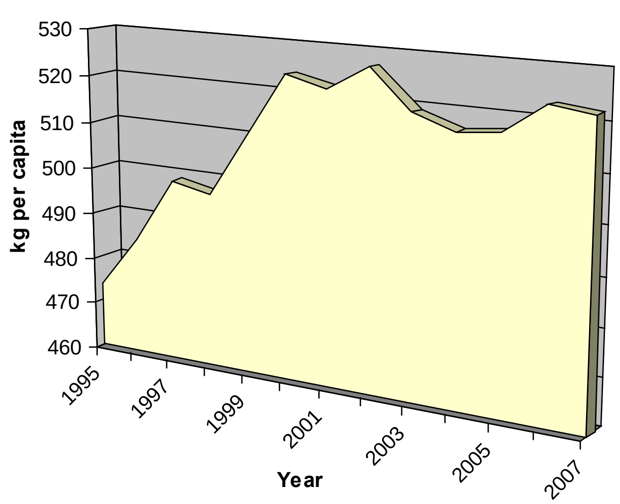


Fig. 1. Municipal waste collected per capita in the EU [1].

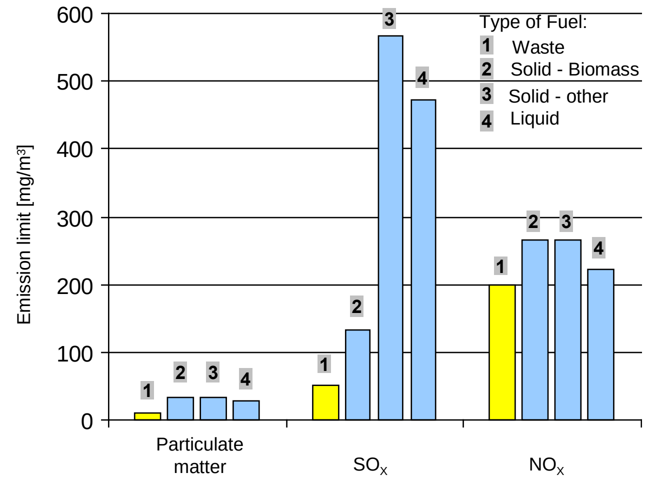


Fig. 2. Comparison of emission limits valid for waste incinerators and other large combustion plants according to fuel used (corrected values for uniform O_2 content 11%) [8,9].

efficiency of waste-based power plants reaches 18%. In the case of a cogeneration, total efficiency of 43% can be expected [15]. A new generation phase of thermal treatment process called Waste Fired Power Plants characterised by improved efficiency is researched [16]. Significantly higher energy conversion efficiencies are achieved through integration with natural gas-fired combined cycles [17,18].

2. WTE and its contribution to primary energy savings

A number of criteria to compare the effectiveness of energy recovery and utilization in incineration plants have been proposed recently. Their overview can be found in [19]. Their common feature can be seen in an effort to describe relation between energy outputs (produced or exported energy) on one side and energy demand on the other. They can be used only for comparison of energy effectiveness in similar facilities – municipal solid waste incinerators. An example of analysis based on one of the criteria can be found in [19].

For assessment of different waste management options, sophisticated approaches can be applied. One of the most frequently used methods is LCA [20]. This well-known method is still in progress – new approaches combining environmental and financial aspects are proposed [21]. Considering the incineration plant as an up-to-date utility system, it is necessary to work with a direct approach which enables comparison of impact of WTE systems with other competitive technologies as for example are highly efficient cogeneration from fossil fuels or utilization of renewable sources. Biomass with its future potential exceeding 300 Mtoe represents the most promising renewable source within the EU [22].

In the following text a simple methodology for comparing environmental impact of WTE systems and other up-to-date systems (cogeneration units, biomass-fired technologies, etc.) is proposed. Energy utilization within incineration plants has two benefits, waste is treated in a safe and environmentally friendly way and at the same time energy is produced. This leads to substitution of fossil fuels, source diversification, and security of supply. WTE contributes to primary energy savings (PES) in conventional power and/or heating plants.

Due to export of energy from WTE PES is, in presented novel approach, defined as the difference between primary energy

Table 1
Balance data per ton of treated waste.

	Energy flows in absolute values (GJ/t)	Conversion coefficient (−)	Energy flows in equivalent values (GJ/t)
Inputs			
Energy supplied by waste resp. alternative fuel, E_w resp. E_{alt}	10.29	1	10.29
Imported energy in the form of auxiliary fuel, E_f	0.05	1	0.05
Imported electricity, $I_{imp,el}$	0.06	2.6	0.16
Imported heat, $I_{imp,th}$	0.05	1.1	0.06
Outputs			
Total amount of exported heat, $Q_{exp,th}$	6.91	1.1	7.60
Total amount of exported electricity, $Q_{exp,el}$	0.25	2.6	0.65
PES (GJ/t)			7.97

consumed in conventional (reference) utility systems corresponding to the same amount of energy which is supplied by the WTE plant (PE^{Ref}) and primary energy necessary for the operation of the incineration process itself (PE^{WTE}):

$$PES = PE^{Ref} - PE^{WTE} \quad (1)$$

If the efficiency of heat and power production in reference plants ($\eta_{th}^{Ref}, \eta_{el}^{Ref}$) is known, Eq. (1) can be transformed into:

$$PES = \left(\frac{Q_{exp,th}}{\eta_{th}^{Ref}} + \frac{Q_{exp,el}}{\eta_{el}^{Ref}}\right) - \left(\frac{I_{imp,th}}{\eta_{th}^{Ref}} + \frac{I_{imp,el}}{\eta_{el}^{Ref}} + E_f\right) \quad (2)$$

where Q_{exp} denotes total amount of exported energy from WTE (thermal and electrical); I_{imp} is energy imported not used for heat production (thermal and electrical) and E_f is imported energy to the combustion process (e.g. supplementary fuel). Efficiencies used can differ according to location or region. At present typical efficiency values can reach 0.91 for heat production and 0.38 for electricity production. Their reciprocal values (i.e. 1.1 and 2.6 for heat and power, respectively) are used to compare different forms of energy (i.e. heat and power; electricity is considered as a more valuable form of energy, see Table 1). Eq. (2) can be written in symbolic form as:

$$PES = (Q_{exp}) - (I_{imp} + E_f) \quad (3)$$

3. Comparison of various concepts

3.1. WTE unit

Following example demonstrates calculation of achievable PES for a real up-to-date municipal solid waste incineration plant (further on as WTE) with a daily capacity of 300 t (Fig. 3). The output released in the combustion chamber by waste combustion is about 33 MW. The plant is in operation for more than 8000 h/y – availability and reliability of the plant are very important

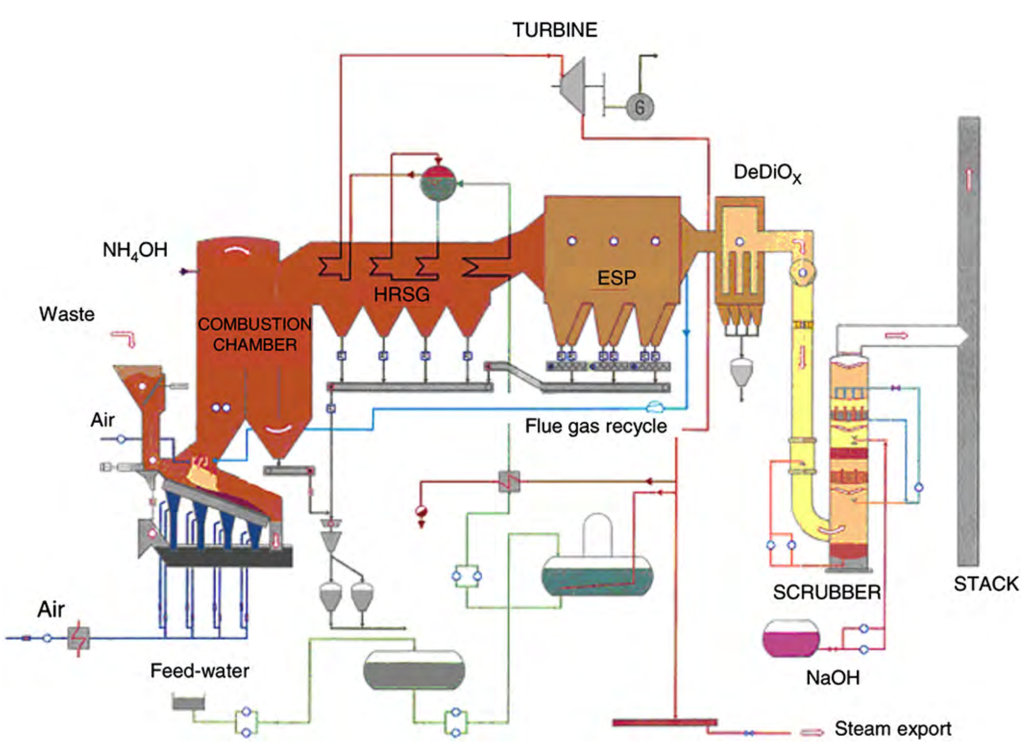


Fig. 3. Flowsheet of an up-to-date municipal solid waste incinerator with nominal capacity 100 kt/y.

Table 2
Results of comparison of different technologies in terms of achievable primary energy savings.

	WTE plant with backpressure turbine	Cogeneration based on reciprocating combustion engine	Biomass-fired heating plant with medium capacity	Biomass-fired ORC power plant	Biomass-fired ORC cogeneration plant
Fuel	Municipal solid waste	Natural gas	Biomass	Biomass	Biomass
No. of installations (−)	1	1	1	1	1
Availability (h/y)	8000	8000	8000	8000	8000
E_w resp. E_{alt} (GJ/y)	957,618	0	34,560	236,800	236,800
E_f (GJ/y)	5036	137,088	0	0	0
$I_{Imp,el}$ (GJ/y)	5560	0	518	0	0
$I_{Imp,th}$ (GJ/y)	4805	0	0	0	0
$Q_{exp,th}$ (GJ/y)	642,815	62,381	28,800	0	167,040
$Q_{exp,el}$ (GJ/y)	22,954	57,888	0	66,240	34,560
PES $= (Q_{exp}) - (I_{imp} + E_f)$(GJ/y)	741,848	83,799	30,284	174,316	274,508
pes $= \frac{Q_{exp}-(E_f+I_{imp})}{(E_{Alt}+E_f+I_{imp})}$(GJ/GJ)	0.76	0.61	0.84	0.74	1.16

parameters affecting the whole waste management chain [23]. Sensible heat of flue gas is used for steam production (temperature 400 °C, pressure 4 MPa) in the heat recovery steam generator (HRSG). This superheated steam subsequently flows onto the backpressure turbine, where it expands down to pressure of 1.2 MPa. Most of this low-pressure steam is exported; small part is consumed by the process itself. Regarding power approx. 60% is consumed on-site and the rest is exported. Performance data summarized in Table 1 were gained from annual reports and balance calculations. Using Eq. (3) and considering approx. 93 kt/y as real amount of processed waste, it was calculated that the plant contributed in relation to energy export to primary energy saving of 741,848 GJ per annum.

3.2. Overview of technologies included in assessment

MSW plant which was mentioned in the previous part has been compared with other environmentally friendly technologies. These competitors have reached high stage of development, they are proven in operation, they are available in the market and have a good potential of further development worldwide.

3.2.1. Cogeneration unit based on reciprocating combustion engine

Cogeneration unit based on reciprocating combustion engine [24] is established and commercially available technology for simultaneous production of heat and power with a high number of successful applications. Natural gas is typically introduced into the engine. Its power output ranges from kW to MW. A cogeneration unit with a power output of 2 MW, which corresponds to thermal output of about 2.2 MW; fuel consumption of $500 m_N^3/h$ is selected for our assessment. Overall efficiency of 88% is then assumed. This type of unit can be operated all year round in energy systems of big cities and as utility system of industrial processes.

3.2.2. Biomass-fired heating plant with medium capacity

Another technology with an increased number of potential applications is biomass boiler with a heat output of units of MW. Forestry residues and waste from wood-processing industry or energy crops are typically combusted. A unit producing hot water with an heat output of 1 MW and efficiency 83% was included in the analysis. Its typical application can be found in small wood-processing enterprises, decentralized heat supply systems for densely populated areas of small villages, utilities in industry and in large commercial buildings [25].

3.2.3. Biomass-fired ORC power plant

Thanks to support of electricity generation from renewable sources, it is obvious that more interest is paid to projects concerning power plants fired by biomass and agriculture residues. The heat recovery system is based on Organic Rankine Cycle (ORC) providing more effective heat utilization. The pressure at the turbine outlet where silicone oil vapour is expanded will be set at the lowest possible level. This will enable to maximize the enthalpy drop over the turbine and highest generator output. Efficiency of electricity production can be expected at around 25% [26]. Power plant with boiler heat output of 7 MW with corresponding power output of 2.3 MW is considered as a model example. The unit will not be connected to any heat distribution network – heat extracted in condenser will be released to atmosphere by air-coolers.

3.2.4. Biomass-fired ORC cogeneration plant

The last technology considered in our assessment is a unit utilizing energy released from biomass combustion process for simultaneous heat and electricity production also involves ORC cycle. In this case the turbine is operated in the backpressure mode, i.e. the condensing steam is utilized for heat production. Once the same boiler configuration as in a previous case is assumed (the boiler efficiency of 85% and 7 MW heat output) efficiency of electricity production will reach approx. 15%. Such unit is typically connected to district heating systems of large cities where this heat produced from biomass covers the basic load.

3.3. Performance data, emissions released and primary energy savings achieved by individual facilities

Important energy flows for these technologies were evaluated first. Obtained values were then introduced into Eq. (3) and annual PES was determined.

Table 2 shows the result obtained. First column summarizes (in the same manner) data related to WTE plant. It is necessary to emphasise that the availability of 8000 h/y was assumed for each technology involved. Regarding technologies producing heat (all except biomass-fired power plant) high operating hours can be guaranteed only if the output is dispatched to corresponding networks (i.e. large district heating networks, industrial heating). If not, the availability can decrease significantly. Since the capacity of the technologies is not identical (for example this can be expressed by total fuel input $E_{Alt} + E_f$) the absolute PES estimated cannot be compared directly.

For that reason, criterion defining specific savings is introduced. A number of possibilities exist. Specific primary energy savings can be related to imported primary energy ($E_f + I_{imp}$), to primary energy consumed in reference system corresponding to the same amount of energy exported by the unit (Q_{exp}) or to total process energy input ($E_{Alt} + E_f + I_{imp}$). In this paper last mentioned option is introduced:

Table 3
Results of environmental analysis of stand-alone technologies included into the assessment.

	WTE plant with backpressure turbine	Cogeneration based on reciprocating combustion engine	Biomass-fired heating plant with medium capacity	Biomass-fired ORC power plant	Biomass-fired ORC cogeneration plant
Fuel	Municipal solid waste	Natural gas	Biomass	Biomass	Biomass
No. of installations (−)	1	1	1	1	1
Availability (h/y)	8000	8000	8000	8000	8000
Emissions					
Carbon monoxide, CO (kg/y)	22,272	18,684	8915	61,087	61,087
Nitrogen oxides, NO_x (kg/y)	87,840	240,477	3269	22,398	22,398
Particulate matter, PM (kg/y)	2986	5	4993	34,209	34,209
Sulphur oxides, SO_x (kg/y)	26,592	35	371	2545	2545

$$\text{pes} = \frac{Q_{\text{exp}} - (E_f + I_{\text{imp}})}{(E_{\text{Alt}} + E_f + I_{\text{imp}})} \tag{4}$$

With reference to Table 2, the highest pes in this study is reached by biomass-fired cogeneration plant. On the other hand, the least positive environmental impact is featured at cogeneration unit based on reciprocating combustion engine. The benefit of WTE plant in the configuration as shown in Fig. 3 is comparable with the positive impact of biomass-fired heat only plant and power plant.

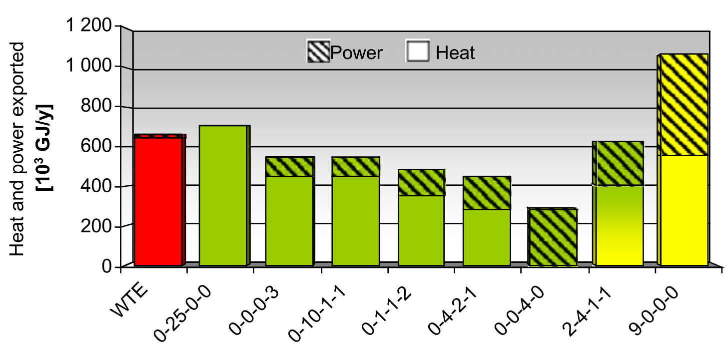
The energy-focused analysis is completed by environmental analysis which specifies the emission rate of basic pollutants - i.e. CO, NO_X, particulate matter (PM) and SO_X. Level of emissions released into atmosphere was determined using emission factors. It is a standard tool for emission estimation in air quality management. General simple equations which provide mass-flow rate of emissions are as follows:

$$E = A \cdot \text{CEF} \tag{5}$$

$$E = A \cdot \text{UEF} \cdot \left(1 - \frac{\text{ER}}{100}\right) \tag{6}$$

where E emissions production rate (kg/y); CEF controlled emission factor (kg/t or kg/MJ); A activity rate (t/y or MJ/y); UEF uncontrolled emission factor (kg/t or kg/MJ); ER overall emission reduction efficiency (−).

Emission factors used for calculation were obtained from database *AP*-42 [27], which distinguishes between uncontrolled emission factors UEF (describes the emissions rate generated by thermal processes not considering any flue gas cleaning system) and controlled emission factors CEF (describes the emissions rate generated by the process after the exiting products of combustion are more or less effectively controlled). In the case where used emission factor was uncontrolled (UEF), average overall emission reduction efficiency (ER) is estimated and controlled emission factor (CEF) is counted as the product of the previous two (see Eq. (6)). Typical values of ER can be found (for example) in publications devoted to combustion processes [28], waste processing [29] and utilization of biomass for energy production [30]. The amount of



Note: Marking of columns on horizontal axis – example 2-4-1-1 denotes 2 units A, 4 units B, 1 unit C and 1 unit D

A - Cogeneration based on reciprocating combustion engine

B – Biomass-fired heating plant with medium capacity

C- Biomass-fired ORC power plant

D- Biomass-fired ORC cogeneration plant

Number of units in each alternative has been selected in order to provide equal primary energy savings as by of one WTE plant with nominal throughput of 100 kt/y

Fig. 4. Heat and power exported.

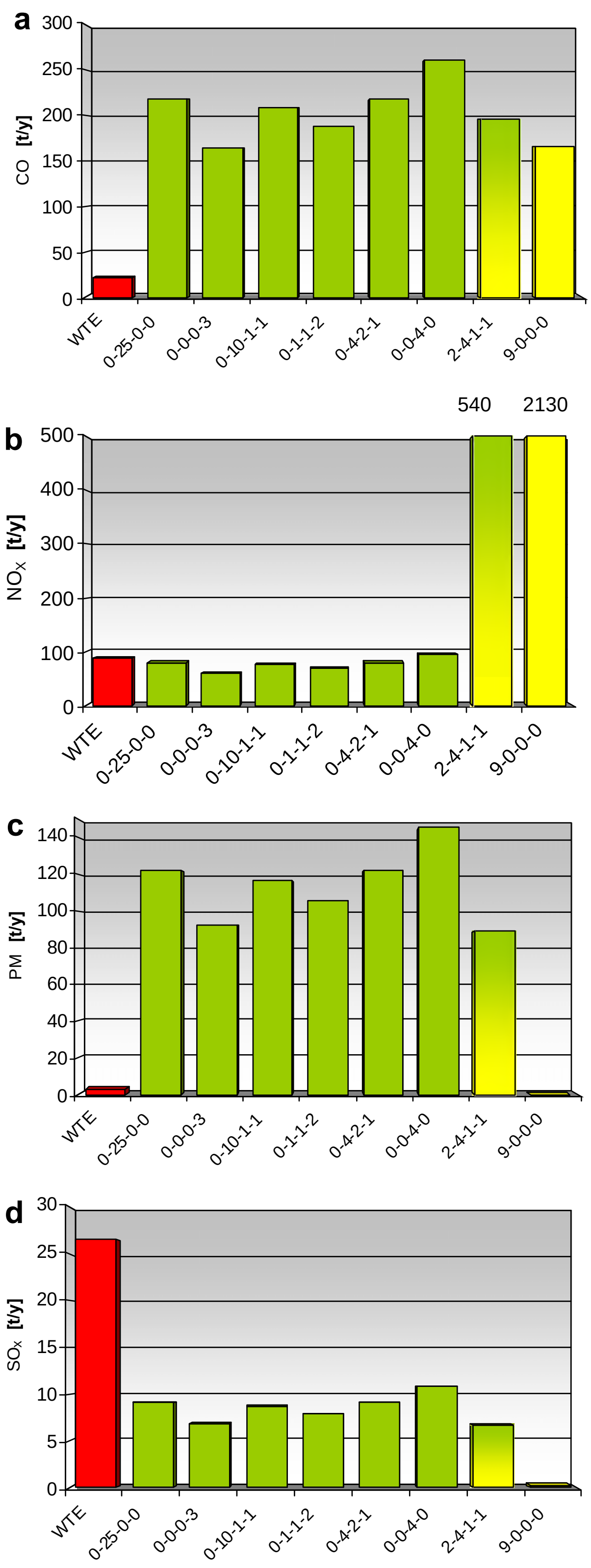


Fig. 5. Annual amount of emissions emitted to atmosphere.

emissions released into atmosphere by each of the technology per annum is shown in Table 3. Annual emission rates presented in Table 3 cannot serve for comparing individual facilities since the technologies involved in the assessment are of different capacities. These results form a base for calculations presented in the next part.

3.4. Energy analysis applied for selected region

As has been mentioned previously, the particular calculations based on the comparison of absolute PES (see Table 2) for the evaluation of different technologies with different capacities/inputs provide no comparable results. However, they can be included in a complex analysis which focuses on assessment of global environmental impact of WTE plant operated in a certain region.

Previous calculations have shown that the analysed MSW incineration plant with an annual throughput of 100 kt contributes to PES of 741,848 GJ (Table 2). Reflecting values presented in Table 2, it can be stated that the same amount of primary energy would be saved at an annual operation of:

- 9 CHP units fired by natural gas or (later in the text denoted as 9-0-0-0),
- 25 heat only boilers running on biomass or (0-25-0-0),
- biomass-fired power plants or (0-0-4-0),
- 3 cogeneration plants producing heat and power from biomass (0-0-0-3).

More detailed specifications of these technologies were mentioned in Section 3.2. The ratio between electricity and heat produced varies for each unit (see Fig. 4). If heat only biomass boilers are operated (labelled 0–25–0–0) the energy stored in fuel is transformed into hot water (or steam) and subsequently utilized for heating purposes. On the other hand, there are biomass-fired power plants producing only electricity (0–0–4–0). Both heat and electricity are produced within cogeneration systems (9–0–0–0 and 0–0–0–3). The total amount of produced energy changes. This is caused due to different specific PES related to a unit of energy exported (PES/Q_{exp}). The evaluation of four above mentioned concepts was extended by alternatives combining these basic processes. As the number of installations of individual facilities producing heat and/or power in the alternatives changes, the power to heat ratio also changes. The choice of combinations included in this study represents conceptually different strategies of utilizing available energy sources. Six alternatives are based only on biomass utilization (see Fig. 4). In the next to the last alternative (2–4–1–1 in Fig. 4) biomass is partly supplemented by natural gas and the last option (9-0-0-0) entirely concentrates on natural gas.

This analysis of PES achievable during energy production in different technological concepts has proved that WTE systems notably contribute to the substitution of fossil fuels. This positive environmental impact related to the amount of produced energy is comparable to the contribution of units utilizing biomass either for heat production or electricity generation. WTE systems in this sense defeat cogeneration systems based on natural gas.

3.5. Environmental analysis

The previous part focused on energy generation and export. This part targets environmental impact assessment based on emissions analysis. A usual way for emissions evaluation is to use a concept of global emissions [31] which includes:

- Local emissions (i.e. the emissions from local plant).
- The emissions produced/saved in reference utility systems.

This work has examined local emissions only. Emissions produced in a reference plants are proportional to the amount of primary energy combusted in those plants. Alternatives included (see Fig. 4) were composed (i.e. number of installation of each concept) that the amount of PES was the same in all cases. If the PES is equal for all combinations, emissions produced and saved in a reference plant are equal. For this reason they could be neglected.

The results of calculations are provided in Fig. 5 a–d. Data related to each concept were used (Table 3) in the evaluation of emissions. It is possible to conclude that the WTE system provides one of the cleanest forms of the energy based on presented figures for main pollutants. Emissions of CO and particulate matter (PM) are several times lower than for the other evaluated technologies. NO_x emissions are comparable with those from biomass-fired technologies and they are several orders lower compared with the CHP generation from the natural gas. Higher emission load is noticeable in the case of SO_x. This is caused by high sulphur content in the incinerated waste.

4. Conclusions

Thermal treatment of solid municipal waste with heat recovery represents without any doubt one of most efficient ways of treating this specific type of waste. In this case the waste stops being a problem and becomes a valuable alternative/partially renewable fuel. The energy generated in WTE units contributes to primary energy savings and consequently to the reduction of greenhouse gases emissions and other pollutants in the extent comparable to the energy produced from the biomass. This has been in the paper documented for a real WTE unit with annual throughput 100 kt.

With respect to negative attitudes to constructions of new WTE facilities, alternative plans for waste management are typically presented and discussed. The presented work concludes that at the same time energy-securing point of view should be considered. Alternative solutions based on conventional energy producing systems for securing the energy supply with comparable contributions to the environment should be also provided by the opponents of WTE processes. Presented results and novel methodology described in the paper support the decision-making process since it can be easily used for evaluation of the importance of WTE plants as up-to-date utility systems.

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ORIGINAL PAPER

Waste incineration with production of clean and reliable energy

Martin Pavlas · Michal Touš · Petr Klimek · Ladislav Bébar

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Abstract Discussion about utilization of waste for energy production (waste-to-energy, WTE) has moved on to next development phase. Waste fired power plants are discussed and investigated. These facilities focus on electricity production whereas heat supply is diminished and operations are not limited by insufficient heat demand. Present results of simulation prove that increase of net electrical efficiency above 20% for units processing 100 kt/year (the most common ones) is problematic and tightly bound with increased investments. Very low useful heat production in Rankine-cycle based cogeneration system with standard steam parameters leads to ineffective utilization of energy. This is documented in this article with the help of newly developed methodology based on primary energy savings evaluation. This approach is confronted with common method for energy recovery efficiency evaluation required by EU legislation (Energy Efficiency—*R*1 Criteria). New term *highly-efficient WTE* is proposed and condition under which is the incinerator classified as highly efficient are specified and analyzed. Once sole electricity production is compelled by limited local heat demand, application of non-conventional arrangements is highly beneficial to secure effective energy utilization. In the paper a system where municipal solid waste incinerator is integrated with combined gas–steam cycle is evaluated in the same manner.

M. Pavlas (✉) · M. Touš · P. Klimek · L. Bébar
Department of Process and Environmental Engineering (UPEI VUT Brno), Brno University of Technology, Technická 2, 616 69 Brno, Czech Republic
e-mail: pavlas@fme.vutbr.cz

Keywords Waste-to-energy · Waste incinerator · Primary energy savings · Energy efficiency · Electrical efficiency · Combined cycle

Introduction

Heat utilization makes up one of the most important aspects related to design and operations of systems for thermal treatment of waste. Electricity of roughly 16 TWh and heat of 30 TWh are expected to be produced from waste in the EU in 2010 (Manders 2008). Waste contributes to renewable energy production and represents an important item of energy-focused policies at the level of region (Čuček et al. 2010) as well as microregion (Ucekaj et al. 2010). Regarding the thermodynamic principle the majority of operated plants exploit Rankine cycle, where expanding steam at turbine drives the generator. The effectiveness of energy transformation from energy chemically bound in waste to its final useful forms (heat or electricity), i.e., efficiency of WTE system, is affected by numerous aspects including properties of incinerated waste, technology applied within limited financial resources of investors, local conditions, and current energy prices. Reimann (2006) has published results on energy efficiency investigation at 97 European municipal solid waste (MSW) incinerators associated in Confederation of European WTE Plants (CEWEP) organization. Author of this survey has divided the facilities according to the energy utilization strategy into three groups:

- Group 1: facilities with major electricity production, i.e., heat production does not exceed 5% of total energy production (25 plants)

- Group 2: facilities with major heat production, i.e., electricity production does not exceed 5% of total energy production (28 plants)
- Group 3: facilities with combined electricity and heat production (cogeneration systems, 44 plants)

Based on operating data, major heat fluxes were identified for each group. Graphical presentation of selected published data is given in Fig. 1.

Overall energy efficiency of WTE system is related to ratio of produced electricity and heat, as with all cogeneration systems working according to Rankine cycle. Average net overall efficiency in facilities producing mostly electricity (see Fig. 1, group 1) reaches approximately 20%. Efficiency of facilities with major heat production reaches 64% (group 2). Considering cogeneration (group 3), overall efficiency may reach 43%. If we focus our attention on electricity generation, efficiencies are lower if compared to the efficiencies commonly achieved in conventional energy-producing facilities (power plants, heating plants, etc.). Graus and Worrell (2009) declare average values for conventional plants combusting fossil fuels. Based on the published data, average gross efficiency of fossil-fired power generation ranges between 30 and 45% according to the type of fuel, technology, and development stage. Auxiliary equipment consumption up to 3% may be expected.

Development trends

Main objective of every incinerator is and ever will be to “process waste”. Terminology designating this process evolved along with developments of technologies and key equipment. Original designation of “incineration” was dropped and today we talk about energy from waste (waste-to-energy, hereinafter referred to as WTE). Complying with all stringent limits upon quality of emissions from the process (not only gaseous, but also solid and liquid) with sufficient reserve is implied for every new plant. This development trend is demonstrated for example by Porteous (2001). Comparison of emissions into air from two generations of plants is presented. It is shown that the discharge rate of pollutants (including extremely hazardous dioxins) is several orders lower in up-to-date facilities. Therefore, WTE today provides us with one of the cleanest and reliable energy. Legislation also imposes achieving minimum energy utilization (see further on).

Development of technology continues and new stage of thermal processing of waste is evolving (the so called *waste fired power plants—WFPP*, Berlo 2006). This new generation of thermal processing is discussed frequently. These facilities focus on electricity production. By taking advantage of high capacity they try to reach net electrical efficiency above 30%. Heat supply is diminished and operations are not limited by heat demand. Such technology is operated for example in Amsterdam (Berlo 2006). Processing capacity exceeds 500 kt/year and measures common in power plants are employed such as increased steam pressure up to 12.5 MPa, steam temperature up to 480°C, staged steam expansion at turbine with reheating based on intermediate circuit where saturated steam from boiler is used; maximum utilization of flue gas sensitive heat for condensate preheating (flue gas temperature at the boiler exit 180°C, heat extraction from flue gas in flue gas cleaning system), etc. Only thanks to these provisions uncommon in waste incinerators, this particular plant reaches net efficiency of 30%. For comparison, efficiency for state-of-the art plant reflecting current knowledge reaches 22%. However, even these values may be obtained for high processing capacity (hundreds of kt/year) and maximum efficiency of boiler with corresponding high steam flowrate which subsequently expands in steam turbines (ST) with higher thermodynamic efficiency. This solution is applicable in highly populated areas with large waste production.

Many projects tend to favor electricity generation even for facilities with low processing capacity (100–150 kt/year) where the potential for afore mentioned measures leading in increased efficiency is limited and/or financially

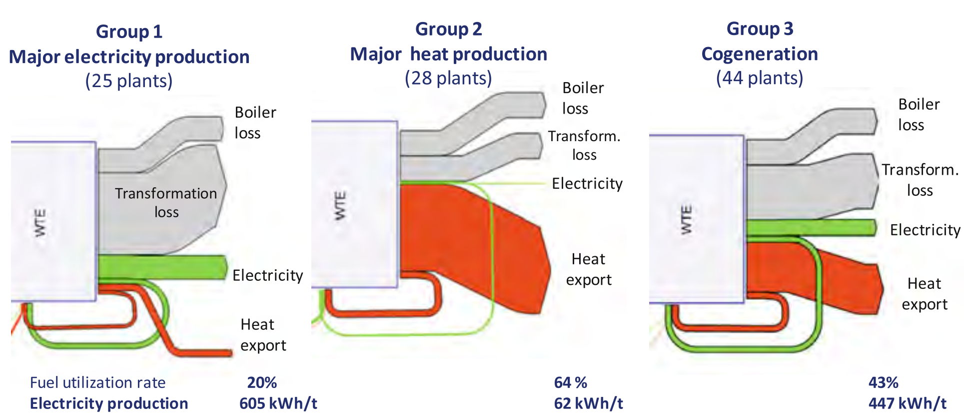


Fig. 1 Classification of facilities and average efficiencies (97 facilities associated in CEWEP, Reimann 2006)

not feasible. Performance of such a plant is investigated by using simulation approach and consequences regarding the environment are pointed out. First, achievable production data are assessed using simulation model.

Technology description

In our assessment the following technology was considered as a typical one (see Fig. 2). Waste is burned on a moving grate, the products of oxidation are led onto the secondary combustion chamber (SCC), where at a sufficient temperature and time of residence the decomposition of even the most stable compounds takes place. The operational temperature 900–950°C in SCC is maintained. According to EU legislation the minimum operational temperature for MSWs 850°C is required. Burning supplementary fuel in SCC may be used in cases where necessary. Hoverer this is only done during non-standard regimes as is putting into operation and shutting down. Auxiliary energy consumption is negligible if compared to the overall energy input by waste. This part of incineration plant is called thermal system. Off-gas from the SCC then flows to heat recovery system where in the waste heat boiler (heat recovery steam generator—HRSG) their sensitive heat is utilized for production of superheated steam. The steam produced is then utilized within flexible cogeneration system comprising a condensing turbine with extraction. The advantage of this arrangement is the ability to quickly react to changes on heat demand represented here by district heating system (heat utilization in Fig. 2). During demand cut-off (summer operation) the most of steam is utilized for electricity production without having to reduce the throughput of the incineration plant. Thermal output is reduced and electricity output is increased. Excessive low-grade heat is rejected via air-cooling system (see Fig. 2). Cooled down flue gas is then cleaned in the flue gas treatment (FGT) system. Dust is first removed mechanically in an electrostatic precipitator (ESP). ESP is followed by dioxin removal (DeDIOX). This catalytic fabric filtration system secures removal of fine particulate matter (PM) and very efficient destruction of dioxins and furans (PCDD/F). Acid compounds as SO_2, HCl, and HF and heavy metals are removed under the effect of water solution of NaOH in wet scrubber. Concentration of NO_X is reduced by applying selective non-catalytic reduction method (SNCR) by which urea is introduced into the SCC in proper temperature range of 900–1000°C. The lay-out of FGT system downstream the boiler influences the flue gas temperature profile which is in this case as follows: 250°C at the boiler exit, ca. 230°C after the ESP (temperature necessary for securing sufficient efficiency of dioxin filter), ca. 200°C after the dioxin filter and about 60°C at the outlet from wet scrubber into stack.

There are available several different of FGT system varying in type of the process, locations of every piece of equipment, removal efficiency and temperature profile. This has impact on efficiency of energy utilization. Following modifications are very common:

- minimization of number of equipment to decrease internal energy consumption especially for applications where dry and/or semi-dry method for acid gas removal is applied
- decrease in temperature of flue gas at the boiler outlet down to 150°C as a trade-off between maximum boiler efficiency and emission control efficiency
- SNCR method for NO_X removal is replaced by selective catalytic reduction method (SCR $DeNO_X$) situated downstream the wet scrubber—necessity for flue gas reheating (which is obviously energy demanding way).

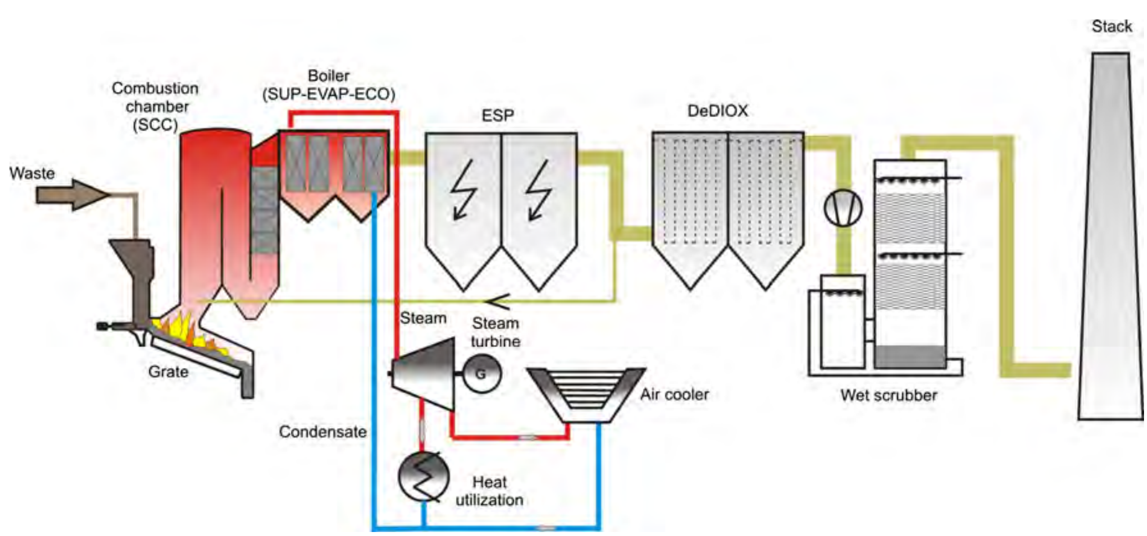


Fig. 2 Simplified flowsheet of up-to-date technology

Table 1 Comparison of emission limits set by EU legislative and performance of flue gas cleaning system in up-to-date incinerators

Pollutant	Emission limit—daily average (mg/m^3_N)	Raw gas concentration (boiler exit) (mg/m^3_N)	Cleaned gas concentration (stack) (mg/m^3_N)	Emission control system efficiency (%)
PM	10	10,000	0.03	>99.9
HCl	10	150	6	96
SO_2	50	100	3	97
NO_X	200	600	120	80
CO	50	10	10	N/A
Dioxins/furans (PCDD/F)[a]	0.1 (ng TEQ/m^3_N)	2.5 (ng TEQ/m^3_N)	0.05 (ng TEQ/m^3_N)	98

[a] Toxicity of a mixture of dioxins and dioxin-like compounds is expressed by the toxic equivalent, TEQ

The set-up involved in this article represents a system which sufficiently complies with currently valid emission limits in the EU (see Table 1). Since the technology fills in with BAT (best available techniques), it is suitable for potentially more restrictive legislation.

The performance of flue gas treatment system summarized in Table 1 is based on data from real plants. Although it is influenced by many specific aspects (properties of waste, legislation, etc.) presented average values can be generalized for this type of up-to-date facility.

Simulation approach and performance analysis

Simulation model of an unit with capacity 100 kt/year

Simulations presented in this article were conducted using in-house built software tool *Waste-to-Energy—W2E.* Software is dedicated to perform mass and heat balances of technologies in the area of energy utilization of waste and biomass. It is based on Java platform (Tous et al. 2009). Software provides user friendly environment and intuitive operating. Principles for modeling and simulations are similar to other commercial products. Process includes generation of flowsheet, setting of input data and calculation itself. W2E engages sequence modular approach for the analysis.

A complex model was created in this tool. Model flowsheet is designed so that it enables to solve the whole problem, i.e., in the general model of the incinerator, it is possible to alter many parameters. These are for example: waste lower heating value, amount of processed waste, air excess, steam properties after the boiler, temperature of flue gas at the boiler exit, ST arrangement (backpressure turbine, condensation turbine with extraction), steam properties for heat supply (direct steam export, hot water, and direct steam supply), pressure in the turbine condenser, etc. Analysis presented in this article focuses on heat utilization strategy. Only selected parameters from afore mentioned related to cogeneration system were subject of modification. Figure 3 displays part of the model considered in the analysis. Analogous models of thermal part (i.e., model of incineration itself) with waste heat boiler and flue gas cleaning system are available as well. Since the parameters related to these systems remained fixed these models are not presented here.

Boundary conditions of the calculation

In case of electricity generation, following features and aspects are necessary for securing high efficiency:

- boiler efficiency
- flexible arrangement and efficiency of cogeneration system, i.e., ST.

Boiler performance is influenced by exiting flue gas temperature and its amount which forms thermal losses by sensible heat. Other losses (thermal losses by radiation and convection, chemical losses by incomplete combustion, thermal losses in unburned fuel) are not that important and altogether make up to percent (commonly 3–4%). Thermal loss by sensible heat may reach from 7 up to 25% of waste energy input according to the flue gas temperature and air excess. Boiler efficiency ranges between 75 and 85%. Boiler efficiency in up-to-date plants should excess 80%. MSW incinerators commonly operate with flue gas temperature of 250°C at the boiler exit (this secures optimum operating conditions for subsequent flue gas cleaning). Efficiency reaches 81% under this temperature and 6% oxygen content after the last air supply (which is a common value achievable in operations). Significant increase of efficiency is conditioned by decrease of flue gas temperature, which on the other hand puts more requirements on FGT system. Low temperature corrosion has also to be considered (Villani and Greef 2010).

Specific electricity production from ST is influenced by enthalpy drop in the turbine which is influenced by difference between steam parameters at the inlet and outlet of

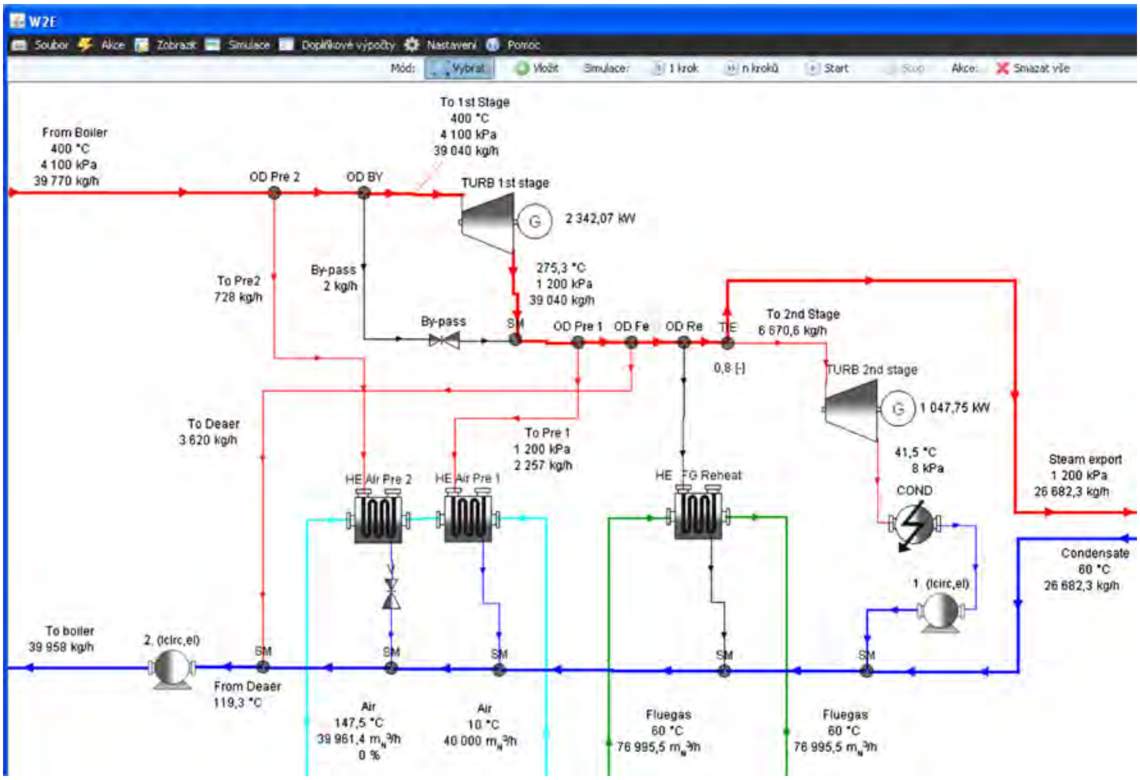


Fig. 3 Simulation model of energy recovery system of WTE plant in in-house software *W2E*

the turbine. Parameters of superheated steam generated in boiler are commonly limited by pressure of 4–5 MPa and temperatures of 380–400°C for MSW incinerators (IPPC 2005). Higher temperatures create a serious corrosion risk in first tube bundles of superheaters, which requires using special materials (austenitic super alloy) or application of special provisions (expansion of steam in turbine with more stages and steam reheating). Higher inlet parameters are compromised with investments, expected decreases of plant availability and profit related to efficiency increase and electricity sale. Output parameters are determined according to the type of turbine and way of heat utilization. Backpressure turbine exports steam directly into district heating system and/or uses its condensation heat for heating other process medium (very often hot water). Pressure at the condensing turbine outlet is influenced by cooling medium, its temperature (IPPC 2005) and plant capacity. Pressure for air cooled condensers is significantly related to temperature of surrounding air. Temperature of 10°C enables pressure of 10–8 kPa, temperature of 20°C has a negative impact on increase to 17–12 kPa (IPPC 2005). Pressure is distinctly lower for closed loop with atmospheric cooling tower.

Simulation model respects technological restrictions related to steam and subsequent electricity production (boiler efficiency, limited live steam parameters to avoid increased corrosion risks, cooling system performance, etc.). The main features of model used are summarized in Table 2.

Table 2 Simulation model—boundary conditions

Parameter	Value
Waste feeding rate (t/h)	11.5
Average lower heating value of waste (MJ/kg)	10.9
Boiler efficiency (%)	81
Flue gas temperature at the boiler exit (°C)	250
Oxygen content in flue gas at the boiler exit (% vol.)	6
Steam from boiler (t/h) [at 400°C and 4 MPa (g)]	39.8
Steam from boiler (t/h) [at 620°C and 6 MPa (g)]	35.2
Pressure at turbine outlet (in the case of back-pressure turbine)/bleed pressure (for condensing turbine with extraction) [MPa (g)]	
Direct steam export into district heating network	1.1
Hot water production	0.3
Pressure in turbine condenser—air cooler (kPa)	8
Turbine isentropic efficiency (%)	70

Simulation in first step included change of flow of process steam in condensation stage (designated as flow "To 2nd Stage" in Fig. 3). Change in steam flow rate through condensation (second) stage alters ratio of

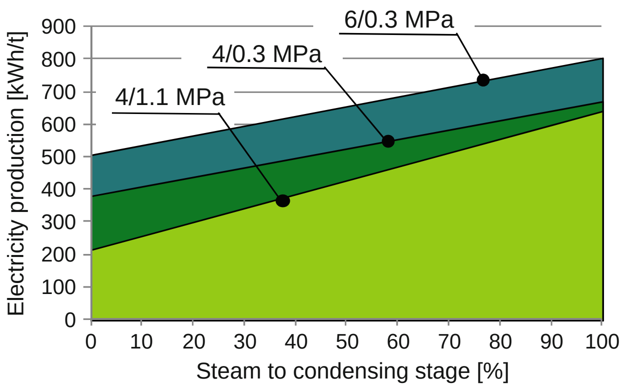


Fig. 4 Specific electricity production

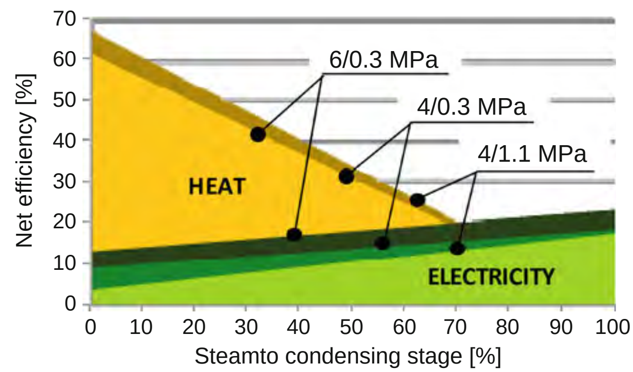


Fig. 5 Net efficiencies of energy production

produced (exported) heat and electricity, which has an impact on efficiency of heat and electricity production and therefore on overall efficiency of utilization of energy from waste. Results of simulations (electricity production related to 1 ton of waste) for two different systems in case of standard and "safe" inlet steam parameters 4 MPa and 400°C (direct steam export at 1.1 MPa and hot water production by steam at 0.3 MPa) are presented in Fig. 4. Flow rate of steam through condensation stage of turbine is given in the graph in percent of total flow rate of steam led to turbine first stage. Second step of the simulation analyzed benefits of increase of produced steam pressure to 6 MPa. Results are also given in Fig. 4.

Arrangement of back-pressure turbine and steam parameters of 4 MPa allow to reach specific electricity production (related to one ton of waste processed) of 200–400 kWh/t depending on value of back-pressure. Increase in pressure from 4 to 6 MPa brings increase by 100 kWh/t. Arrangement with condensation turbine in full condensation mode leads to generation of 600–800 kWh/t.

Further, net efficiency of electricity production (export efficiency) were calculated. Internal electricity consumption (ca. 4% of energy in waste, i.e., 100 kWh/t, Reimann 2006) and steam for internal heating purposes were considered. Net efficiencies of electricity and heat production are given in Fig. 5.

Results clearly show that net electrical efficiency in full condensing operation under conventional steam parameters of 4 MPa does not exceed 20%. With 6 MPa inlet steam parameters more than 20% can be expected. However, increase in efficiency which is related to high steam pressure is linked with high potential of corrosion of superheater's bundles. Increase of efficiency over 20% for units utilizing waste with processing capacity of 100 kt/year is problematic and is linked to implementation of financially demanding materials and measures.

Tendency to produce mainly electricity and minimize cogeneration results in lower overall efficiency of fuel utilization (see Fig. 5). On the other hand, electricity is considered to be a more valuable form of energy. Efficiencies presented in Fig. 5 are not a sufficient reason to claim that significant orientation toward electricity production with low overall efficiency still makes up a sustainable method of energy utilization, or whether we may start talking about energy wasting.

Performance analysis regarding the potential for clean energy production

A number of criteria to compare the effectiveness of energy recovery and utilization in incineration plants have been proposed recently. Their overview, description, and meaning can be found in Pavlas et al. (2010). Their common feature can be seen in an effort to describe relation between energy outputs (produced or exported energy) on one side and plant energy demand on the other. An example of analysis based on one of the criteria can be found in Pavlas and Touš (2009). Directive 2008/98/EC (European Parliament 2008) defines *energy efficiency*, often designated as $R1$ formula, criterion for evaluation of waste incinerators. Despite the fact that it is the only legislative criterion and is different from the one in the aforementioned article, analysis presented by Pavlas and Touš (2009) gives a good insight into this issue.

Criteria energy efficiency (R1)

Equation for Energy efficiency calculation is obvious from Table 3. The meaning of particular symbols is the following:

- Q_{prod}: total amount of produced energy (thermal and electrical, sum of energy exported and internally consumed)
- E_f: imported energy to the combustion process (e.g., supplementary fuel)
- I_{imp}: imported energy not used for heat production (e.g., natural gas consumed for re-heating purposes in FGT system)

Table 3 Definition of *energy efficiency* criterion

Reference	Criterion	Equation	WTE
Directive 98/2008/ EC 2008	Energy efficiency	$\eta_e = \frac{Q_{\mathrm{prod}} - (E_{\mathrm{f}} + I_{\mathrm{imp}})}{0.97(E_{\mathrm{w}} + E_{\mathrm{f}})}$	$\eta_e > 0.6$ $\eta_e > 0.65$[a]

[a] For equipment put into operation after December 12, 2008

- E_{W}: energy released by waste combustion processes.

A new plant which is to be labeled as WTE has to reach minimum value of 0.65 of this criterion. Otherwise, it is classified as waste disposal with all the consequences. Comprehensive analysis of European incineration plants involving these criteria was published by Grosso et al. (2010). The presented results proved that 60% of investigated plants were classified as WTE (recovery). It was also pointed out that first the highest efficiency is reached by cogeneration plants (average value 0.71) and next the size of the plant represents an important factor determining electrical efficiency. The data published by Grosso et al. (2010) were confronted by result of our calculation including afore described simulation model referring to a state-of-the art plant with capacity 100 kt/year (see Fig. 6).

Uptrend in electricity production (in Fig. 6 expressed as increased ratio of steam going to condensing stage over overall steam generation in boiler) leads to fall of *energy efficiency* criterion. It was confirmed that plant which fully takes advantage of cogeneration is characterized by the highest Energy efficiency. Values we calculated for up-to-date facilities are distinctly higher than average values for existing European facilities. Whereas Grosso et al. (2010) presents for mainly electricity producing plants 0.49 and average waste throughput 150 kt/year, we obtained for up-to-date electricity-oriented incinerator a range 0.8–0.9. This shows large potential for improvements in existing

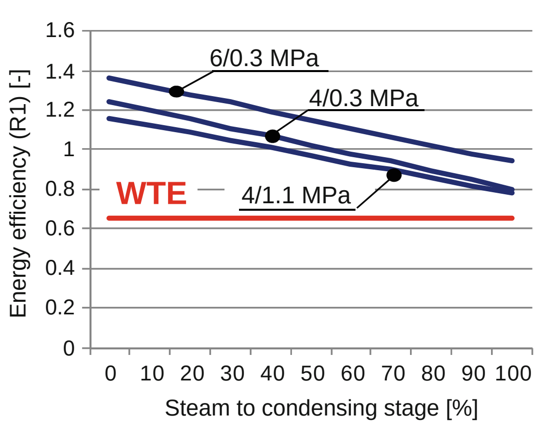


Fig. 6 Results of evaluation—energy efficiency ($R1$)

plants. Cogeneration plants cannot be compared in the same manner since the ratio between electricity and heat produced was not published. Requirement for classification as WTE ($R1 > 0.65$) in all in this article analyzed cases is fully met. The requirements on WTE classification are set in such a way that the electricity production is limited in no way for up-to-date and well-operated plants. However, application of $R1$ does not define global contribution of the plant to primary energy savings. It can be used only for comparison of similar facilities—MSW incinerators. It does not allow for subsequent comparison with other energy-producing sources. Is orientation toward electricity production in accordance with principles of sustainable development? These issues were discussed by Pavlas et al. (2010).

Alternative approach toward incinerators assessment—primary energy savings (pes)

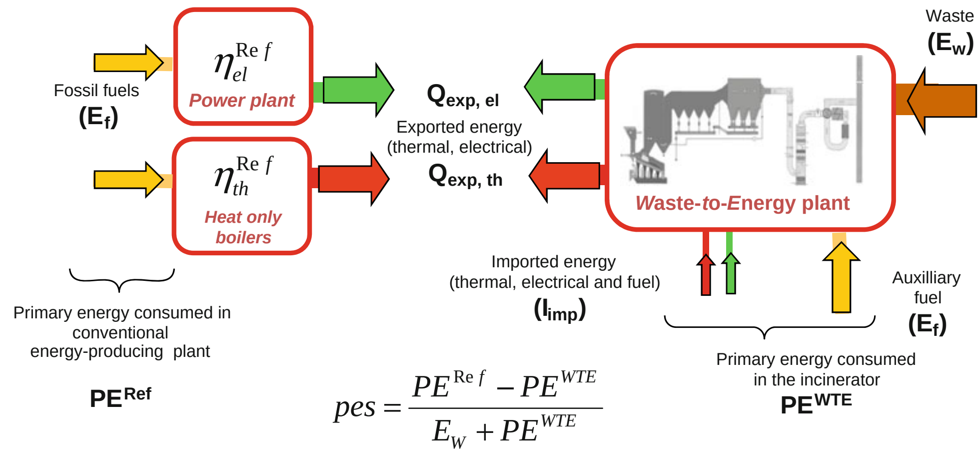
Benefits of the incinerator taking into account other energy-producing plant may also be evaluated using *primary energy savings* criterion (*pes*, Table 4). This criterion was described in detail by Pavlas et al. (2010).

Figure 7 presents its meaning. Contrary to $R1$, this criteria focus on net energy export (Q_{exp} is total amount of exported energy both thermal and electrical). Numerator for calculation of *pes* expresses absolute primary energy savings which is obtained thanks to operation of WTE plant. This may be defined as a difference between primary energy consumed in conventional (reference) plants when producing similar amount of energy supplied by incinerator ($\mathrm{PE}^{\mathrm{Ref}}$) and primary energy consumed by process of incineration itself ($\mathrm{PE}^{\mathrm{WTE}}$). The heat producing reference plant (heating plant) operates with efficiency $\eta_{\mathrm{th}}^{\mathrm{Ref}}$. The reference power plant operates with efficiency $\eta_{\mathrm{el}}^{\mathrm{Ref}}$. Denominator represents total energy input into the process ($E_{\mathrm{w}} + E_{\mathrm{f}} + I_{\mathrm{imp}}$). We may then talk about WTE if the process saves primary energy, i.e., pes > 0. Once energy input E_{W} is generalized with E_{Alt} (energy input by alternative/non-fossil fuel) this approach could easily be applied for any energy-producing technology, which further allows to compare these plants. An example of application for different technologies was introduced by Pavlas et al. (2010).

Table 4 Definition of *primary energy savings* criterion

Reference	Criterion	Equation	WTE
Pavlas et al. 2010	Primary energy savings	$pes = \frac{Q_{\mathrm{exp}} - (E_{\mathrm{f}} + I_{\mathrm{imp}})}{E_{\mathrm{W}} + E_{\mathrm{f}} + I_{\mathrm{imp}}}$	$pes > 0$ $pes > 0.6^{a}$

[a] Value 0.6 for highly efficient process



$$pes = \frac{PE^{\mathrm{Re}\,f} - PE^{WTE}}{E_W + PE^{WTE}}$$

Fig. 7 Graphical representation of Primary energy savings criterion (Pavlas et al. 2010)

Let us summarize the advantages of using this approach for incinerators assessment instead of and/or together with criterion energy efficiency:

- relation origins from objective approach (calculation of primary energy consumption)
- comprehensive for broad scientific public (quantification of amount of saved primary energy for a given period of time)
- versatility (ability to compare with other technologies of energy supplies e.g., energy production from biomass)
- application potential—creation of regional energy conception, support of public opinion using objective criteria.

If applied on the specific model described we can state that as energy efficiency drops along with usage of condensing mode, criterion *pes* do so (see Fig. 8).

Based on previously published data, we suggest defining a new term “highly efficient” energy production from waste. Similar mechanism is engaged in evaluation of cogeneration systems in accordance with Directive 2004/8/EC (European Parliament 2004), where distinction

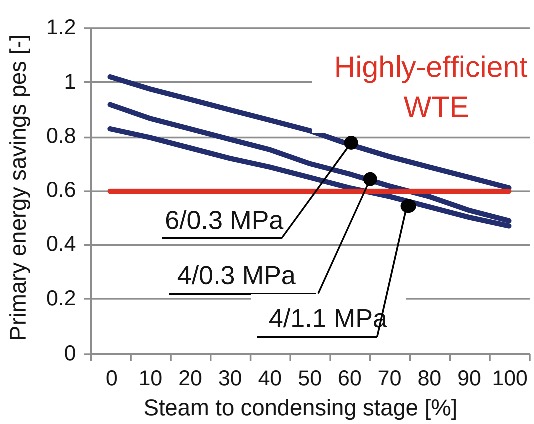


Fig. 8 Results of evaluation—Primary energy savings (pes)

of *cogeneration* and *highly efficient cogeneration* is made referring to the different rate of environmental benefits. Authors of the article with respect to data and previous analyses presented by Pavlas et al. (2010) suggest designating WTE process as highly efficient if value of this criterion exceeds approximately 0.6, which means that system contributes to primary energy savings by 60% of total energy consumed in the process. Excessive electricity production from waste leads to drop of *pes* below 0.6 and thus causes ineffective utilization of energy stored in waste.

Utilization of synergic effects

If local limited heat consumption compels sole electricity production, it is necessary to look for unconventional solutions. One of the many discussed concepts is an integration of municipal waste incinerator with combined steam–gas cycle. There are several arrangements available (Consonni and Silva 2007). All the solutions have common features:

- need to reach higher parameters of steam at the turbine inlet (8 MPa and more)
- avoid corrosion problems (recovery system of incinerator is not equipped with a superheater. Superheating takes part in waste heat boiler after the gas turbine (GT)
- application of common ST with higher isentropic efficiency.

Example of a possible solution is given in Fig. 9. This arrangement was subjected to detailed analysis by Consonni and Silva (2007) and Qiu and Hayden (2009). Let us only summarize characteristic features of such an integrated system:

- parameters of steam led to turbine equal 8.5 MPa and 550°C, pressure in condenser amounts to 7 kPa
- 34% GT efficiency
- 90% isentropic efficiency of ST.

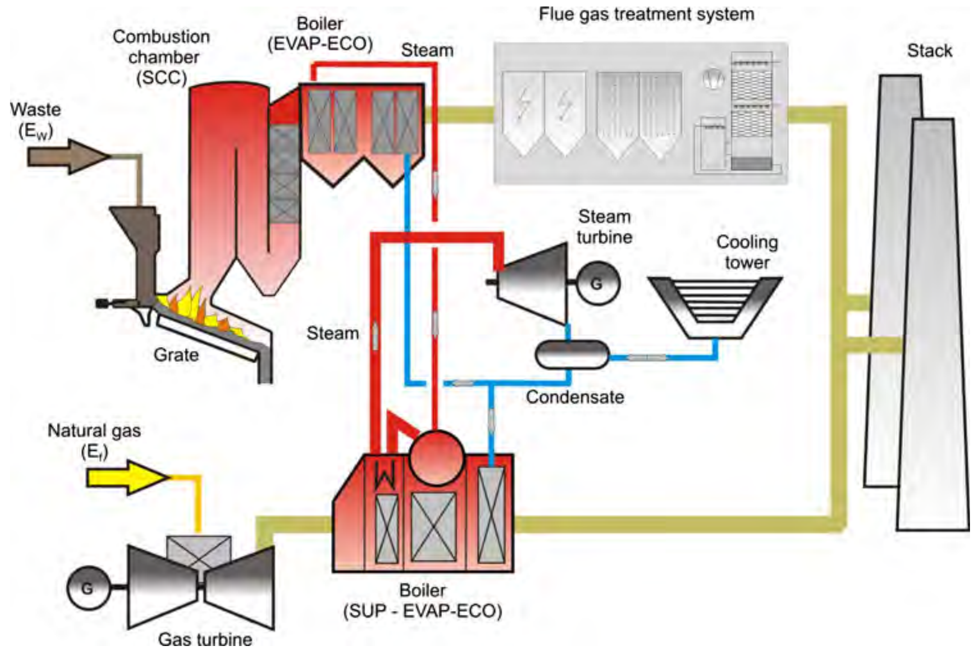


Fig. 9 Simplified flowsheet of an integrated combined steam–gas cycle

Model of such integrated system was created and subjected to simulation including various share of installed capacity of GT to incinerator itself. This ratio is expressed by:

$$\varphi = \frac{E_f}{E_w + E_f}, \tag{1}$$

where, E_w and E_f is amount of energy supplied by incinerated waste (w) and natural gas (f), respectively.

Total electrical efficiency of the combined cycle is a main characteristic of the given cycle:

$$\eta_{el,CC} = \frac{Q^{GT}_{exp,el} + Q^{ST}_{exp,el}}{E_w + E_f}, \tag{2}$$

where $Q^{GT}_{exp,el}$ and $Q^{ST}_{exp,el}$ is amount of electricity produced in GT and ST, respectively.

Efficiency of combined cycle is dependent on share of energy supplied by waste and natural gas (see Fig. 10) and it cannot be compared directly with electrical efficiency of conventional WTE plant because energy supplied by waste participates in such a combined cycle only on production of electricity in ST. Therefore, efficiency of electricity production from waste may be defined as follows Qiu and Hayden (2009):

$$\eta_{el,w} = \frac{\left(Q^{GT}_{exp,el} + Q^{ST}_{exp,el}\right) - \eta_{CC} \cdot E_f}{E_w}, \tag{3}$$

where η_{CC} is efficiency of non-integrated combined cycle combusting natural gas (55% considered). Evaluation of net electrical efficiency related to waste-based energy inputs followed in accordance with Eq. 3. The results are shown in Fig. 10.

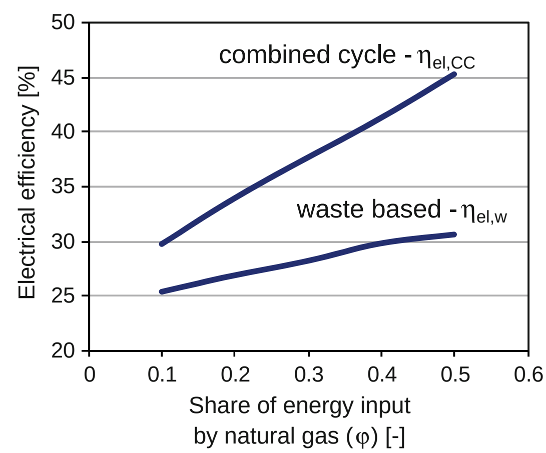


Fig. 10 Efficiency of integrated system

Comparison of efficiency of conventional electricity production from waste (Tables 2, 3) and presented integrated solution with combined cycle (compare Figs. 5, 10) reveals that even slight φ ratio enable to utilize benefits of integration (parameters of steam before turbine 8.5 MPa and 550°C) and secure higher efficiency. Rising φ ratio results in rising efficiency.

Energy efficiency criteria cannot be applied in assessment of integrated system because these criteria are primarily designed for assessment of MSW incinerator and

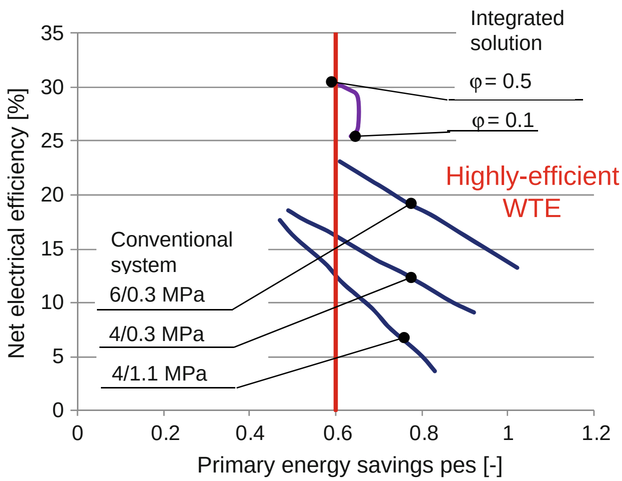


Fig. 11 Efficiency of waste-based electricity production

allows for comparison only between facilities of identical arrangements. However, universal approach of *pes* may be applied. Figure 11 presents the results. Despite the fact that integrated solution focuses only on electricity production, net electrical efficiency from waste may exceed 25%. Process will be labeled as highly efficient. Conventional arrangement of incinerators does not enable achieving this high of a value. Orientation toward electricity production and efforts to maximize efficiency along with decrease in total efficiency of fuel utilization resulted in significant decrease *pes* (see Fig. 11). Required value above 0.6 (primary energy savings equal to 60% of energy supplied into the process) are likely for facilities with limited electricity production and high share of supplied heat. This will always concern facilities with electricity cogeneration. Limited heat demand in the location may push sole electricity production. Common arrangement will lead to electricity production efficiency of 20% at highest. Overall efficiency will be low. Acceptable level of utilization is then reached via integration with combined cycle. Concept is solely focused on electricity production. Efficiency of electricity production from waste may exceed 25%.

Conclusion

Increase of net electrical efficiency above 20% for incinerators processing 100 kt/year is problematic. Although electricity is considered to be a more valuable form of energy, trend to focus on sole electricity production accompanied by limited cogeneration production results in ineffective energy utilization from waste. Process thus cannot be labeled as highly efficient. Only processes where primary energy savings (*pes*) exceed 0.6 may be classified as highly efficient. This value may be reached in technologies with limited electricity production and high share of supplied heat (cogeneration system) or under increased steam parameters where risk of corrosion can cause operational problems and higher investments. Limited local heat consumption may compel sole electricity production. Acceptable degree of utilization then may be reached via integration of municipal waste incinerator with combined steam–gas cycle. This concept focused solely on electricity production has been thoroughly discussed in the article. Net waste-based electrical efficiency may exceed 25%.

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ORIGINAL PAPER

Using a utility system grey-box model as a support tool for progressive energy management and automation of buildings

Vítězslav Máša[1] · Michal Touš[1] · Martin Pavlas[1]

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Abstract The research presented here is focused on improving energy management in a building complex through analytical and empirical modelling of its utilities. First, we introduce current European policy on energy savings in buildings. The modelling starts with a literature review and a thorough study on a heating and cooling system of a particular building complex—the National Theatre in Prague, Czech Republic. Standard building automation and control systems cannot optimize the building's operations to the fullest and thus do not provide the best cost savings possible. A mathematical model of the energy system and its integration into a building control system is an essential prerequisite for any optimization here. The development of a model which can be integrated into a control system during real-time operation of the building is a very complicated task. Our paper presents a procedure to develop such a model and methods to apply it in a real-life operation. First, the mathematical model is implemented in a simulation tool, which enables an efficiency evaluation of the system. This simulation tool offers especially important support for building automation and control systems when deciding the most effective operation of heat or cold utilities. The model greatly helps in monitoring and optimizing daily offtake limits for natural gas, which is highly appreciated by the building's technical management. Our practical applications of the model show new possibilities for simulation and optimization calculations which are completely unique in building management systems so far.

Keywords Data-driven modelling · Simulation · Optimization · Utility system · Control system

Introduction

Our paper presents a case study which documents how important simulation and optimization are in the process of decreasing a building's energy consumption. The case study analysed a real utility system providing heating and cooling for a building complex (four buildings) of the National Theatre in Prague, Czech Republic, with a total capacity of 265,950 m^3. The revamping of the utility system started in 2007 using the EPC method and has brought significant financial savings, as shown in Fig. 1.

However, the energy system of the National Theatre has become rather complex and complicated after the revamping, as will be discussed in the section on the "The Utility system in the Czech National Theatre". The operator is now able to combine various heat sources to supply energy to the building. According to Escrivá-Escrivá (2011), buildings are often managed by non-specialised technicians who need intelligible and cost-effective actions to be implemented in their buildings. Petri et al. (2014) introduced a service-oriented platform, which could be helpful for a building's management. Improper changes to the process can lead to significant losses in the operational costs of the building. For this reason, the revamping of the utility systems is not the only part of energy efficiency improvements. The system has to be operated efficiently as well. Specific and well-targeted research leading to an optimal level of the innovation is needed in this case (Klemeš 2013).

✉ Vítězslav Máša
masa@fme.vutbr.cz

[1] Institute of Process and Environmental Engineering, Brno University of Technology, Technická 2896/2, 61669 Brno, Czech Republic

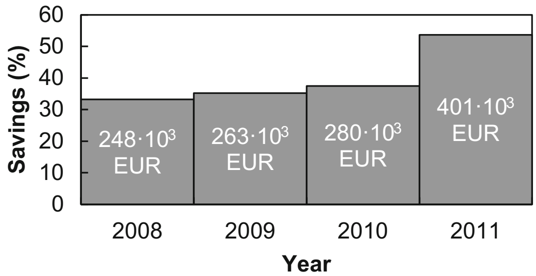


Fig. 1 Financial savings using the EPC method

A core component of building energy control is building energy forecasting models for systems within the building, such as heating, ventilating, and air conditioning (HVAC) systems and on-site energy generation and energy storage systems (Xiwang and Wen 2014).

When selecting a proper heat source for the start-up of the system and deciding important operational issues, we could not solely rely on estimates of the operator. We therefore employed progressive building automation and control systems (BACSs) and technical building management (TBM) functions which can master the complexity of the system to even further increase its operational efficiency and associated energy savings. Simulation and optimization tools helped us support decision-making mechanisms used in advanced control systems. It further shows how to increase the functional properties of BACS and TBM systems using a grey-box model of an energy system. The case study proves that the model may be applied even if the data acquisition system does not provide sufficiently accurate data. The following chapter presents the current European policy on energy savings in buildings. From the European Union (EU) point of view, there is a great potential for decreasing energy consumption in the building sector.

Energy consumption in the building sector and European policy

Decreasing the consumption of primary energy sources is one of the long-term objectives and priorities of the EU. This strategy reflects the current energy situation: Europe is significantly dependent on energy imports [54.3 % of gross final energy consumption in 2012 came from energy imports (Eurostat 2014)], which is, amongst other things, rather costly. In order to minimize the impact of this trend, the EU has introduced 'Europe 2020' (EC 2010a), a strategy which implemented several key documents and outlined relevant objectives of the energy policy. The well-known energy policy package (20-20-20) defines three key objectives for 2020: to reduce EU carbon dioxide emissions by 20 % from 1990 levels, to raise the share of EU energy consumption produced from renewable resources to 20 %, and to improve the EU's energy efficiency by 20 % compared to 2007 projections (EC 2010b). This initiative is expected to promote energy safety in the EU, ensure sustainable development, increase the competitiveness of the EU, and create new jobs. At the same time, EU countries should be able to utilize knowledge, experience, and newly developed technologies and procedures in the future (EC 2007).

EU Directive 2012/27/EU incorporates new strategic objectives and replaces the inadequate and outdated Directive 2006/32/EC. The Member States were expected to implement changes required by the Directive by June 2014. The new Directive introduces an updated framework for a common procedure for all Member States to achieve the 20 % objectives and tries to create framework conditions for further improvements in energy efficiency. According to proposals from the European Commission, energy efficiency should reach 30 % in 2030 (EC 2014).

The European Commission has stated that "the majority of the energy-saving potential is in the building sector, with 40 % of the EU energy consumption" (EC 2014). Fourcroy et al. (2012) demonstrates that energy consumption is underestimated due to the accounting methodology used in official statistics. Energy in services is primarily used for heating, sanitary purposes, hot water production, lighting, and air conditioning. Heating represents half the energy consumed in the services sector (Fourcroy et al. 2012). Directive 2010/31/EU on the energy performance of buildings defines a common framework for measures and requirements imposed on the energy performance of buildings. This Directive replaces Directive 2002/91/EC and implements various novel concepts, such as cost-optimal levels of minimum energy performance requirements (Article 5), nearly zero-energy buildings (Article 9), and technical building systems (Article 8). Altogether, this involves the technical equipment for the heating, cooling, ventilation, hot water, and lighting of a building. Member States are to increase energy efficiency and encourage the introduction of intelligent metering systems (Article 8) whenever a building is constructed or undergoes renovation. Member States may further encourage the installation of active control systems, such as automation, control, and monitoring systems which aim to save energy. The specific nature of this encouragement is within the competencies of individual Member States.

Various international standards were drafted in order to harmonise the terminology and standardize procedures used to identify a building's energy performance. International standard EN 15217:2007 supplies methods for rating energy performance and for certification of buildings; EN 15459:2007 defines economic evaluation procedures for energy systems in buildings; ISO 50001:2011 sets a management system of continual improvement for the energy intensity of organizations. EN 15232:2012 is an important tool for assessing the impact of automation, control, and management on a building's energy performance. The standard contains a structured list of BACS and TBM functions which have an impact on the energy performance of a building. The Standard further introduces an evaluation of existing BACSs (efficiency class A–D) based on the impact of the system on energy consumption. Class A refers to a high-energy performance BACS and TBM, while class D refers to a non-energy-efficient BACS which should no longer be installed in newly built premises. The buildings of the National Theatre can be categorized in the efficiency class C.

The utility system in the Czech National Theatre

Revamping and optimizing heating, ventilation, and air conditioning (HVAC) can significantly contribute to reducing energy use. Energy service companies (ESCO) which apply energy performance contracting method (EPC) provide complete services as far as HVAC revamping is concerned. They also provide the replacement of lightning, deployment of renewable energy sources (solar panels, photovoltaic), heat pumps, and CHP systems as well as the insulation of a building envelope. Basically, this method helps finance energy efficiency improvements from savings which were achieved thanks to application of the improvements. The energy system of the National Theatre in Prague underwent a major revamping between 2007 and 2009. New energy sources (two condensing gas boilers and a water-cooled reverse chiller) and forms of low-potential heat were integrated into the system. These included, for example, cooling of sun-exposed facades, use of water from the Vltava River and waste heat from cooling of return water for condensing boilers. The operator is now able to combine various sources of heat to supply energy for the building.

Building critical components

The utility system provides heating and cooling for four buildings of the National Theatre in Prague. A simplified flow sheet is shown in Fig. 2.

As for the heating, two highly efficient condensing gas boilers (B3-G, B4-G) were installed to replace an old multi-fuel boiler. There are also two more multi-fuel boilers (B1-MF, B2-MF) operating. The efficiency of the condensing boilers reaches up to 99.5 %, and the boilers are able to satisfy almost 100 % of the demand for heat. The older boilers run only occasionally when there is peak demand or in the event of a gas boiler fault.

Hot potable water can be heated up with a heat pump (HP), which utilizes waste heat from hydraulic oil in a stage system. The oil gets hot when the coulisses move, curtain is lifted, and so forth. When the stage system is in use, the amount of waste heat is large enough to replace natural gas for hot potable water production.

The cooling system consists of two water-cooled chillers (CH1, CH2) which cool down sun-exposed facades. This extracted heat is then released to the Vltava River via a cooling circuit (heat exchanger—river water). Direct cooling without any operating unit is also possible.

A key unit of the revamping, which interconnects both the heating and cooling systems, is the reverse water-cooled chiller. The chiller can also run in a heating mode (as a heat pump) and a combined cooling and heating mode (the low-grade heat from cooling may be utilized for heating). In addition to cooling the heat from sun-exposed facades, river water and waste heat from the cooling of return water for B3-G and B4-G (enhancement of condensing effect) are other possible sources of low-grade heat.

The performance (design) parameters of the key units are summarized in Table 1.

RCH and the possibility of utilizing heat from the facades and return water cooling to improve the efficiency of B3-G and B4-G represent unconventional features of the system.

However, it is very complicated to control the system optimally due to many operational modes. Their contributions to cost savings change according to prices, ambient temperature, and other factors. To achieve the maximum possible savings within complex EPC projects, it is necessary to develop advanced BACS and TBM utilizing the model of the system.

Building automation and control system

A conventional, hierarchical control system is responsible for acquiring data and managing the energy system in the National Theatre in Prague. The BACS operates on the lowest level with standard control mechanisms, such as on/off switching, proportional-integral-derivative controllers (PID controllers), and equitherm control. These features are typical for control systems in practice.

Recently, novel methods of control, usually designated as advanced process control, have been developed. These novel approaches seem very promising for industrial practice, but they are especially popular with the researchers. Testing and potential implementation of these advanced control methods require certain knowledge of the

Fig. 2 A simplified flow sheet of the heating and cooling system

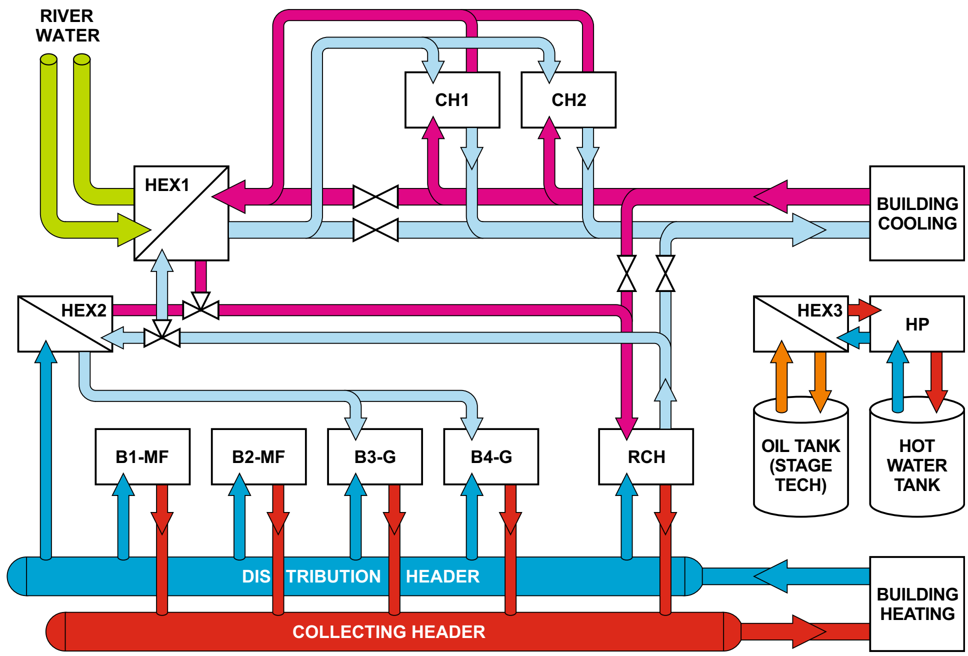


Table 1 Performance parameters of the key units

Unit	Heat output (kW)	Cooling output (kW)
Multi-fuel boiler (B1-MF)	3120	
Multi-fuel boiler (B2-MF)	3120	
Gas boiler (B3-G)	1440	
Gas Boiler (B4-G)	1140	
Water-cooled chiller (CH1)		826
Water-cooled chiller (CH2)		826
Water-cooled reverse chiller (RCH)	1422	470
Heat pump (HP)	30	

mathematical model of the controlled system. This is called a model-based approach. The model-based approach is common in supervisory and optimal control strategies. Optimal control strategy for a central chiller plant using the genetic algorithm was introduced by Ma and Wang (2011). The authors also discuss self-tuning of the models. The models may be automatically adapted using an online learning from operational data. However, this feature is valuable only if the operational data are of a high quality and are acquired with a sufficient sampling frequency. Fuzzy logic-based controllers are an alternative to the model-based approach. Saving of energy using fuzzy control applied to a chiller was published by Silva et al. (2012). These advanced control methods are commonly not applied in most commercial facilities due to poor quality of data acquisition and hardware restrictions in the plant. This is also the case of BACS in the National Theatre in Prague. However, even in this type of facilities, it is possible to reach significant improvements of the control system.

The existing control system reacts only to changes in temperature in the monitored premises and/or in the water return lines of the sources. The specific value of the required heating/cooling power is a key unit for energy system management. The specific value is affected by the ambient temperature and other criteria (vacancy/occupancy of the premises, time programs, etc.).

A supervisory control and data acquisition (SCADA) is part of the BACS. The SCADA system archives the data and is further responsible for master control mechanisms using an operator's PC (the personnel must be always present). Main features of the SCADA system in terms of energy efficiency are summarized in Table 2 (left column). The integration of a reliable mathematical model may have a great positive impact on these features. An advanced SCADA system may offer the extra features summarized in Table 2 (right column).

The model can significantly contribute on the TBM level as well. Optimization of daily peak for natural gas for

Table 2 Key features of the SCADA system and expected benefits connected with implementation of the mathematical model

Key features of the current SCADA system	Extra features of an advanced SCADA system
Monitoring performance and consumption, including displaying history trends in charts	Monitoring and prediction of performance and consumption, including display of all trends in charts
The manual selection of a particular heating/cooling source	An optimum automatic selection of a particular heating/cooling source
Warning alerts in the event of exceeding the daily amount of natural gas (using data from a gasometer)	Prediction of natural gas consumption (weather forecast dependent) and exceeding the daily peak for natural gas

contract with gasworks is a very progressive feature. It will be presented in the "Model applications" section.

The developers of black-box/grey-box models must possess previous data which is reliable. Common impediments of the data's reliability include systematic measurement errors and/or the accuracy of measurement devices. Model developers usually consider these errors, and the errors are thoroughly analysed in a review of previous data. For now, we would like to discuss problems associated with a data acquisition system that has been designed for control, and not for developing an energy system model. The developers of the model predominantly work with data from heat-meters, transferred by an M-BUS interface, which creates a problem.

The application potential of the M-Bus is relatively narrow and highly specialised, and therefore the requirements are rather specific. The M-Bus has to deliver data from many pieces of equipment, commonly designated as slaves, to a common master over large distances (hundreds of metres). Data transfer must be secured against errors. On the other hand, the system does not read the utility meters very often and the requirements on real-time reactions are low. The M-Bus interface is based on the asynchronous serial transmission of data using a two-wire bus. Data transmission is half-duplex and has a master–slave structure. The bus allows data to be sent only from one station at a time (Miehlisch 1998). This means that the database acquires data foremost from the first heat-meter, from the second heat-meter second, and so on. The time marks of particular data differ (the difference may be several minutes and even tens of minutes, depending on the complexity of the system). The speed and synchronization of data transmission are not a priority in common heat source meters. In contrast to this, the development of a mathematical model highly prioritizes speed and synchronization. Random time delays in data acquisition significantly complicated the development of the energy system model for the National Theatre in Prague. The "Models of Building Critical Components" chapter presents the particular effects of the time delays on the case study.

Other impediments for the model's development include features of the control system which are designed for the efficient use of storage capacity, namely the capacity of the hard discs. Thus we face a problem in which old data are erased and only recent data are kept. Due to these system features, the model development can be complicated.

We may conclude that even a well-structured BACS does not provide reliable data for modelling, and we have to consider all the risks mentioned above. The following chapter presents approaches to the development of system models.

A review of suitable modelling techniques

Improvements to control systems based on simulation and optimization are frequently discussed. A good mathematical model describing the system and its related aspects is essential. The model may be white-box (based on physics/chemistry laws), black-box (based on empirical data—regression), or grey-box (a combination of white-box and black-box principles). A comparison of different modelling approaches can be found in the article by Afram and Janabi-Sharifi (2014). The authors present a summary of techniques used for all three types of modelling.

Based on our experience and the statements of other authors, black-box modelling (Ochoa-Estopier et al. 2014) or grey-box modelling (Xiwang and Wen 2014) is recommended when phenomena or properties affecting the process are not fully known. These models have less parameters to determine and need a shorter computation time, which is important for their implementation into the control system. The analytical models may be too complex and do not have to reflect specific conditions influencing the modelled system. On the other hand, black-box and grey-box models are valid only according to the range of data they are based on.

Heating and cooling systems typically consist of boilers, heat pumps, and chillers, and occasionally also micro-turbines and solar power generators. There are research articles describing various methods of black-box modelling in either the entire system or a particular technological unit and for various purposes (control, settings, operation planning).

In the field of black-box models, linear regression (LR) models and neural network (ANN) models appear to be the most frequently used. By LR, we mean linear with respect to regression coefficients. In comparison with LR models, ANN models can successfully identify nonlinear relations between variables and are generally very suitable for regression-type problems. On the other hand, LR models show a lower level of complexity than ANN models, which can be advantageous in further applications.

There are many papers discussing chiller modelling. A review of ANN applications for chillers and heat pumps was presented by Mohanraj et al. (2012). It shows that ANN models are widely applied in this field. Kusiak et al. (2010) modelled HVAC energy consumption by several data-mining algorithms (C&RT trees, support vector machine, etc.), and ANN showed the best accuracy. Swider (2003) concludes that ANN models give better results for complex vapour-compression liquid chillers without more detailed knowledge of a system. On the other hand, when further information is available, extended LR models (different LR models for different operational modes for example) are almost equally accurate.

None of the mentioned papers deal with a HVAC system with boilers. Our literature search showed that performance modelling of boilers used in utility systems has not been conducted yet. The boiler-related research is usually focused on large-scale boilers in power plants. ANN models prevail here too, see for example an ANN-GA approach for predictive modelling and optimization of NOx emission in a tangentially fired boiler (Ilamathi et al. 2012).

It would have been useful if a comparison of ANN models with LR models had been presented in these papers. In further applications, such as optimization, LR models may provide a better trade-off between complexity and accuracy.

Applications of LR models are not as frequently presented as ANN models in the HVAC field. Solati et al. (2003) applied a linear regression approach to model the energy performance of screw chillers. Cui and Wang (2005) used an LR model to develop a strategy for detecting and diagnosing faults in centrifugal chiller systems. Jeon et al. (2010) used LR models derived from models implemented in EnergyPlus to simulate a water-screw chiller's performance. Lee et al. (2012) presented an overview and comparison of centrifugal water chiller LR models frequently used for simulations, including both black- and grey-box models. The comparison shows that biquadratic and polynomial black-box models are the most suitable of all the models included in the test.

To extend the application of the system model, a tool for predicting heating and cooling demand is usually integrated. This is also a frequently discussed issue within the literature. A review of the models for prediction is presented by Suganthi and Samuel (2012). For example, Mařík et al. (2008) developed a methodology for forecasting energy demand where he specified inputs which are sufficient for the majority of these problems.

In most of the studies mentioned, data used for black-box modelling are either provided by the manufacturer or obtained using well-managed processes (e.g. an experimental utility system). Based on our experience, modelling is very complicated in the case of a building-scale, common utility system. Problems may especially occur since perfect data acquisition is not necessary for a control system (see "Building automation and control system" section). However, they decrease the quality of the data set and consequently the quality of a model. Solving the problems improves the data quality. On the other hand, it requires additional time and investment, and therefore a trade-off between improvements and investments is needed.

As presented in the section on modelling, we produced both LR and ANN models. We opted for LR models because ANN models do not provide significantly better accuracy, probably due to data quality as discussed before (thus, these more complex models are not beneficial). Great progress has been made in applying energy models for building control and operation to save energy and costs. However, there is still a long way to go to make these methods applicable and guarantee a desirable performance in practice (Xiwang and Wen 2014). Our paper is instrumental in these efforts and discusses the development and use of a model which greatly enhances BACS/TBM in a complex of existing buildings. We present efficient model development and its easy implementation into the control system. We have not found any paper dealing with these issues in literature so far.

The following sections present the modelling process of the energy management in the National Theatre in Prague and two concrete examples to illustrate the application of the model within the control system.

Modelling the building utility system

Our objective was to develop advanced functional properties of the National Theatre BACS based on a model (see Table 2 in the section on the Control System). Before we can integrate the model in the BACS, we first have to make sure that it is reliable. In the first step, we had to verify the following features of the model:

- An analysis of particular operational modes from a technical-economic point of view. This feature is a prerequisite for predicting utility performance and

energy consumption and the optimal automatic selection of particular heating/cooling sources.
- The prediction of NG, oil, and power consumption in various operational regimes. This feature is a prerequisite for predicting the risks of exceeding the daily peak for natural gas and daily peak optimisation.

Modelling methods and approaches should be chosen according to the purpose of the model, and so it is not worth making a complex model if it is not necessary. Furthermore, there may be requests for easy implementation or clear interpretation as well.

In addition to impediments concerning data acquisition (see "Building automation and control system" section), we further have to consider that black-box models are valid only in the range of data used for their development. This could be a problem in optimization. If a solver finds a solution which is technically feasible but out of the data range used in modelling, we cannot be sure that the approximation is valid in this case. Furthermore, we may have to exclude an important model input due to missing variability in operational data. For example, when a value of an input is fixed (e.g. fixed temperature set point), we cannot evaluate its significance for a model and therefore we do not include it as a model input. Therefore, we lose a decision variable when considering optimization.

We need a systematic approach (e.g. design of experiment) to get data without the aforementioned weaknesses. This can be time demanding and challenging considering a daily operated utility system which has to satisfy the current heating and cooling demand. It is for this reason that our models are based only on data from routine operation. Nevertheless, we can investigate operation regimes different from typical ones using these data.

Models for building critical components

The most important units regarding the model's application were already discussed in the "Building critical components" section. These are

- multi-fuel boilers (B1-MF, B2-MF),
- gas-fired condensing boilers (B3-G, B4-G),
- reverse water-cooled chiller (RCH), and
- water-cooled chillers (CH1, CH2).

Looking at the simplified flow sheet (Fig. 2) we can see that, in addition to these units, there are also heat exchangers, mixers, and dividers. To propose a mathematical description of the units, it is important to know which parameters are measured and which are not. Since the operator monitors many mass and energy flows, there are many opportunities to make black-box models. In some cases, there are not enough data and, in the other cases, it does not make sense to develop black-box models. Simple white-box models (based on mass or energy balances) are used to model mixers, dividers, and heat exchangers.

Also, B1-MF and B2-MF are modelled with a simple energy balance equation [assuming a constant efficiency—Eq. (1)] because there are no long-term operational data which could be used for the model.

$$P_{\mathrm{B}1/2} = lhv_{\mathrm{oil/gas}} \times m_{\mathrm{oil/gas}} \times \mu_{\mathrm{B}1/2}, \quad (1)$$

where $P_{\mathrm{B}1/2}$ is the heat output, $lhv_{\mathrm{oil/gas}}$ is the lower heating value of a fuel, $m_{\mathrm{oil/gas}}$ is the fuel flow rate, and $\mu_{\mathrm{B}1/2}$ is the boiler efficiency.

The other units are modelled using operational data. The modelling and validation is presented for the condensing gas boiler B3-G only. The procedure is the same for the other units getting very similar results.

Performance modelling of gas boilers

We made both LR and ANN models to compare their accuracy. LR model is presented in Eq. (2); ANN model is an MLP 3-8-1 with an exponential hidden activation function and identity output activation function. Natural gas consumption $m_{\mathrm{gas,B3}}$ ($\mathrm{Nm^3/h}$) is a function of heat load P_{B3}(kW), temperature of return water $t_{\mathrm{in,B3}}$(°C), and temperature of cooled return water $t_{\mathrm{c,in,B3}}$(°C). Models of the other units are presented in the appendix.

$$m_{\mathrm{gas,B3}} = 0.08 \times P_{\mathrm{B3}} + 0.49 \times t_{\mathrm{c,in,B3}} + 0.62 \times t_{\mathrm{in,B3}} - 30.98 \quad (2)$$

Considering the goodness-of-fit measures, the coefficients of correlation (R—correlation between observed and predicted values) is 0.936 for LR and 0.944 for ANN. These values seem to be acceptable. But when we consider the mean absolute error (MAE) and mean relative absolute error (MRAE), the models do not seem to be accurate enough. MAE values for LR and ANN are 7.99 and 7.52 $\mathrm{Nm^3/h}$, and MRAE values for LR and ANN are 13.93 and 13.26 %, respectively. The average error of more than 13 % is too high. However, this conclusion might be premature.

Moving on to the model validation in more detail using the B3-G, if we look at Fig. 3, the heat output is fluctuating; however, observed gas consumption is smooth (see, for example, consumption at around 18:00). Heat output is low at one step and high at the following step, while observed gas consumption is almost steady. We assume that this mismatch is caused by delayed acquisition of data (heat output is delayed in this case). Predicted gas consumption is responding to fluctuating heat output (one of the model input parameters) and, therefore, it is fluctuating too. This situation leads to differences between predicted and observed values and provides unacceptable MAE and MRAE. With skewed heat output, predicted gas consumption is also skewed and comparison with observed gas consumption is meaningless. In the following section, we investigate how much the model is affected by delays in the data acquisition.

The effect of delays on a model is described in Fig. 4. Both gas consumption and heat output are stored as a cumulative quantity. To get the hourly gas consumption and heat output, the previous value of cumulative quantity is subtracted from the current value. The gas consumption seems to be correct as it changes smoothly. However, the heat output seems to be delayed because gas-meters are directly connected to the pulse inputs of the controller, whereas heat-meters are connected via the above-discussed M-Bus. Clearly, when an acquired value corresponds to a value measured before a time point, the difference between the current and previous values is smaller than it should be. Consequently, the difference is bigger than it should be in the next time point if it is stored almost "on time". This results in a very irregular fluctuation in heat output. The model responds to the fluctuating heat output by fluctuating gas consumption (predicted values), and so the residuals of predicted values from observed values are significant.

This comparison leads us to the conclusion that the model for predicting gas consumption is not good enough. In fact, the model may predict gas consumption with reasonable accuracy. Low heat output (long delay) is balanced by high heat output (no delay or short delay) in the next time point; and as the fitted function (model) minimizes residuals of gas consumption (least square method), it should result in a negative residual for high heat output and an equal, yet positive, residual for low heat output. The "curve" of the function is therefore not biased by the delays.

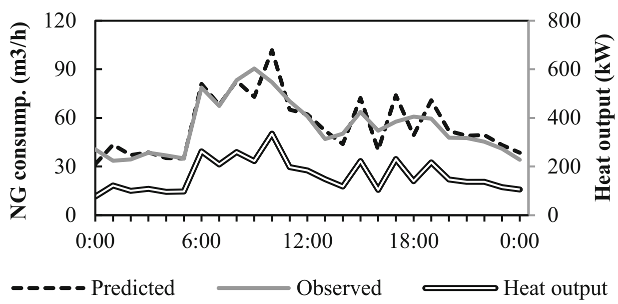


Fig. 3 A line chart of gas consumption for B3-G

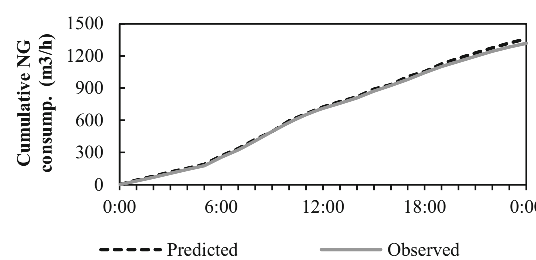
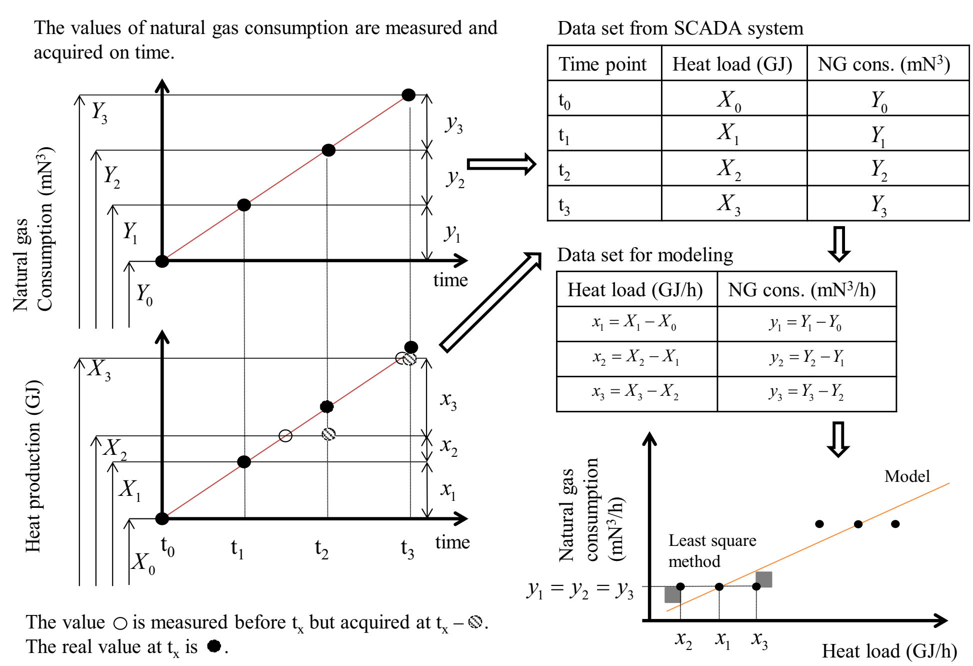


Fig. 5 The cumulative sum of gas consumption (B3-G)

Fig. 4 The effect of delays in acquisition on a model



However, this idea is hard to prove. One factor which supports this idea is a comparison of the cumulative sum of gas consumptions. Comparing the cumulative sum of predicted and observed values (Fig. 5), we can see that the model is able to predict gas consumption accurately over a long-term period. Clearly, an overestimated prediction (due to high heat output) is followed by an underestimated prediction (due to low heat output) in the next time point. If we sum these two predictions, we get a value equal to the sum of the two corresponding observations. This pattern was observed in other models, too.

Modelling summary and evaluation

Black-box models driven by operational data can provide sufficient support in operation planning and in other long-term problems:

- The simulation of operations based on predicting energy demand;
- The prediction of NG, oil, and power consumption in different operational regimes; and
- The prediction of risks originating from exceeding the daily peak for natural gas.

This was proven with a cumulative gas/electricity consumption test. The results are summarized in Table 3. For short-term problems (the optimum selection of a particular heating/cooling source), the accuracy of the models is hard to prove due to delays in data acquisition. However, based on the cumulative consumption test, we think that the models may be reasonably accurate.

We carried out manual measurements on B3/4-G (once) and RCH (twice). Many more measurements are necessary to properly test the models; however, these manual measurements are very time- and manpower consuming (the measured values are displayed at different locations in the machine room). A comparison of manually measured values with black-box models is provided in Fig. 6. We also received the manufacturer's data (catalogue) for B3/4-G and for RCH. A comparison of manufacturer's data-driven models is also presented in Fig. 6.

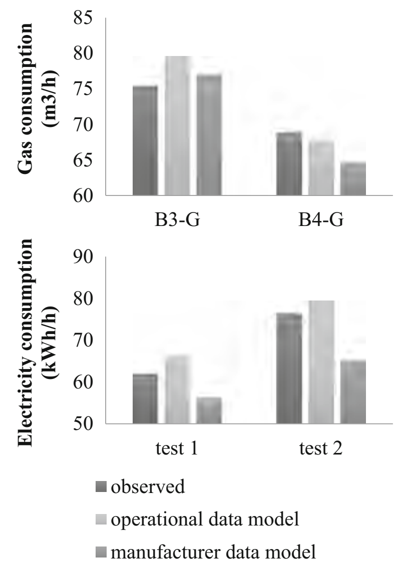


Fig. 6 Comparison of the developed data-driven models against manually measured values

The values predicted by the models are very close to the observed values. In all cases, except for B3-G, the operational data-driven models show better accuracy than the manufacturer's data-driven models. Of course, we cannot make a definitive conclusion on the models' accuracy based on these tests alone (i.e. only two measurements). However, these manual measurements also support our idea that black-box models based on operational data with time delay can be sufficiently accurate. Moreover, it indicates that it is better to use operational data than manufacturer's data for modelling since manufacturer's data are obtained under specific conditions, usually different from the conditions of the investigated process.

Table 3 The goodness of fit from daily cumulative consumptions

Unit	Mean absolute error	Mean relative absolute error (%)
B3-G gas consump.	52.3 Nm^3/day	2.8
B4-G gas consump.	37.7 Nm^3/day	2.1
RCH electricity consump.	19.6 kWh/day	0.0
CH1 electricity consump.	22.2 kWh/day	0.0
HP electricity consump.	8.7 kWh/day	3.3

Unit	Sum of observed	Sum of predicted	Difference (%)
B3-G gas consump.	109,115 Nm^3	110,551 Nm^3	−1.3
B4-G gas consump.	107,229 Nm^3	107,817 Nm^3	−0.6
RCH electricity consump.	39,054 kWh	38,159 kWh	2.3
CH1 electricity consump.	23,838 kWh	23,955 kWh	−0.5
HP electricity consump.	11,352 kWh	11,496 kWh	−1.2

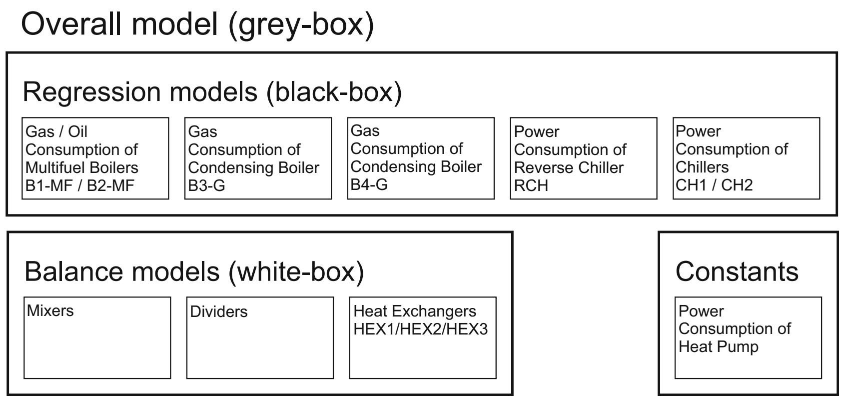


Fig. 7 Summary of the overall model

Overall grey-box model

The concept of the overall model is shown in Fig. 7. The overall model can be considered as a grey-box model since both regression models and balance models are included. The overall model incorporates all technologies which help produce heat and cold in the National Theatre in Prague. Therefore, it sufficiently describes the whole utility system. A practical application of the model is given in the following chapter.

Model applications

Some examples of the model's applications are described in the following text to demonstrate the benefits of the model. The first example describes a short-term planning problem, and the other refers to a long-term problem.

The optimum selection of heating/cooling source

The expected application of the model is at the SCADA level. This is the basic level where operators directly control the parameters of the utility system. The biggest asset of the model we developed is that it helps select the right source of heat and cold.

In general, B3-G and B4-G are used together with RCH for heating. RCH utilizes low-grade heat from cooling water which returns to the boilers. Another source is water from the river (with a minimum temperature of 6 °C). The operator is interested in how to distribute the heat load among B3-G, B4-G, and RCH, so the efficiency or the operational costs are minimal. The solution is not straightforward because load distribution influences temperatures at the inlet and outlet of each unit, and this influences the COP of RCH and thermal efficiencies of B3/4-G.

In this example, we assume a winter day when the total heat load is 2600 kW. The question is how to distribute heat loads among RCH and B3/4-G. Return water for B3/4-G is the only source of heat for RCH because the temperature of the river water is below 6 °C. Usually, the RCH unit works at the available maximum (700 kW) to cool down return water for B3/4-G (see Fig. 8).

Surprisingly, however, the optimal solution says that RCH utilization should be much lower. The optimal heat loads are as follows: RCH—170 kW, B3-G—1215 kW, and B4-G—1215 kW. We carried out a sensitivity analysis of the optimal solution to RCH heat load in order to better understand this solution. The operator naturally expects a much higher RCH heat load because it provides a lower return water temperature (i.e. a positive effect on condensation in boilers and their efficiency); a lower boiler load also provides better efficiency (better condensation). However, the other effect of a high RCH load is low COP. The flow rate of water in the RCH condenser is constant, and water temperature in the collecting header is fixed (given by the ambient temperature). Therefore, the temperature at the outlet of the condenser side increases with the heat load. This has a negative impact on COP, which negates the increased boilers' efficiency. The difference in cost is not enormous, 3 EUR/hour, but considering a heating period of 4 months, it may save over 8600 EUR every year (the difference is similar for a wide range of the total heat load).

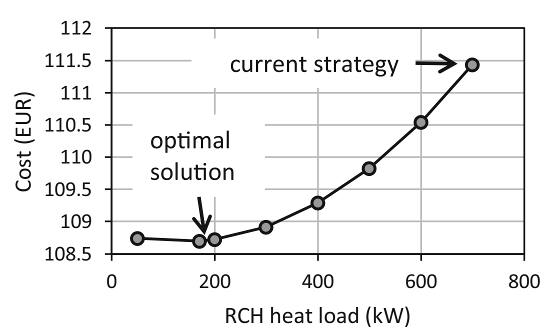


Fig. 8 Sensitivity of operational costs to RCH load

This is one example of optimum source selection. The operator repeatedly faces many other dilemmas in controlling energy systems in the summer time as well. There are two options for cooling, RCH, and/or CH. The RCH has a lower COP than CH, but the RCH is more efficient when there is also a demand for heat. The operator decides if it is still cost effective to run the RCH according to the heat demand and other parameters (e.g. target temperatures of chilled and cooling water). Other difficulties arise during the transition period when the system switches from heating to cooling and/or both regimes run in parallel. The model and optimization may bring important answers and more savings to the operational costs.

So far in the testing, the model functioned as a supporting computational tool which the operator runs in MS Excel as required. First, the model can display recommendations concerning the optimum sources of heat and cold. If the system proves reliable, it could assume decision-making competencies and select the energy sources on its own. We recommend integrating it into the existing BACS for the optimum automatic selection of a particular source performed by a control system.

The previous example shows the application of the model for a short-term control problem on the SCADA level. Let us now analyse how the model can contribute on the TBM level, in our case, with the operation of the heating system.

Optimizing the daily peak for natural gas

The costs of gas consumption may be structured as variable and fixed costs. Variable costs simply depend on the amount of gas consumed. Fixed costs are related to payments for the daily peak. The daily peak is the maximum volume of gas which can be delivered on any one day during a given period. There are very high penalties for consumers if they exceed this limit. A high daily peak in a contract means high costs for gas. The goal is to find the optimum value of the daily peak and thus minimize the costs.

Let us now assume that we have perfect information (prediction) about heat demand during the heating period (hourly data) which needs to be satisfied with B1/2-MF, B3/4-G, and RCH. In addition, we have perfect information about the return water temperature (equitherm control based on the actual demand and ambient temperature). The energy management needs to know how to set the daily peak in a contract and how to operate the boilers to achieve minimal operational costs.

The objective function to be minimized is given by Eq. (3):

$$z = \sum_{\substack{\text{heating}\\ \text{period}}} E_{\text{ele}} \times c_{\text{e}} + \sum_{\substack{\text{heating}\\ \text{period}}} Q_{\text{gas}} \times c_{\text{gas}} + \sum_{\substack{\text{heating}\\ \text{period}}} m_{\text{oil}} \times c_{\text{oil}} + Q_{\text{gas,day}} \times c_{\text{gas,day}} + \sum_{\substack{\text{heating}\\ \text{period}}} Q_{\text{gas,pen}} \times c_{\text{penalty}}, \quad (3)$$

where E_{ele} is the electricity consumed (kWh/day), c_{e} denotes the electricity costs, Q_{gas} is the gas consumed (Nm^3/day), c_{gas} denotes the unit costs of the gas consumed, m_{oil} is the oil consumed (kg/day), c_{oil} denotes the unit costs of the oil consumed, $Q_{\text{gas,dp}}$ is the volume of the daily peak (Nm^3/day), $c_{\text{gas,dp}}$ is the cost of the daily peak, $Q_{\text{gas,pen}}$ is the gas consumed over the daily peak (Nm^3/day), and c_{pen} is denotes the penalty costs. The start-up costs for B-MF are not considered. Approximate prices are summarized in Table 4.

Assuming that the heating period lasts 109 days and heat demand corresponds to real operational data, the average hourly heat demand (multiplied then by 24) is considered instead of a different hourly demand during the day to make the problem easier to solve. The average return water temperature is used as well.

Since we evaluate daily fuel consumptions, we can use a model driven by operational data which has been proved accurate for this purpose. The model was implemented into the GAMS modelling system.

The minimal value of the objective function is EUR 136,300, and the optimal daily peak is 4315 Nm^3/day. The operation or, more precisely, the gas and oil consumption is shown in Fig. 9. There are only 3 days (31, 78 and 81) with a higher heat demand in which gas consumption is on its daily peak, and therefore it is partially replaced by oil. There are other days when gas is on its daily peak; the rest of the heat load goes to RCH.

The cost sensitivity to the value of the daily peak was analysed. The results are shown in Fig. 10. The operation is never penalized because the penalty is too high and so oil is used when needed. If the operator wants to be on the safe side, the daily peak of 4800 Nm^3/day is the best choice (no need for oil according to the given heat loads). However, overestimating daily peak leads to significantly increased costs. Compared to the optimal value of 4320 Nm^3/day, it

Table 4 Approximate prices used in the optimization

Electricity cost c_{e}	(EUR/kWh)	0.2
Natural gas cost c_{gas}	(EUR/Nm^3)	0.38
Oil cost c_{oil}	(EUR/kg)	0.74
Daily peak cost $c_{\text{gas,day}}$	(EUR/Nm^3 of daily peak volume)	4.07
Penalty cost c_{penalty}	(EUR/Nm^3 of gas over the peak)	20

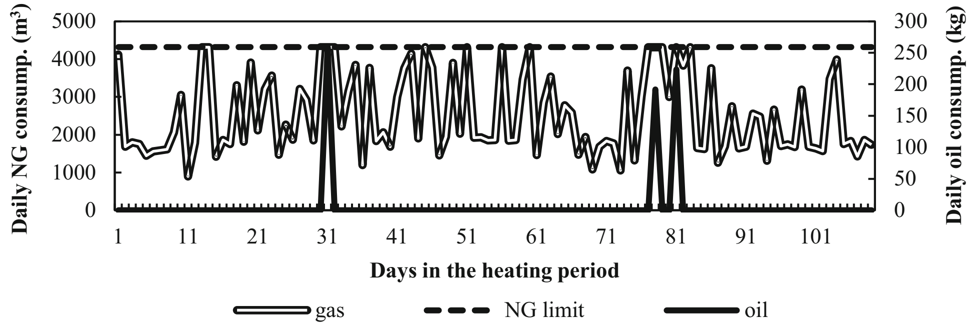


Fig. 9 Gas and oil consumption over the heating period for optimal NG daily peak

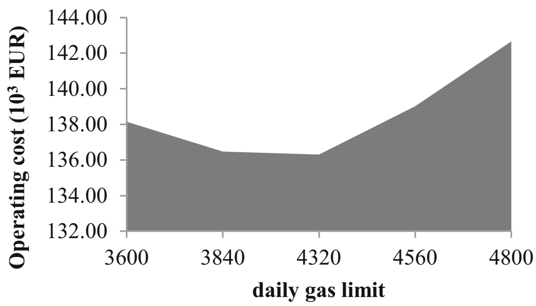


Fig. 10 Sensitivity of operational cost to NG daily peak

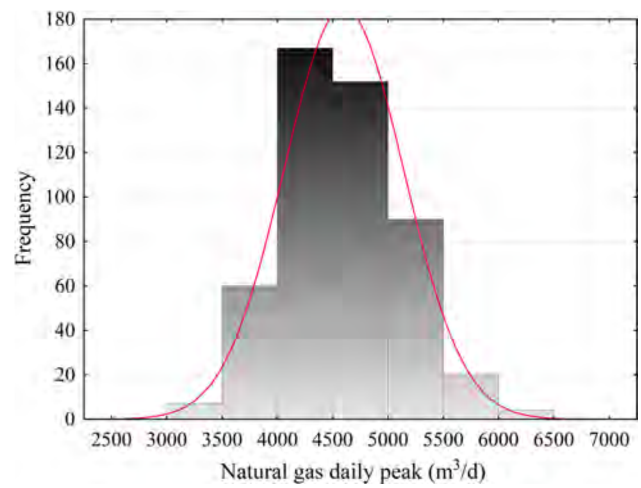


Fig. 11 A histogram of optimal daily peaks from Monte Carlo simulation

is EUR 6400 more (about 5 % of the total costs), whereas underestimating shows a slight increase in costs. On the other hand, underestimating is at more high risk. The oil is stored on site in a tank with a limited volume, and the option is not as flexible should there be an increased demand for oil.

This example was a case of perfect information about the future, but, of course, heat demand is extremely uncertain in the long term. There are well-known methods of dealing with this uncertainty. For example, the Monte Carlo method can be applied. The procedure consists of solving an optimization problem for a series (hundreds or thousands) of random heat demands. The results are then statistically evaluated and we choose the best value.

We carried out a Monte Carlo simulation with 500 randomly generated heat loads (the aforementioned fixed heat load was multiplied by a randomly generated number from normal distribution with a mean of 1 and standard deviation of 0.1). Figure 11 presents the results. In this method, we do not get one number but a histogram showing a probability distribution of the daily peak, which is a good tool for supporting decision making. For example, if we want to avoid using oil or sanctions, we can choose the value of 5500 Nm^3/day (the probability that gas consumption will be equal to or lower than this value is very high—95 %). However, looking at Fig. 10, total costs rapidly increase in relation to the daily peak, and the decision is not that straightforward. It is up to the decision maker which value is the best choice. A value close to 4800 could be a good decision.

The other way of handling this uncertainty is a two-stage stochastic programming. The first-stage decision (the maximum daily gas demand) is made before the observation of uncertain parameters (heat demand). The second stage decision(s) is a reaction (boilers' operation) to the observation of uncertain parameters. So, there is only one daily peak and not a series, as in the Monte Carlo method.

Conclusion

With increasing energy prices and pressure on environmental protection, energy-efficient processes and cost-effective energy management are in demand. HVAC systems are particularly significant energy consumers with huge potential for improvement. In addition to replacing old technological units to guarantee better efficiency, there is also a potential for "soft" improvements, such as better BACS and TBM, better operation planning, and so forth.

In this paper, we dealt with the heating and cooling system in the National Theatre in Prague. Since there are lot of operational data available, we decided to employ a grey-box modelling approach. The system is operated daily with standard energy data acquisition using an M-Bus protocol. An analysis of the data showed that the acquisition system causes a significant time delay, which is problematic for the modelling.

The model validation showed that the prediction accuracy could not be clearly proved over a short-term period (i.e. 1 h in validation step) due to time delays in acquisition. However, we were able to demonstrate good accuracy of the model over longer periods (several hours or a day), and the manually performed test indicated that the model is sufficiently accurate. The effect of delays was shown to be balanced, and the regression function was not biased. In fact, the model's predictions were demonstrated to be closer to real values than data from the acquisition system.

The application of the model demonstrated its benefits on the BACS level as well as on the TBM level. These "soft" improvements are not expensive and provide efficient operation and cost savings. Our paper is instrumental in these efforts and discusses the development and implementation of the model into the control system. The successful integration of the saving tools is conditioned by an agreement between the technical manager of the building and an expert in the area of modelling and optimization.

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Appendix

B4-G

LR: $m_{\text{gas,B4}} = 0.08 \times P_{\text{B4}} + 0.15 \times t_{\text{c,in,B4}} + 0.57 \times t_{\text{in,B4}} - 16.91$

ANN: MLP 3-10-1; hidden activation function: logistic; output activation function: hyperbolic.

$m_{\text{gas,B4}}$	natural gas consumption (Nm^3/h)
P_{B4}	heat load (kW)
$t_{\text{in,B4}}$	temperature of return water (°C)
$t_{\text{c,in,B4}}$	temperature of cooled return water (°C)

Regression type	R	MAE	MRAE
LR B4-G	0.9024	6.50	13.84
ANN B4-G	0.9129	6.11	13.24

RCH

It can work in combined heating and cooling mode so two equations are needed (one for condenser and one for evaporator).

LR cond.: $P_{\text{pow,RCH}} = 0.57 \times t_{\text{out,co,RCH}} - 0.36 \times t_{\text{in,ev,RCH}} + 0.25 \times P_{\text{heat,RCH}} - 12.46$

ANN cond.: MLP 3-7-1; hidden activation function: logistic; output activation function: hyperbolic

LR evap.: $P_{\text{pow,RCH}} = 0.75 \times t_{\text{out,co,RCH}} - 0.31 \times t_{\text{in,ev,RCH}} + 0.41 \times P_{\text{cool,RCH}} - 29.25$

ANN evap.: MLP 3-5-1; hidden activation function: hyperbolic; output activation function: exponential

$P_{\text{pow,RCH}}$	power consumption (kW)
$P_{\text{heat,RCH}}$	heat output (kW)
$P_{\text{cool,RCH}}$	cooling output (kW)
$t_{\text{in,co/ev,RCH}}$	temperature of water at condenser/evaporator inlet (°C)
$t_{\text{out,co/ev,RCH}}$	temperature of water at condenser/evaporator outlet (°C).

Regression type	R	MAE	MRAE
LR RCH condenser side	0.9623	9.56	18.07
ANN RCH condenser side	0.9682	8.66	15.00
LR RCH evaporator side	0.9484	6.29	9.02
ANN RCH evaporator side	0.9560	6.04	8.94

CH1

Data for CH2 are not available due to occasional operation so CH2 is assumed to have similar performance as CH1.

LR: $P_{\text{pow,CH1}} = 5.34 \times t_{\text{in,co,CH1}} - 0.17 \times t_{\text{in,ev,CH1}} + 0.15 \times P_{\text{cool,CH1}} - 107.62$

$P_{\text{pow,CH1}}$	power consumption (kW)
$P_{\text{cool,CH1}}$	cooling output (kW)
$t_{\text{in,co,CH1}}$	temperature of water at condenser inlet (°C)
$t_{\text{in,ev,CH1}}$	temperature of water at evaporator inlet (°C).

ANN: MLP 3-5-1; hidden activation function: hyperbolic; output activation function: hyperbolic.

Regression type	R	MAE	MRAE
LR CH1	0.9310	9.67	11.88
ANN CH1	0.9404	9.39	11.36

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Combined heat and power production planning in a waste-to-energy plant on a short-term basis

Michal Touš [a,*], Martin Pavlas [a], Ondřej Putna [a], Petr Stehlík [a], Lukáš Crha [b]

[a] Institute of Process and Environmental Engineering, Faculty of Mechanical Engineering, Brno University of Technology (UPEI VUT), Technická 2896/2, 616 69 Brno, Czech Republic
[b] Pražské služby a.s. - ZEVO, Průmyslová 615/32, 10800 Praha, Czech Republic

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ABSTRACT

In many cases, WtE (waste-to-energy) plants are CHP (combined heat and power) producers. They are often integrated into a central heating system and they also export electricity to the grid. Therefore, they have to plan their operation on a long-term basis (months, years) as well as on a short-term basis (hours, days). Simulation models can effectively support decision making in CHP production planning.

In general, CHP production planning on a short-term basis is a challenging task for WtE plants. This article presents a simulation based support. It is demonstrated on an example involving a real WtE plant. Most of the models of relevant WtE sub-systems (boilers, steam turbine) are developed using operational data and applying linear regression and artificial neural network technique. The process randomness given mainly by fluctuating heating value of waste leads to uncertainty in a calculation of CHP production and a stochastic approach is appropriate. The models of the sub-systems are, therefore, extended of a stochastic part and Monte-Carlo simulation is applied.

Compared to the current planning strategy in the involved WtE plant, the stochastic simulation based planning provides increased CHP production resulting in better net thermal efficiency and increased revenue. This is demonstrated through a comparison using real operational data.

1. Introduction

This work was motivated by the need to improve how energy is managed in a plant for energy recovery from waste, also called WtE (waste-to-energy). Greater efficiency and increased revenue are the two goals for improving the planning of energy production in the plant. In this contribution, we present a planning approach based on black-box modelling and sequential stochastic simulation.

The WtE facility concerned in this paper is located in Prague, the Czech Republic. Its simplified flow-sheet is in Fig. 1. Its processing capacity is 300 kt/y. It was put into operation in 1998 and consists of four lines with a processing capacity of 15 t/h of waste per line. The corresponding production of steam in one boiler is 36 t/h at a pressure of 1.37 MPa and temperature of 235 °C. Since the WtE facility was originally assumed to deliver heat only for a DHS (district heating system), the steam parameters at the boiler outlet were designed specifically with this in mind. No steam turbine was installed in its original arrangement and so it was run without electricity production. Although the facility was a minor heat supplier within the DHS, the lack of heat demand, especially during the summer, caused its limited performance.

In 2009, the plant underwent massive modernization. Its flue gas treatment system was expanded with DeNOx/DeDiox technology, which is a combined process for the catalytic removal of nitrogen oxides and dioxins from flue gas [1]. At the same time, a new condensing steam turbine, with a nominal output of 16 MW, with one uncontrolled extraction was installed. Since then, it has been simultaneously producing heat and electricity, i.e. it became a CHP (combined heat and power) producer. However, there were no changes implemented on the boilers to increase steam parameters. Regarding the current state-of-the art, the steam parameters are low compared to other WtE plants. Typical values for a plant of this type are 4 MPa and 400 °C or more [2]. In addition to heat from CHP production, there is also a live steam supply as a utility for

* Corresponding author. Tel.: +420 541 144 961.
E-mail addresses: tous@fme.vutbr.cz (M. Touš), pavlas@fme.vutbr.cz (M. Pavlas), putna@upei.fme.vutbr.cz (O. Putna), stehlik@fme.vutbr.cz (P. Stehlík), crha@psas.cz (L. Crha).

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Nomenclature

Variables

m_{st}	steam production in boilers (t/h)
Δm_{st}	an increment in steam production in boilers (t/h)
$\Delta m_{st,\ max}$	a reference value for a decision if an increment in steam production is large or not (t/h)
$m_{st,\ bo}$	the flow rate of steam for boilers' blow off (t/h)
$m_{st,\ da}$	the flow rate of steam to deaerator (t/h)
$m_{st,\ ec}$	the flow rate of steam to external consumer (t/h)
$m_{st,\ TG}$	the flow rate of steam to the steam turbine (t/h)
$m_{st,\ bp}$	the flow rate of by-passed steam (t/h)
$m_{st,\ ex}$	the flow rate of extraction steam (t/h)
$m_{st,\ ex,\ DHS}$	the flow rate of steam for district heating (t/h)
$m_{st,\ ex,\ sc}$	the flow rate of steam for self-consumption (t/h)
$p_{st,\ ex}$	the pressure of extraction steam (kPa)
$T_{st,\ ex}$	the temperature of extraction steam (°C)
$T_{st,\ ex\ +\ bp}$	the temperature of extraction and by-passed steam mixture (°C)
T_{min}	the minimum temperature required at the inlet of the district heating heat exchanger (°C)
$h_{st,\ ex}$	the specific enthalpy of extraction steam (kJ/kg)
h_{st}	the specific enthalpy of steam produced in the boilers (kJ/kg)
$h_{st,\ ex\ +\ bp}$	the specific enthalpy of extraction and by-passed steam mixture (kJ/kg)
$h_{st,\ ex/ex\ +\ bp,\ T\ =\ 70\ ^\circ C}$	the specific enthalpy of condensate at the outlet of the district heating heat exchanger with the outlet temperature of 70 °C (kJ/kg)
W_{TG}	steam turbine electricity output (MW)
$W_{TG,\ exp}$	electricity export (MW)
$W^0_{TG,\ exp}$	calculated electricity export with zero by-pass and planned heat delivery (MW)
Q_{DHS}	heat delivery to a district heating system (MW)
$Q_{st,\ TG\ +\ bp}$	heat content in steam before by-pass (MW)
μ_{th}	net thermal efficiency (%)
d	drift of mean (t/h)
$\xi,\ \omega$	random numbers (−)

Superscript

t	time parameter

Parameters

H	hour in a day
D	day in a week
NB	number of boilers in operation

Abbreviations

WtE	waste-to-energy plant
CHP	combined heat and power
DHS	district heating system
MC	Monte-Carlo simulation
PC	plan confidence
LR	linear regression model
ANN	artificial neural network model
LHVW	lower heating value of waste
FRW	the waste flow rate
MAE	mean absolute error
MRAE	mean relative absolute error

industrial heating. This steam is supplied according to current demand which is not regular and is difficult to predict.

The new plant arrangement brought with it more flexibility but, at the same time, an increased need for energy management. CHP production is governed by contracts on heat and electricity delivery. These contracts specify things such as amount of heat/electricity, prices, penalties, and so on.

The amount of heat delivered in a year is specified and then distributed into months (higher in winter, lower in summer). A month's delivery is uniformly distributed into days in the month and a day's delivery uniformly into hours. A delivery deviation within a specific range from the planned amount is feasible (given by a contract), otherwise there are penalties.

Furthermore, the facility has a contract on electricity delivery. The electricity is offered to a retailer, after which, the retailer takes it to the electricity market. The same rule of delivery deviation from the planned amount holds. The electricity delivery has to be kept within a specific range from the planned amount, otherwise there are penalties.

The contract's conditions, together with WtE plant's actual performance, govern the planning of heat and electricity delivery on an hourly basis for the next day. The goal of planning is to prepare a balanced production plan where the plant's performance is maximized from an economic point of view. To summarise, the plant's efficiency and risk of not-meeting the plan should be addressed at the same time.

In general, WtE heat and electricity planning is a challenging task, especially due to inhomogeneous waste. The properties (composition and lower heating value) fluctuate over the time. In addition, the WtE plant delivers live steam to the external consumer. However, the steam demand is strongly irregular and significantly contributes to uneasy operation planning. The external consumer is a facility producing dairy products and the irregularity is due to variable production.

Considering the operation of a WtE plant in general, there are three situations which may occur in relation to a proposed production plan (see Fig. 2):

- First, a plan underestimates a plant's actual performance, the amount of steam leaving the boiler house and entering the turbine house is higher than expected. More heat and power could be produced. Penalties are accepted and/or part of energy has to be wasted to meet the plan (e.g. turbine bypassing or heat releasing into environment). This leads to a financial loss or loss in CHP efficiency, respectively.
- Second, a plan overestimates a plant's performance. This may cause an inability to satisfy the planned delivery which leads to penalties or high operation cost by utilizing natural gas to increase steam production.
- Third, a plan reflects a plant's actual performance within common fluctuations, which leads to an uncomplicated operation with maximized financial effect and CHP production.

Clearly, a balanced plan represents an ideal situation and is preferred whenever possible. Underestimating represents a conservative approach and overestimating may be observed when an unexpected drop in steam production appears. We want to avoid underestimating and overestimating as much as possible.

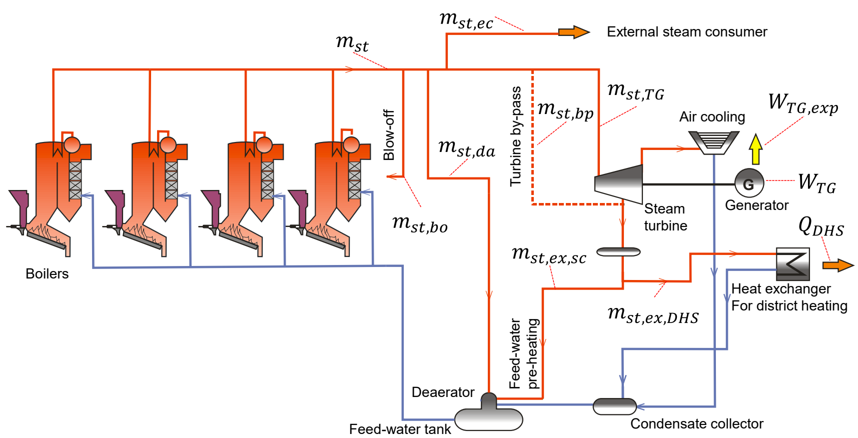

Fig. 1. A simplified flow-sheet of the steam–condensate cycle used in WtE technology (red lines represent steam, blue lines represent water, flue gas treatment system excluded). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

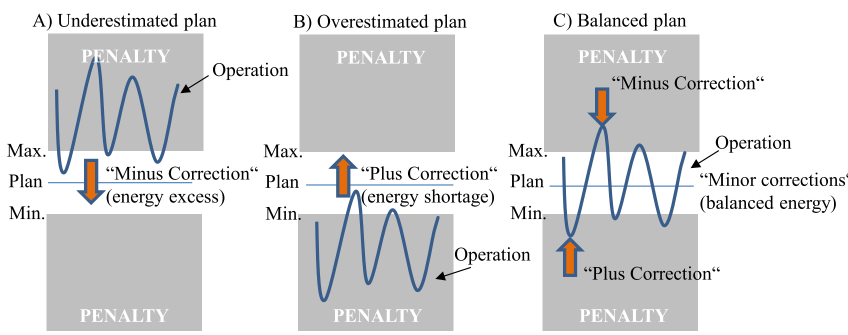

Fig. 2. Situations which may occur in relation to a proposed production plan.

Current planning strategy in the considered WtE plant in Prague is given by conditions in contracts. In this case, there is a high penalty when electricity delivery is over the agreed deviation, which is ±0.5 MW. On the other hand, there is a low penalty when the planned heat delivery is not kept on a short term basis. Naturally, the focus in terms of planning and subsequent operation is on the electricity delivery. The planned electricity delivery is conservative to make sure that the plant will be able to satisfy it. If the steam production is higher the steam turbine by-pass is used to decrease it (see Fig. 1 $-m_{st,\ bp}$). This means higher heat delivery but it is not penalized as much as for electricity. This is not beneficial for CHP production and maximising financial revenue. Support based on an advanced simulation tool is one possible method to minimize these situations and enhance the performance, with an acceptable risk of penalties resulting from fluctuating and unpredictable operation.

The proposed plan should be accurate enough regarding the agreed deviation of electricity export, as stipulated by the contract. Regarding the aforementioned aspects, an uncertain LHVW (lower heating value of waste) and live steam extraction, this is challenging. However, these are not the only source of uncertainty. We apply regression models developed using operational data (data-driven models). These models are called black-box in scientific papers.

Naturally, there is also some uncertainty presented because the data is influenced by random errors or there can be lack of explanatory variables – for example when the modelled system is too complex we do not consider all influencing factors or when we want to simplify the model in order to make a calculation simple (see the model of steam extraction for deaerator). In some cases the uncertainty is higher in some cases lower. For these reasons, we shall introduce a stochastic model and stochastic simulation (Monte-Carlo method, MC) for CHP production planning in the WtE plant.

Based on our literature research, improvements in energy management based on simulation and optimization are frequently discussed. Salgado and Pedrero [3] presented a review of short-term operation planning on CHP systems. They concluded that stochastic models should be included more frequently. Recently, Bischi et al. [4] presented optimization based, short-term planning for combined cooling, heat and power production where the daily operating cost is minimized. Short-term operation planning is also typical for some renewable energy systems (solar, wind). Nemet et al. [5] presented a paper which dealt with an increase in solar energy in order to minimize utility consumption by rescheduling. Pereira et al. [6] introduced a mixed integer nonlinear programming model to manage power systems, including wind power plants. Researchers in operation planning of CHP production systems including renewable sources of energy usually consider uncertainties. It is typically electricity price (e.g. Ref. [7]), natural gas price and uncertainty in renewable energy production (e.g. Ref. [8]).

WtE plant CHP production planning has to consider uncertainties as well. Lower heating value of waste represents an uncertain parameter common to all WtE plants. However, the attention is not paid to this topic in scientific papers.

Optimization of operational plans or control is an objective of recent research papers (e.g. Ref. [8]). However, we introduce a simulation tool only since there are no degrees of freedom in the operation planning procedure considered in this paper.

An inappropriate plan is only met by remedy actions (turbine by-passing, energy wasting) during an operation (see Fig. 2 and related description). These remedy actions provides degrees of freedom during the operation; they help to meet a plan. But these actions make the operation less efficient. With a very accurate plan, these actions does not have to be applied. When making a plan we have to consider three operational parameters: steam for energy production (given by steam production and self-consumption), heat production and electricity production. These three parameters are in a relation. Let us assume that we want to estimate electricity production with respect to heat production which is fixed in a contract. To do it, we need amount of energy (amount of steam) used for heat and electricity production. WtE plant operates at maximum load since its primary goal (and the main revenue) is waste processing. So steam production for the next day is estimated with respect to this. In summary, there is nothing to optimize in an operation planning procedure and a simulation tool is sufficient.

A good mathematical model describing the system and related aspects is essential for simulation and optimization. According to Ochoa-Estopier et al. [9], data-based (statistical) models are preferred in circumstances where computation time is important, when phenomena or properties affecting the process are not fully known, or when the scope of the application does not require extensive deterministic models. In scientific papers, we can find researches using analytical models of WtE plants. Kropáč et al. [10] investigate hazardous waste incineration from an energy production point of view using a balance model developed in W2E software and Šomplák et al. [11] use a balance model for optimizing the basic design of a new WtE plant. According to our literature review, a data-driven model of WtE plant operation, which is presented in this paper, has not been published yet. Research with a similar focus was, however, presented by Bunsan et al. [12] where an ANN (artificial neural network) model was used to predict dioxin emission production in order to plan strategies for reducing pollution.

In our contribution, we combine data-driven models and analytical models (in some cases, black-box models does not make sense). Our literature review into black-box modelling of process units has shown that LR models (linear regression) and ANN are the most frequently used. For example, Mohanraj et al. [13] presented a review of more than one hundred applications of ANN. In comparison with LR models, ANN models can successfully identify nonlinear relationships between variables and are generally very suitable for regression-type problems. On the other hand, LR models show a lower level of complexity than ANN models, which can be advantageous in further applications. In our contribution, we use both LR and ANN.

In the following sections, we present development and application of a simulation tool for CHP production planning in the WtE plant. Section 2 introduces CHP production process in the WtE plant and deals with the modelling of crucial parts, including a stochastic nature. A wide range of modelling techniques was applied to different parts of technology and the models' accuracy is shown applying commonly used goodness of fit measures. Simulation procedure is presented in Section 3. Section 4 provides an analysis of benefits from using our proposed tool. Section 5 summarizes the most important findings.

2. CHP production modelling

2.1. The steam cycle description

First, we shall have a look at all steam streams which influence the CHP production process in a WtE. A simplified flow sheet is shown in Fig. 1 and was shortly introduced in the previous section. We shall now add some more details. Steam is produced in four boilers. Part of the steam exiting the boilers is utilized in WtE technology and part is exported to an external consumer. Afterwards, it goes into the condensing steam turbine with one uncontrolled extraction. Steam from the extraction is used for preheating feed water and for district heating. Steam from the condensing stage of the turbine is condensed in the condenser. If needed, the steam turbine can be by-passed. By-passed steam joins steam from the extraction. With models which calculate the aforementioned steam streams and turbine performance, we can built a simulation model of the entire process and use it for planning CHP production.

2.2. The modelling approach

First, let us summarize the basic principle of the modelling approach. Since there is operational data available, we prefer black-box modelling (regression). We also need to use a simple mass and heat balance for mixing or dividing amongst other things.

The goodness of fit of the black-box models is measured by MAE (mean absolute error) and MRAE (mean relative absolute error), see Eq. (1) and Eq. (2) respectively.

$$\mathrm{MAE} = \frac{\sum_{i=1}^{n} |\overline{y}_i - y_i|}{N} \tag{1}$$

$$\mathrm{MRAE} = \frac{\sum_{i=1}^{n} \frac{|\overline{y}_i - y_i|}{y_i}}{N} \tag{2}$$

Here, $\overline{y}_i$ is predicted value and y_i is observed value and N is number of observations.

This is a commonly used measure for ANN models in many papers, e.g. Ref. [14]. If the LR model provides an accuracy rate negligibly worse than ANN we prefer LR as it is easier to implement and debug the simulation tool. All ANN models are MLP (multilayer perceptron) networks with an input layer, one hidden layer and an output layer. Due to ANN models complexity we only mention very basic parameters of each model in the following text: number of neurons of each layer and an activation function of a hidden layer and an output layer. For example: MLP 10-4-1, exponential/hyperbolic tangent is a multilayer perceptron with 10 neurons in the input layer, 4 neurons in the hidden layer, 1 neuron in the output layer and the activation function of the hidden layer is exponential and of the output layer is hyperbolic tangent.

There are two ways to carry out the simulation; sequential and equation-oriented. We prefer the sequential simulation in this case as, when designed suitably, it is easier to solve. However, to make it feasible there was a trade-off between the accuracy of the models and keeping them acceptable for the sequential simulation. In that case, we may simplified those models which had a lower impact on the results, e.g. the accuracy of the model calculating the deaerator steam flow rate was less important than the accuracy of the model calculating the steam turbine output.

In the second step, we consider the aforementioned uncertainties in a WtE process. We introduce stochastic models which may handle this uncertainty. The models are stochastic in a simple way. The output of a black-box model $f(x_1,\dots,x_n)$ is slightly modified by a random number, see Eq. (3).

$$f(x_1,\dots,x_n,\xi) = f(x_1,\dots,x_n) + \xi;\ \xi \sim PD(par_1,\dots,par_n) \tag{3}$$

where $f(x_1,\dots,x_n,\xi)$ is the modified black-box model output and $\xi \sim PD(par_1,\dots,par_n)$ is a random number from a probability distribution PD with specific parameters par. The random number is generated from a probability distribution which is given by probability distribution of residuals of a model. This form of a model is used for all models except the boilers performance model (steam production), which is based on a time series.

We should note that an exploratory analysis and error detection happens before the modelling itself.

2.3. The boiler performance model

Using municipal solid waste as a fuel brings significant complications compared to common CHP systems. Besides the complex flue gas cleaning system, the LHVW (lower heating value of waste) fluctuates more or less randomly. This makes modelling boiler performance a tough task.

First, we discuss the basic regression model for steam production. Naturally, it needs two inputs: fuel flow rate and fuel heating value; in our case FRW (waste flow rate) and LHVW. But it is impossible to know LHVW *a priori*. For example, plastic waste has a high heating value while wet food residues have a low heating value. Even though mixing waste before feeding into a boiler helps to decrease LHVW fluctuation, the differences are still significant. However, if LHVW is not considered as an input, regression provides useless results. This is demonstrated in Fig. 3. We can see that for a FRW of 15 t/h we have an interval of steam production from 30 to 40 t/h, which is not acceptable for practical use.

So we have to investigate another method for modelling steam production. The solid line in Fig. 4 (denoted as Observed) shows the hourly average steam production for 36 h (the other two lines are explained below). Using time series techniques we tried to estimate the steam production trend for a sequence of hours. However, it showed that there was no predictable trend.

The conclusion is that steam production is random (mainly due to random LHVW) and therefore a good prediction is impossible. The solution is to make a purely stochastic model. A model called random walk seems to be suitable for this case. Random walk is a very simple stochastic model. It is a special case of time series models and is given by Eq. (4).

$$m_{st}^{t} = m_{st}^{t-1} + \xi^{t} \quad (4)$$

where m_{st} is steam production in boilers, t is a time parameter (hour in our case) and ξ is a random increment. So steam production in the following hour is given by steam production in an actual hour plus a random increment. The Eq. (4) can be rewritten in the form in Eq. (5).

$$m_{st}^{t} = m_{st}^{t-1} + \xi^{t} = \left[m_{st}^{t-2} + \xi^{t-1}\right] + \xi^{t} = m_{st}^{t=0} + \sum_{t=1}^{n} \xi^{t} \quad (5)$$

We only need to know the initial value of steam production in boilers $m_{st}^{t=0}$ and all future predictions are random; however, not

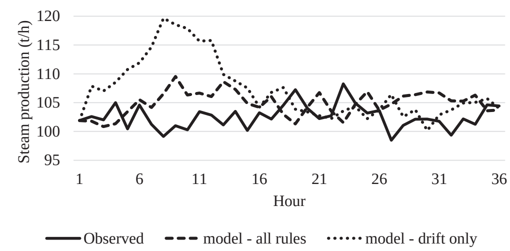

Fig. 4. Observed steam production and random walk models.

absolutely random. This model has to be further modified to correspond to nature of steam production. There are three important findings about steam production.

First, the probability distribution is not identical all the time. The data analysis showed that increments are normally distributed thus: $\xi \sim N(\mu, \sigma)$, where μ is mean and σ is standard deviation. But the mean value drifts according to the value of m_{st}^{t-1}, thus: $\mu = f(m_{st}^{t-1})$. Standard deviation σ is almost constant no matter what the μ value is. So the random increment is given by $f(m_{st}^{t-1}) + \xi^{t}$, where $\xi^{t} \sim N(\mu = 0, \sigma)$. We call the term $d^{t} = f(m_{st}^{t-1})$ a drift. For values of steam production around usual values, the mean value of increments distribution is zero. However, for values of steam production above average and below average, the mean value of increments distribution is approximately 1 and -1, respectively. In other words, steam production tends to decrease when already high. And vice versa, it tends to increase when already low. Looking at Fig. 5 the increments in steam production has mean value 1 for steam production around 100 t/h while it is −1 for steam production about 112 t/h.

However, analysing only the histogram of increments is insufficient for our needs. It does not consider the development of increments over time. Further investigation revealed that if two increments in a sequence are of the same sign (either positive or negative) the following increment is the opposite sign in the vast majority of observations. Furthermore, if an increment is large (more than 4 t/h) then the following increment is reasonably, but randomly, large with an opposite sign. So the actual increment is multiplied by a random number from a uniform distribution $\omega \sim U(a, b)$, where $0, 5 \le a, b \le 1$. This is also valid if the sum of two increments with the same sign in a sequence is large. We have to realize that we predict approximately 36 h, based on the last known value before a plan is made. It may happen that the sequence of 36 random numbers is such that, for example, there are positive values in a sequence so big that even the drifting mean does not balance them. This was observed when testing the model with the drifting mean only. However, the aforementioned rules take care of it. This is demonstrated in Fig. 4; dotted line corresponds to steam production using the model with drifting mean rule only and dashed

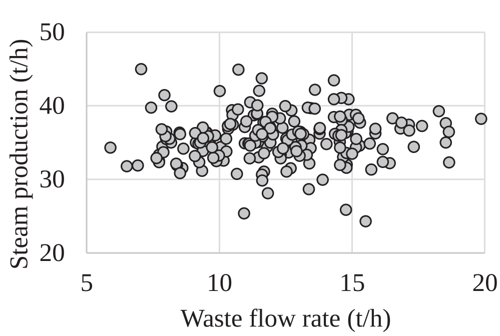

Fig. 3. Scatter plot of waste flow rate vs. steam production.

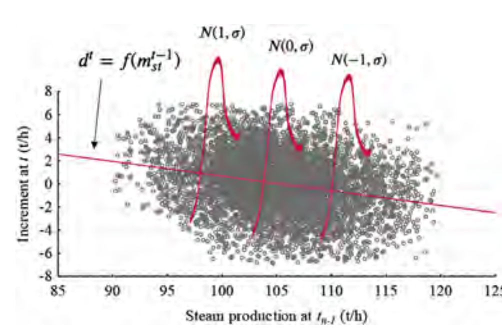

Fig. 5. Drifting probability distribution of increments in steam production.

line corresponds to steam production using the model with all mentioned rules. Looking at the dotted line, the peak between hours 6 and 11 does not follow the nature of the real steam production (solid line) while dashed line has no significant peak and the nature is very similar to the real steam consumption. The algorithm for calculating steam production in the following time step (1 h) is shown in Fig. 6.

Steam production calculated using the algorithm has the same nature as the steam production from operational data. These are not general rules and may differ from facility to facility. However, steam production in another WtE plant analysed has a very similar nature and, therefore, we believe that the principle of the presented approach is applicable for many other WtE plants.

2.4. Live steam extraction models

There are three steam extractions before steam enters the steam turbine: steam for boilers blow-off, steam to the deaerator and steam for an external consumer.

Steam for the external consumer $m_{st,\ ec}$ (see Fig. 1) is a very important parameter due to the high flow rate which fluctuates between 5 t/h to 12 t/h. This consumption is considered to be unpredictable from the operator's point of view. After a comprehensive analysis of the available data, steam consumption shows a significant dependency on the ambient temperature T_{amb}, an hour in a day H and a day in a weak D (for example, production on a Sunday night differs a lot from production on a Monday morning). Here, we decided for ANN (Eq. (6)) as if we wanted to use a LR model it would mean a model for every day and hour resulting in 168 individual models. In order to compare the ANN model accuracy and LR model accuracy, we made several of the 168 models and found that their accuracy was more or less equal to ANN's accuracy.

$$m_{st,ec} = f(H, D,\ T_{amb}) \tag{6}$$

where $f(H, D, T_{amb})$ is MLP 32-3-1 sigmoid/identity. There are 32 inputs because categorical input is split up so each category becomes a 0/1 input. For example, if we calculate the $m_{st,\ ec}$ for hour 10, only the input corresponding to hour 10 is set at the value of 1 and the inputs corresponding to the other hours are set at the value of 0. For hours, we have 24 inputs, for days we have 7 inputs and for temperature we have 1 input (it is continuous).

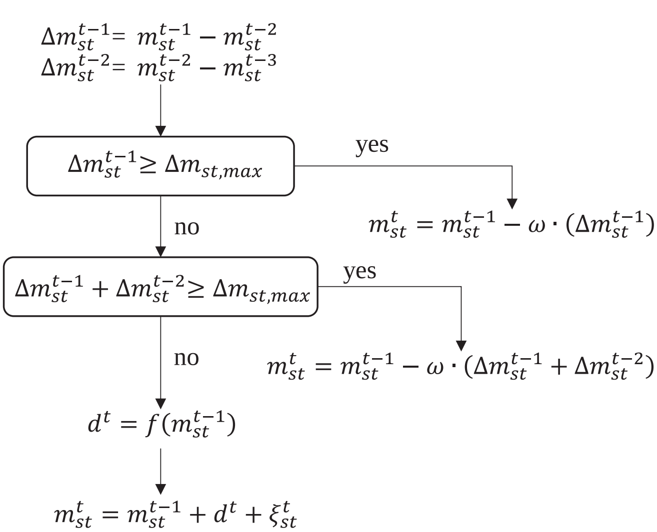

Fig. 6. The algorithm for calculating steam production.

The boilers' blow-off (see $m_{st,\ bo}$ in Fig. 1) consumes a very small amount of steam compared to the other extractions. The blow-off steam flow rate $m_{st,\ bo}$ is about 0.6 t/h on average with a standard deviation of 0.2. Due to a small average and small deviations we decided for a constant value without random fluctuation (Eq. (7)). The fluctuations would almost not affect the CHP production and it would only slow the computation down.

$$m_{st,bo} = 0.6 \tag{7}$$

The steam flow rate to a deaerator $m_{st,\ da}$ is given by an enthalpy balance of the deaerator where a close-to-boiling temperature should be kept in order to eliminate the dissolved oxygen. A black-box model was proposed in agreement with this principle and considering the trade-off between accuracy and complexity. The deaerator inlet and outlet streams are shown in Fig. 1. The inlet streams are condensed steam (from the condensing stage of the steam turbine and from the DHS heat exchanger), steam from turbine extraction, live steam extraction to deaerator and make-up (demineralized) water.

A very accurate model for $m_{st,\ da}$ calculation would lead to increased complexity in the computations because an equation-oriented approach or more complex iterative algorithm would be needed to perform the simulation. Considering the application of the model for MC simulations (thousands of simulation runs), we want to avoid this.

To make the sequential simulation feasible we decided for a model where the independent variables are steam production and steam for the external consumer. In the sequence of computations, these values are already known and their use corresponds to the principle of the deaerator. Steam production m_{st} provides information about the condensed steam flow rate. Steam for the external consumer does not return back and therefore it provides information about the make-up water flow rate. We do not consider $m_{st,\ ex,\ sc}$ because it is calculated later in the sequence. This decreases the model accuracy but a residual analysis of this model shows that the mean absolute error is 0.4 t/h, which does not have a significant impact on CHP production. The trade-off between accuracy and complexity is therefore very good. Here, we decided for the LR (Eq. (8)) model because the ANN model does not provide better accuracy.

$$\begin{aligned} m_{st,da} &= f(m_{st}, m_{st,ec}) \\ &= -2.5 + 0.1 \cdot m_{st} - 0.003 \cdot m_{st}^2 + 0.1 \cdot m_{st,ec} \end{aligned} \tag{8}$$

2.5. Turbine house model

So far we have introduced the models which are needed to calculate the steam flow rate to the turbine house. In this section, we present models for units within the turbine house where CHP production takes place. Heat and electricity production are strongly related. A key unit of the CHP production is the condensing steam turbine with one uncontrolled extraction. Besides the steam flow rate at the turbine inlet $m_{st,\ TG}$, the extraction steam flow rate $m_{st,\ ex}$ significantly influences power and consequently electricity production. In the sequential computation, we need to calculate the extraction steam flow rate first and then we can calculate electricity production. The calculation of the extraction steam flow rate is not straightforward due to the uncontrolled extraction (a variable outlet pressure and thus variable enthalpy). The approach is presented in the following section.

2.5.1. The heat production model

Extraction steam (see in Fig. 1) is used for pre-heating feed water (self-consumption) and for DHS. We denote the steam flow rate for self-consumption and for DHS $m_{st,\ ex,\ sc}$, and $m_{st,\ ex,\ DHS}$, respectively. The extraction steam flow rate is thus given by Eq. (9).

$$m_{st,ex} = m_{st,ex,sc} + m_{st,ex,DHS} \tag{9}$$

First, we introduce a model for calculating $m_{st,\ ex,\ sc}$. In the section on the model for steam to the deaerator, we mentioned that this steam also contributes to the feed water's temperature increase. As a follow-up to this model, we may expect $m_{st,\ ex,\ sc}$ to be dependent on steam production, steam extraction for the external consumer, and steam to the deaerator. We deployed the ANN model (Eq. (10)) due to its significantly better accuracy in this case.

$$m_{st,ex,sc} = f(m_{st}, m_{st,da}, m_{st,ec}) \tag{10}$$

where $f(m_{st}, m_{st,\ da}, m_{st,\ ec})$ is MLP 3-5-1 sigmoid/sigmoid. Now, we shall deal with a model for calculating $m_{st,\ ex,\ DHS}$. Heat for DHS, Q_{DHS}, is known from the heat delivery contract. We may calculate $m_{st,\ ex,\ DHS}$ from an energy balance equation (we know that the condensed steam temperature after the DHS exchanger is 70 °C), see Eq. (11).

$$m_{st,ex,sc} = \frac{Q_{DHS}}{(h_{st,ex} - h_{st,T=70^{\circ}C})} \tag{11}$$

The problem here is the specific enthalpy of the extraction steam, $h_{st,\ ex}$, which is dependent on the extraction pressure, $p_{st,\ ex}$, and temperature, $T_{st,\ ex}$. A regression analysis showed that both are dependent on $m_{st,\ TG}$ and $m_{st,\ ex}$ (Eq. (12) and Eq. (13)).

$$\begin{aligned} p_{st,ex} &= f(m_{st,TG}, m_{st,ex}) \\ &= -90.5 + 5.6 \cdot m_{st,TG} - 3 \cdot m_{st,ex} + 0.01 \cdot m_{st,TG}^2 \\ &\quad + 0.07 \cdot m_{st,ex}^2 - 0.08 \cdot m_{st,TG} \cdot m_{st,ex} \end{aligned} \tag{12}$$

$$T_{st,ex} = f(m_{st,TG}, m_{st,ex}) = 142.2 + 0.4 \cdot m_{st,TG} - 1.1 \cdot m_{st,ex} \tag{13}$$

The value of $m_{st,\ TG}$ is calculated using Eq. (14).

$$m_{st,TG} = m_{st} - m_{st,ex,sc} - m_{st,ec} - m_{st,bo} - m_{st,da} \tag{14}$$

But to calculate $m_{st,\ ex}$ we need the specific enthalpy of the extraction steam, $h_{st,\ ex}$, given by energy balance (Eq. (11)). The enthalpy is given by steam tables using pressure and temperature, which need $m_{st,\ ex}$ as the input of the calculation. Therefore, we need an iterative algorithm to avoid an equation-oriented approach. With a good initial point, the simple fixed-point algorithm finds the solution in a few iterations (see Fig. 7).

We cannot forget the turbine by-pass. In a real-life operation, the by-pass is mostly used to decrease the amount of steam to the steam turbine when the electricity production/delivery is significantly higher than the planned electricity production/delivery (otherwise there are penalties). This means that the energy in the by-passed steam is used directly for heating. The other reason why a by-pass is used is to keep the steam temperature at higher values in the DHS exchanger. This happens occasionally. The use of a by-pass to decrease electricity production/delivery is not desirable because we want to utilize all of the steam for CHP production. Therefore, we focus on the steam temperature in DHS exchanger problem only.

Using the aforementioned iterative algorithm we calculate the temperature of the steam in extraction $T_{st,\ ex}$. If the temperature is lower than required temperature T_{min}, we have to calculate the steam flow rate of by-passed steam $m_{st,\ bp}$ to achieve the required temperature. However, this flow-rate should be minimal to provide maximum steam for CHP production. This leads to a nonlinear

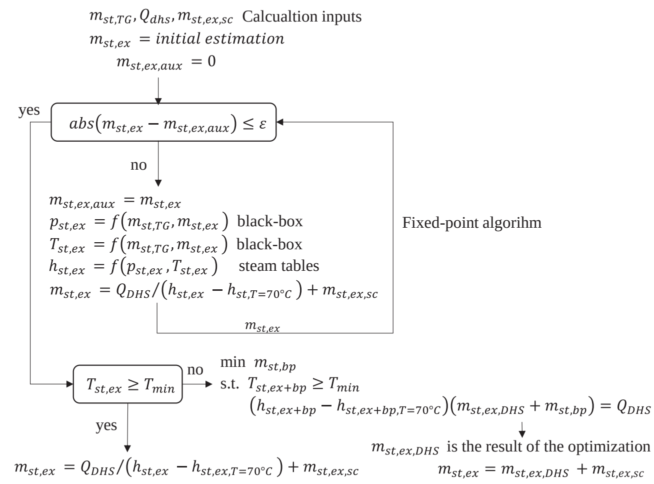

Fig. 7. The algorithm for calculating the extraction steam flow rate.

optimization problem. Luckily, it is not a large problem (only two decision variables – the extraction steam flow rate for DHS, $m_{st,\ ex,\ DHS}$, and by-passed steam flow rate $m_{st,\ bp}$) so it is not so difficult to find good initial value of the decision variables and the solution time is very short. Moreover, the by-pass use is needed only if steam production is very low and extractions before the turbine house are high at the same time. Of course, it also depends on the required temperature. For typical temperature values (115 °C in summer up to 125 °C in winter), the use of the by-pass is needed only occasionally. So in practice it has almost no effect on simulation time.

For this optimization problem we need energy balance of mixing extraction steam with by-passed steam to calculate the specific enthalpy of this mixture, $h_{st,\ ex\ +\ bp}$ (Eq. (15), where h_{st} is the specific enthalpy of steam produced in the boilers).

$$h_{st,ex+bp} = \frac{m_{st,ex} \cdot h_{st,ex} + m_{st,bp} \cdot h_{st}}{m_{st,ex} + m_{st,bp}} \tag{15}$$

Using steam tables, the temperature of the mixture, $T_{st,\ ex\ +\ bp}$ is given by the specific enthalpy $h_{st,\ ex\ +\ bp}$ and the extraction pressure $p_{st,\ ex}$ (by-passed steam pressure is reduced to the pressure of extraction steam). Note that also Eq. (12) to Eq. (14) are also used in the optimization, however Eq. (14) is modified (see Eq. (16)).

$$m_{st,TG} = m_{st} - m_{st,ex,sc} - m_{st,ec} - m_{st,bo} - m_{st,da} - m_{st,bp} \tag{16}$$

The algorithm is summarized in Fig. 7.

2.5.2. The electricity production model

In this section we introduce a model for calculating electricity production and export.

For electricity production $W_{TG,\ exp}$ (not export), steam flow rate to the turbine $m_{st,\ TG}$ and extraction steam flow rate $m_{st,\ ex}$ are the most important inputs. Respecting the operator's opinion, we also included ambient temperature T_{amb} which has impact on the condenser's performance and, therefore, on the outlet pressure at turbine condensing stage. The ANN model provides significantly better results (MAE is 0.1 MW lower) than LR so we apply the ANN model (Eq. (17)).

$$W_{TG} = f(m_{st}, m_{st,\ ec}, T_{amb}) \tag{17}$$

where $f(m_{st}, m_{st,\ ec}, T_{amb})$ is MLP 3-4-1 hyperbolic tangents/identity.

Considering electricity export $W_{TG,\ exp}$, we have to think about which variables may influence electricity self-consumption. Some of the electricity's consumption is related to steam flow rates (mainly the pumps' consumption). In addition to this, there are a number of boilers in operation (there are many electricity consumers related to boilers, such as air fans, feeders, grate movers, etc.). We also consider the time in the day since appliances used by employees and electricity for lightning differs throughout the day. We deployed the ANN model (Eq. (18)) to predict electricity export for the same reason as in the case of the $m_{st,\ ec}$ model (a higher number of categorical independent variables).

$$W_{TG,exp} = f(W_{TG},, NB, H) \tag{18}$$

where $f(W_{TG}, NB, H)$ is MLP 28-4-1 sigmoid/identity.

We should note that we also tested the performance of a LR model. We tested several of the 72 models for each combination of hour and number of boilers (24 h and number of boilers in operation 2, 3, 4) and found that their accuracy was more or less equal to the accuracy of the ANN model.

To summarize this section on model development, we made sub-models from the different parts of the technology to predict electricity export. Some of the sub-models are LR and some of them ANN. We also need to use mass and energy balance equations. In some models there are categorical independent variables, which make the LR model development and implementation time-consuming. Therefore, we decided on ANN for these models. However, a quick test showed that if LR models are made for every combination of categorical variables, then LR provides as good accuracy as ANN. The models are summarized in Table 1. The sequential simulation process is shown in Fig. 8.

3. Stochastic simulation

Having the stochastic model of the WtE plant, we can introduce the concept of MC simulation.

The simulation procedure is described in Fig. 9. There are usually thousands of simulation runs; each run is with different randomly generated numbers. The result is a sequence of numbers which have to be statistically processed.

The model of the CHP production was implemented in MS Excel. The optimization problem described within the section on heat production model can be handled by Solver add-in. The CPU time to perform MC simulation with 1000 simulation runs and to process the results was 15 s on an Intel i5 (2.8 GHz).

The simulation results are processed with respect to the nature of heat and electricity delivery contracts and possibilities of operation control.

The results of MC simulation give us information about probability distribution of electricity delivery. As described later in section Application and analysis of benefits, the operator prefers underestimating of electricity delivery because decreasing of delivery in subsequent operation is more convenient than increasing. Energy excess than usually occurs. With respect to this and using the probability distribution, we are able to quantify the probability of electricity delivery being equal or higher than a given value. Clearly, we are also able to find electricity delivery which is for given probability.

We assume that the lowest simulated electricity delivery from MC simulation can be achieved in a subsequent operation with a confidence of 100% (every other value is higher and therefore only decreasing in subsequent operation is possible); the highest simulated electricity delivery with almost 0% (1/number of simulation runs). The operator can choose a risk of not meeting the plan.

Therefore, we introduce a parameter called PC (plan confidence) to provide the operator with the ability to take current circumstances into consideration. This parameter is expressed as a percentage. The electricity delivery value corresponds to quantile $q_{1\ -\ PA/100}$.

When the plant performance is stable the median (or mean in the case of normal distribution) value is a good choice which corresponds to PC = 50%. But we should consider other options for different situations.

Imagining the following situation, there is a problem with steam production in one of the boilers. Its performance is unstable and it is difficult to estimate its behaviour for next day. The operator wants to be on the safe side and chooses (according to how significant the instability is) PC higher than 50%.

On the other hand, it may happen that the boiler is expected to increase its performance rapidly next day and the operator chooses PC lower than 50%.

Fig. 10 shows three examples:

- Case 1: PC = 50%; we expect normal steam production,
- Case 2: PC = 75%; we expect troubles in steam production or we want to be certainly on the safe side,
- Case 3: PC = 40%; we expect unusual or rapid increase in steam production.

4. Application and analysis of benefits

The simulation tool was tested against real-life operational data and operator's planning strategy. To be able to evaluate the accuracy of predictions and benefits of application, we have to expand the operational data with extra information.

The operator plans heat and electricity delivery for next day. As mentioned, the current planning strategy is driven by heat and electricity delivery contracts – high penalty, resp. low penalty, when electricity delivery plan, resp. heat delivery plan, is not met (more precisely, if it is not within a feasible range with respect to planned value). Recalling Fig. 2, in real-life operation an energy shortage is the worst situation (expensive energy from natural gas is then needed) and the operator wants to avoid it at all costs. The operator estimates electricity delivery from previous operational data – for given heat delivery (Q_{DHS}) estimates electricity delivery using a scatter plot in Fig. 11. Clearly, the estimation of electricity delivery is burden with conservative planning. The value of 3 MW corresponds to a wide range of heat delivery (from 24 to 34 MW). Looking at the scatter plot from a different point of view, we have a wide range of electricity delivery (from 3 to 5 MW) for heat delivery of 25 MW. The planning is very rough and there is a potential for improvement by using the presented model.

To be on the safe side, the operator often underestimates electricity delivery (obviously the vast majority of points is at 3 MW no matter how high heat delivery is). This ensures that there will be

Table 1
A summary of sub-systems models.

Sub-model	Model type	Function	MAE	MRAE
m_{st}	RW	see Fig. 6	–	–
$m_{st,\ bo}$	Const.	–	–	–
$m_{st,\ da}$	LR	$F(m_{st}, m_{st,\ ec})$	0.4	0.09
$m_{st,\ ec}$	ANN	$F(H,D, T_{amb})$	0.86	0.12
$m_{st,\ ex}$	–	see Fig. 7	–	–
$p_{st,\ ex}$	LR	$F(m_{st,\ TG}, m_{st,\ ex})$	1.18	0.01
$T_{st,\ ex}$	LR	$F(m_{st,\ TG}, m_{st,\ ex})$	1.6	0.01
$h_{st,\ ex}$	–	steam tables	–	–
$m_{st,\ ex,\ DHS}$	–	energy balance	–	–
$m_{st,\ ex,\ sc}$	ANN	$F(m_{st}, m_{st,\ ec}, m_{st,\ da})$	0.35	0.16
W_{TG}	ANN	$F(m_{st}, m_{st,\ ec}, T_{amb})$	0.03	0.01
$W_{TG,\ exp}$	ANN	$F(W_{TG}, NB, H)$	0.07	0.03

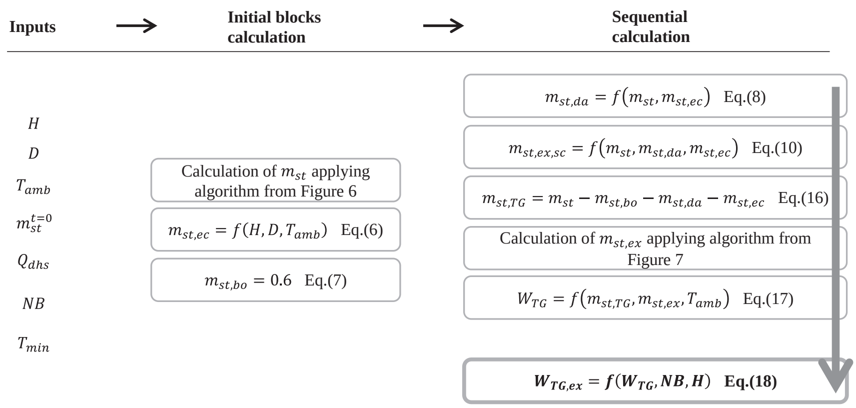

Fig. 8. Sequential calculation of the flow sheet.

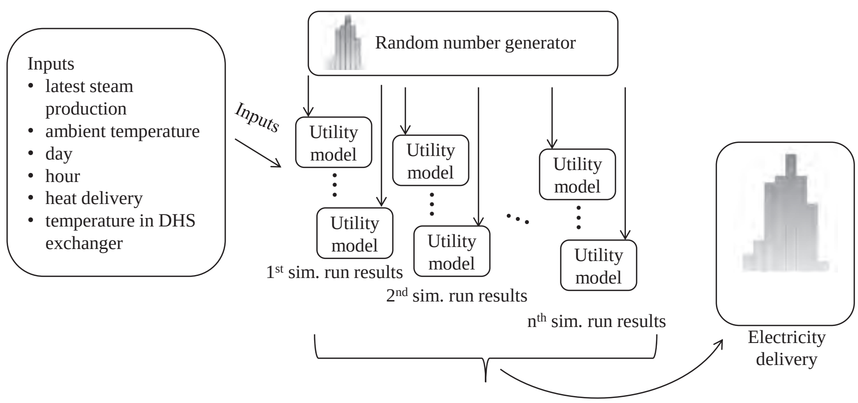

Fig. 9. Scheme of the simulation procedure.

enough energy and no penalties will occur. On the other hand this always leads to the situation that there is energy excess for electricity production in real-life operation. The operator then uses turbine by-pass ($m_{st,\ bp}$ – by-passed steam flow rate, see Fig. 1) to decrease electricity production/delivery. Consequently, there is increased heat production/delivery which means penalties. However it is accepted because it is more profitable than energy wasting.

The purpose of the simulation tool is to provide more accurate estimation of electricity delivery in order to minimize by-pass utilization and further to provide information about probability of meeting such estimation. To test the simulation tool accuracy we therefore need the electricity delivery which corresponds to a zero by-passed steam flow rate for each data point (if not needed to increase the temperature in extraction). We denote it as $W^0_{TG,\ exp}$. Since the by-pass is used most of the time, we do not find it in operational data and so we have to calculate this value using the model of the turbine. The steam flow rate to the turbine house is measured and thus available from operational data. As was proven by the goodness of fit analysis (see Table 1), the model of the turbine is very accurate and we assume that the difference between real operation and calculated operation would not be significant. Moreover, this is the only approach how to test the model unless operational data without by-passed steam are provided.

The objective of the test is to compare the simulation based plan with the current method of planning regarding the overall

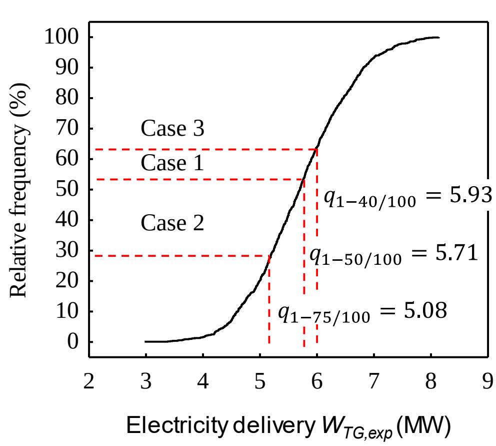

Fig. 10. Examples of plan confidence.

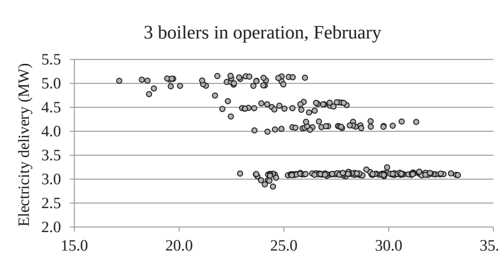

Fig. 11. Current planning strategy in the waste to energy plant.

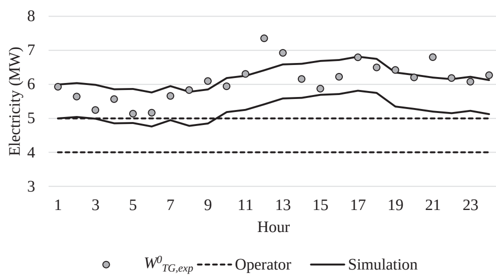

Fig. 12. Successful rate of electricity delivery plan.

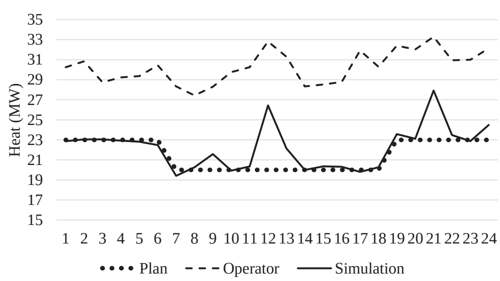

Fig. 13. Successful rate of keeping planned heat delivery.

efficiency of the combined cycle and financial effect. We also tested the success rate of the simulation based planning. PC was set at 50% as there were no reasons to expect unusual operation.

Figs. 12 and 13 show a comparison of a selected day 03/11/2013, which is a typical example of a cold winter day. The operators expected a stable electricity output of 4.5 MW during the whole day (this corresponds to the feasible region bounded by dashed lines in Fig. 12) and a heat dispatch of 23 MW, reps. 19.6, MW between 7am and 6pm (dotted line in Fig. 13). The operator's plan is conservative and underestimates electricity delivery in order to avoid penalties. This results in higher heat delivery than planned. The steam turbine was by-passed to keep electricity delivery lower and the energy in the by-passed steam was used for heating.

As far as the simulation-based plan is concerned (the feasible region bounded by solid lines in Fig. 12), possible electricity, $W^0_{TG,\ exp}$, is mostly within the feasible deviation. It was successful in 19 cases from 24 (the dots within the region bounded by solid lines), which corresponds to 79%. This results in keeping heat delivery according to the plan as the deviation from the plan was only 4% (daily sums). The improvement in keeping heat delivery according to the plan is clear from Fig. 13. The dashed line shows much higher heat delivery compared to the plan (dotted line) due to underestimated electricity delivery by the operator while the solid line shows only few deviations from the plan due to better electricity delivery plan by the simulation tool.

To confirm the benefits of the simulation-based planning over a long-term period, we chose 10 days from the first half of 2014 (the most recent available data not used for modelling) and performed the comparison in terms of Figs. 12 and 13. Fig. 14a) shows the average percentage of possible electricity within a feasible deviation. The low rate for the operator is given by conservative planning. Then Fig. 14b) shows the expected result: higher deviation from the plan due to by-passing the steam turbine.

We also compared the effect on efficiency. We apply net thermal efficiency given by Eq. (19) [15].

$$\mu_{th} = \frac{W_{TG,exp}}{Q_{st,TG+bp} - Q_{DHS}} \cdot 100\ (\%) \tag{19}$$

Since we do not know the energy content of the waste, we use energy content in the steam before the turbine by-pass $Q_{st,\ TG+bp}$. The comparison is shown in Fig. 14c). Following the previous results, simulation-based planning provides better net thermal efficiency.

If the by-passed steam was used for CHP production, it would bring about 130 EUR per day extra on average. This value is obtained from the potential of by-passed steam utilization for CHP production. If the amount of steam corresponding to the amount of by-passed steam was utilized in the first stage of the turbine (before extraction) and then extracted for heat production we would get increase in electricity by the first stage but, at the same time, lower heat production compared to the case where by-passed steam is

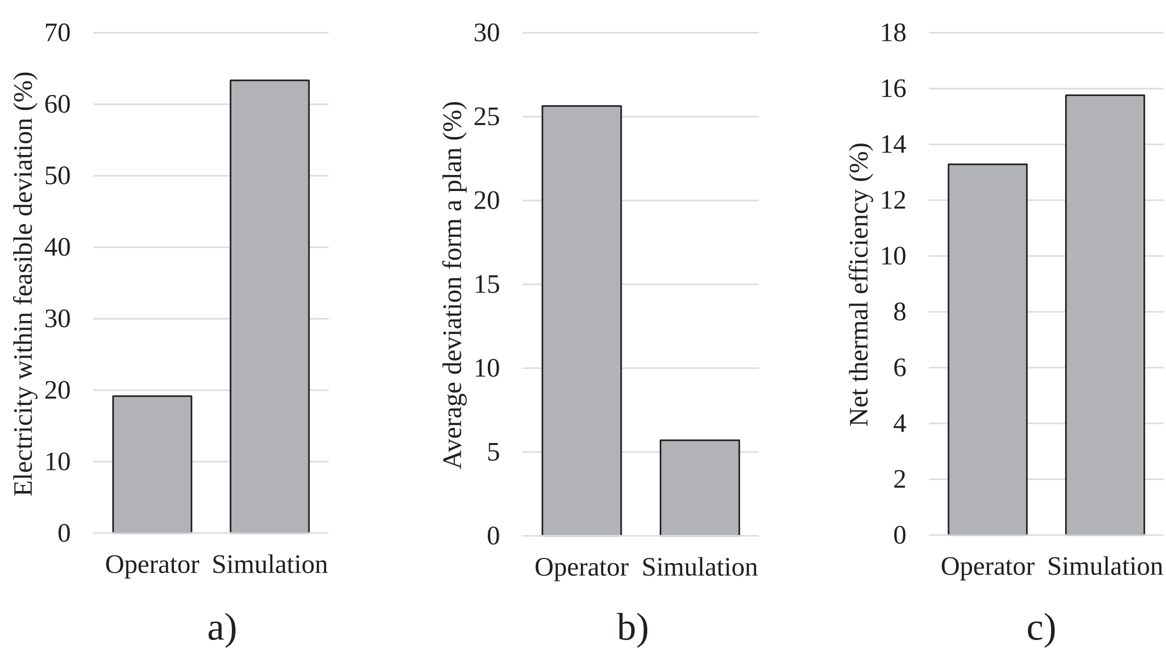

Fig. 14. Benefits of simulation-based planning over a long-term period.

used for heating directly. Therefore extraction steam flow rate would have to be increased a little to achieve the same heat production. This would mean slight decrease of flow rate to the second (condensing) stage of the turbine and therefore slight electricity production decrease by this stage. If this amount of electricity is subtracted from the electricity produced by the first stage we get extra amount of electricity due to CHP production. Multiplying by electricity price we get the increase in revenue. Penalties are not included since electricity penalty is always avoided and heat penalty is negligible. Furthermore, this simulation tool could be used to analyse in what range electricity export fluctuates with a certain probability (for example, with a probability of 90%) and so the operator can be almost sure to be within this range. An analysis of operational data in this sense could provide the operator with crucial information for negotiating the tolerance interval in a contract.

5. Conclusion

This research presents how a stochastic simulation based tool improves CHP production planning in WtE plants on a short-term basis. It is a challenging task due to some uncertainties. One typical uncertainty is presented in the boilers performance, which is caused by the heterogonous composition of waste, although there may be other plant-specific uncertainties. The uncertainties can be handled by stochastic models and these models further used for stochastic simulation or optimization tailored to the specific circumstances of CHP production in a WtE plant.

This approach was applied to an existing WtE plant. We presented a stochastic data-driven model of a CHP production to predict electricity delivery with a given heat delivery for the next day. Data analysis has shown that the boilers' performance (steam production) is very uncertain and a regression-type model is not suitable. Therefore, we decided for the random walk model with some additional rules to make the results' nature similar to the real boilers' performance. Other models used were either ANN or LR with a stochastic part (i.e. a random number from a distribution of model residuals).

This model was further used for Monte-Carlo simulation. The results were processed with respect to the specific circumstances of CHP production in the WtE plant. The testing of the stochastic simulation-based planning against the current planning strategy showed an improvement on the plan's accuracy as well as in net thermal efficiency and potential revenue.

We tested the simulation tool for10 days using operational data. The estimation of electricity delivery by the simulation tool was successful in nearly 65% of observations. On the other hand the current planning strategy succeeded only in 20% of observations. Better electricity delivery estimations leaded to better results in heat delivery; the deviation from the plan was only 5% in average. In case of current planning strategy the deviation was about 25%. Net thermal efficiency was also significantly improved; current planning strategy provides 13.2% and the simulation tool based planning provides 16%. The improved planning has a positive effect on revenue as well. The average increase in daily revenue is 130 EUR. It could be 47,450 EUR annually.

Future work will consist in investigating conditions of planning in other WtE plants in order to develop a tool applicable for CHP planning under various conditions. Further, the tool will be modified into a tool for analysis of operational data in order to provide the operator with crucial information for negotiation about conditions in a contract regarding feasible range (not penalized). Applying stochastic approach it is possible to estimate a feasible range in which electricity delivery fluctuates with a given, very high, probability.

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VIEWS & COMMENTS

Greenhouse gas emissions from thermal treatment of non-recyclable municipal waste

Tomáš Ferdan[1], Martin Pavlas (✉)[2], Vlastimír Nevrlý[1], Radovan Šomplák[2], Petr Stehlík[1]

1 Institute of Process Engineering, Faculty of Mechanical Engineering, Brno University of Technology, 616 69 Brno, Czech Republic
2 Sustainable Process Integration Laboratory – SPIL, NETME Centre, Faculty of Mechanical Engineering, Brno University of Technology, 616 69 Brno, Czech Republic

Abstract This paper analyses factors affecting the production of greenhouse gases from the treatment of residual municipal waste. The analysis is conducted so that the environmentally-friendly decision-making criteria may be later implemented into an optimisation task, which allocates waste treatment capacities. A simplified method of life cycle assessment is applied to describe environmental impact of the allocation. Global warming potential (GWP) is employed as a unit to quantify greenhouse gases (GHG) emissions. The objective is to identify the environmental burdens and credits measured by GWP for the three fundamental methods for treatment of residual waste unsuitable for material recovery. The three methods are waste-to-energy (WTE), landfilling and mechanical-biological treatment (MBT) with subsequent utilization of refuse-derived fuel. The composition of the waste itself and content of fossil-derived carbon and biogenic carbon are important parameters to identify amounts of GHG. In case of WTE, subsequent use of the energy, e.g., in district heating systems in case of heat, is another important parameter to be considered. GWP function dependant on WTE capacity is introduced. The conclusion of this paper provides an assessment of the potential benefits of the results in optimisation tasks for the planning of overall strategy in waste management.

Keywords waste management, greenhouse gases, global warming potential, allocation planning, waste-to-energy

1 Introduction

The current emphasis in waste management (WM) is on revamping of the WM infrastructure. The whole system is designed in compliance with the waste treatment hierarchy. In addition to the economic aspects, environmental criteria also play a crucial role. This paper deals with the environmental issues in the form of greenhouse gases (GHG) emissions. Particular attention in this paper is paid to the residual (RES) municipal solid waste (MSW) that is not suitable for subsequent material recovery, and technologies for its treatment. This type of waste is produced by municipal residents and public institutions and since it has a low potential for material recovery, it is preferably used for energy recovery (waste-to-energy, WTE). Other methods for elimination of RES are a landfilling and mechanical-biological treatment (MBT). Analysis of the waste treatment methods is conducted so that the results may be integrated into a complex optimisation work, generally designated as the sustainable supply chain management (SCM) [1]. In case of application on the waste management, it is called "reverse logistics problem" (for current research challenges in this field, see [2]), where the developed network usually has a convergent structure and waste produced in many locations is concentrated into nodes for further treatment. The aim of the strategic decisions is to evaluate candidate locations, their optimum allocation, sizing of the processing capacities and design of the relevant infrastructure. This type of optimisation task may be called the "allocation of capacities". In case of SCM, the final decision should be based not only on economic factors but also on sustainability pillars which include environmental and social aspects.

1.1 Allocation planning within reverse logistics problems

An extensive research was done by Barbosa-Póvoa et al. [1] discusses ways of addressing the issue of allocation planning in SCM. The research summarizes more than 200 papers published in the recent years which were categorized by various criteria, such as level of the

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E-mail: martin.pavlas@vutbr.cz

decision-making process, sustainability pillars that were included, methods of the research used, and so on. First, a detailed analysis of papers was made; these papers may be classified as reverse logistic problems made to facilitate strategic decision making in the area of waste management. Categorization done by Barbosa-Póvoa et al. [1] stipulates that every SCM in waste management (WM) intrinsically deals with both economic and environmental aspects. This notion complies with the idea that waste treatment has become a worldwide environmental problem. However, regarding the modeling task, this may be a mono-objective optimisation where only the economic elements enter the objective function. Therefore, a much more thorough analysis of ways to implement the particular economic and environmental pillars is necessary.

Two rather short research studies in WM [2] and [3] have been published lately. Ghiani et al. [3] note, among others, that economy of scale is commonly applied in reverse logistics problems. As an example, let's refer to [4] where the authors define a so-called gate-fee function, which is a dependence of net processing costs (income from energy delivery and other product sale are included) on the capacity of the WTE units (for example see Fig. 1 (a)). This curve reflects changes in the economy for various WTE capacities and it also represents a specific input for each of candidate locations. Incomes and costs related to WTE operation were comprehensively analyzed in [5] or [6], for example. The curve also addresses drop in income from heat supply to district heating systems. This is demonstrated in Fig. 1(b) for particular district heating system in the Czech Republic. Whereas annual heat delivery from WTE increases with rising capacity compare areas under supply curves of capacity 100 and 200 $kt \cdot year^{-1}$ in Fig. 1(b), specific heat delivery per ton of waste is decreased due to missing demand in summer months. The importance of heat delivery through the year on WTE plant performance was studied in details in [7]. As for the WTE units, the main parameters affecting the gate-fee are first, amount and composition of the waste and second, the potential to export the produced energy in the form of power and heat. These parameters depend on the allocation of the plant and local conditions [8]. A similar profile may be designed for every candidate location. The pre-processing phase, which is done before the calculation of the allocation task itself, is very important. For this article, a locality with heat demand from Fig. 1(b) is used as a reference one.

Considering environmental pillars of SCM, the question remains whether or not the CO_2 emissions would behave analogically, that is nonlinearly. The question then is to what detail and how the nonlinear dependence of environmental impact on the capacity is implemented today. Garcia and You [9] comment on an interesting paper which brings together economic and environmental factors. Nonlinear relation between the capacity of a unit for production of biofuels from biomass and treatment costs is tackled using a linear approximation. However, in case of emissions, only constant unit production of GHG for a random capacity is presumed. In their paper, Neto et al. [10] addressed two key questions for a multi-objective problem: How to spot the preferred solution(s) when balancing environmental and business concerns? And how to improve our understanding of the trade-offs between these two dimensions? The ideal solution to these problems is to transform all criteria into one identical unit. In case of GHG emissions, this solution is available thanks to the emission allowances market and this paper will further explain the mechanism of this solution. Transformation of the economic and environmental factors into a single unit was done by e.g., Harijani [11] who compared these two factors using environmental costs that were defined in [12]. Whereas aforementioned paper focused on global CO_2, paper [13] introduces an idea how environmental impacts could be addressed when siting waste treatment facilities using reverse logistic models.

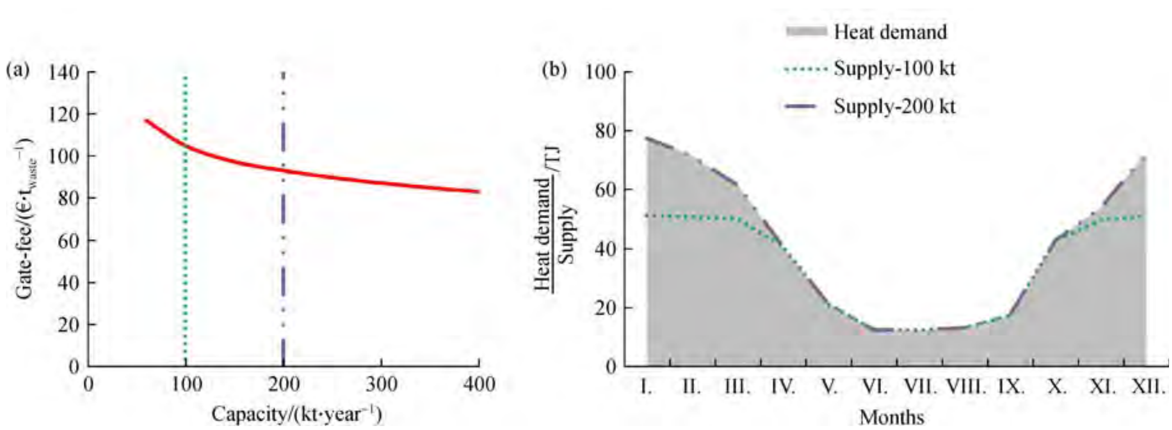

Fig. 1 (a) Example of a "Gate-fee curve" as an important input for state-of-the art reverse logistics problem in WM (modified after [4]) and (b) heat demand/supply for particular location and WTE capacities

The research part of the paper is based on [1] and is further elaborated on using other papers published in 2017. A study by Cristóbal et al. [14] is also worth discussing. This paper addresses the situation in which a decision-maker has to design a food waste prevention program, with limited financial resources, in order to achieve the highest total environmental impact prevention along the whole food life cycle. A methodology using life cycle assessment (LCA) and mathematical programing is proposed, and its potential is shown in a case study. A paper by Asefi and Lim [15] is also worth mentioning. This study aims to satisfy the sustainability requirements for designing an integrated solid WM system by taking economic, environmental and social factors into account. The multi-objective function was transformed using secondary limitations (that is the ε-constraint). The proposed model according to [16] addresses the economic, environmental, and social perspectives for municipal solid waste management. Their model combines economic, environmental and social viewpoints simultaneously by minimizing the total cost, the GHG emission, and the resulting visual pollution.

All of the papers discussed above work with a linear relationship between the waste amount and emission production. Sometimes, this relationship is called the emission factor. The previosuly analyzed papers work with a constant emission production per t of treated waste here. The nonlinear relationship between capacity and emission production is not taken into consideration. Barbosa-Póvoa et al. [1] note that carbon footprint and its derivatives (GHG, global warming potential (GWP), CO_2) represent the most common environmental criteria used in SCM applications. A similar conclusion may also be drawn from an extensive study on footprints, presented in [17]. This approach complies with the worldwide effort to reduce amounts of these substances in the atmosphere. GWP is standardized using carbon dioxide emissions and is defined as a unit in kilograms of carbon dioxide equivalents (GWP of 1 kg of CO_2 equals 1 kg of CO_{2eq}) [18]. GWP defines a relative amount of heat trapped by emissions of 1 ton of a particular gas over a given period of time in contrast to heat trapped by 1 ton of CO_2. Other GHGs are calculated as multiplications of the basic unit.

GWP is one of the impact categories in the recognized and standardized LCA method. This paper will evaluate how adequate it is to use GWP in SCM for the conclusions of the LCA studies which were made on WM without considering SCM.

1.2 LCA as supportive tool to designing of WM

LCA is nowadays a common tool developed for assessment of environmental factors of a particular product or process in all stages of its life [19]. Each LCA study must comply with methods defined in ISO 14040:2006 [20]. Application of LCA in WM is very popular and also common. Many papers and studies have been published recently which either apply or assess the application of LCA in WM. Cleary et al. [21] writes about a comparative analysis of 20 LCA studies regarding WM from 2002 to 2008. The studies are evaluated based on several criteria: area and scope of the study, objective of the study, functional unit, inclusion of transport (studies usually did not include the waste transport due to its insignificance for the waste treatment plant as a whole) and life cycle impact assessment methods (LCIA), environmental categories (GWP being the most common one). Laurent et al. in [22] and [23] presents a similar, yet more extensive list of studies on LCA in WM with identical conclusions. Regarding the application of LCA for evaluation of WTE, Astrup et al. [24] made a comparison of recently published case studies. Most of the studies on the issue of LCA in WM do not present an optimisation task but they rather compare final environmental impacts for one particular capacity and location, or they present a limited number of static scenarios which are later compared. LCA studies assess the impact of waste composition or compare various methods of MSW or RES treatment. The functional unit is mostly defined as one ton of processed waste. Individual studies then work with waste treatment plant's parameters related to a ton of waste (production of power and heat, emissions of pollutants, etc.) and fail to include the dependence of these parameters on the location of the waste treatment plant or its capacity (see Fig. 1). The previously discussed review studies lead to a conclusion that LCA in MSW is performed in order to: (1) Compare one type of waste treatment for various compositions of input MSW. (2) Compare various types of waste treatment with identical MSW composition. (3) Compare various types of waste treatment with one waste component (paper, plastic, wood, bio, etc.). (4) Compare various categories of environmental impacts.

Lausselet et al. [25] and Finnveden et al. [26] present LCA analyses for one type of waste treatment with varying waste compositions. Conclusions of these studies make it clear that the waste composition is one of the key parameters affecting the amount of produced GHG. Other studies analyzing the impact of waste composition on emissions include [27] where LCA method is used to compare results of the predicted environmental impact of WTE plant that was being newly designed with an actual impact of the plant later calculated thanks to real data from the constructed plant. Schwarzböck et al. [28] verifies the impact of the waste composition on GHG production and evaluates the amount of GHG emissions from Austrian incinerators using balance method. Other uses of LCA in WM include a comparison of results for various treatments of waste that has a given unified composition. Arafat et al. address this topic in his study [29]; he disintegrates the waste onto particular components (paper, plastic, glass, etc.) and defines LCA for the waste treatment in various treatment facilities. Other studies on LCA for treatment of unified mixed municipal waste (RES) include [30] and

[31]. Results of their studies validate the use of three technologies for the treatment of mixed municipal waste: landfilling, WTE and MBT. Analyses not directly concerning MSW arrive at similar results. Some of these analyses are [32] where biowaste treatment is focused on, and [33], where is research was run on the topic of hospital waste treatment using co-incineration with MSW. Conclusions of these analyses highlight importance of the energy export (heat or power) and its impact on LCA results. Energy export is represented in this task as a local disposition of the district heating (DH) network and thus also as the heat supply potential.

There are various categories of environmental burdens in LCA. Most discussed categories include: GWP, human toxicity potential (HTP), acidification potential (AP), ozone depletion potential (ODP), photo-oxidant compound production (POCP), and others [20]. This paper works with GWP that is the amount of released GHG, as the relevant category. The previously mentioned studies [33] and Jensen et al. [32] agree that GWP is the most significant environmental category. Other analyses on a comparison of environmental categories are, for example [34], and [35]. Results of these analyses accentuate that GWP is the most significant environmental indicator for units processing MSW. These statements are further confirmed by Jia et al. [36] who compares LCA for calculation of GWP for MSW treatment with a method of Carbon Emission Pinch Analysis. Genovese et al. [37] further define environmental categories for general supply chains. Both studies accentuate GWP as the most important environmental category. As for example Mumford et al. [38] and De Guido et al. [39] prove the reducing of CO_2 emissions is in forefront of interest even in the energy sector. The substitution of fossil fuels with RES is then an interesting opportunity.

Research proves that GWP category is suitable for the description of the environmental impact of RES treatment (that is waste suitable for thermal treatment) using LCA. The composition of the waste and type of energy export are the key parameters affecting the whole production of GHG. These parameters depend on the allocation of the treatment plant, which is the output of the SCM; integration of these aspects in SCM is a research challenge that has not been addressed so far. As much as these aspects form nonlinear dependence for the economic pillar (Fig. 1), an analogical nonlinear dependence may be anticipated for the environmental pillar. Following facts apply for current SCM: (1) SCM implements simplified methods of environmental burden assessment (GWP, for example). Use of GWP is fully justified, which has been declared by comprehensive LCA studies. (2) Benefits of LCA include exact delimitation of the system that is being assessed. In case of SCM application, delimitation of the system has not been fully understood and results are hard to interpret or even compare. (3) Application of SCM, based on the authors' experience and studies mentioned in this paper, disregards changing environmental burdens and has not been considered nonlinear dependence, which is a serious simplification. Disregard of the nonlinear nature should not be a default setting and the simplification must always be validated first.

On the other hand, various complex LCA studies in WM were published which covered a large spectrum of indicators and RES processing technologies. These studies show: (1) GWP is a major indicator for assessment of WTE technologies. (2) The analysis is conducted for one given location and capacity, which means that scenarios with varying capacity are later compared. (3) There is also LCAO (Life Cycle Assessment Optimisation) where capacity is optimised for a given location using the multi-objective optimisation. For example, Gerber et al. [40] present a systematic methodology for sustainable process systems design, combining the principles of industrial ecology, process design and process integration, LCA and multi-objective optimisation. The methodology can be used to design eco-industrial parks or urban systems. However, the methodology provides no concept-based solution to large-scale regions where there is an interaction between the regions and transport, and waste availability must be addressed.

1.3 Scientific contribution of the paper

Study of the previosuly discussed papers showed a research gap in absence of a method for complex optimisation that would combine economic and environmental pillars dependent on processing capacity. Current models work with a linear relationship between the amount of waste and unit's production of GHG emissions. The nonlinear relationship between capacity and emission production is not taken into consideration.

The aim of this paper is to summarize recommendations and requirements for implementation of GWP into reverse logistics problem that optimises a network of RES treatment plants. A research study of various publications was done in section 2.1, 2.2 and 2.3 and the aim was to create a comprehensive set of data for three scenarios of RES treatment methods. Description of environmental impact assessment is done using the so-called GWP parameter. Calculation using the LCA standards will be conducted for model case studies in order to assess all key factors affecting the final GWP. Model examples are applied on the Czech Republic. In addition to direct environmental impacts (that is, the burdens), the optimisation task will include secondary effects of substituting the primary raw materials and fossil fuels (that is, the credits). The paper gives a detailed analysis of input data, a brief characteristic of the waste treatment plants, such as direct energy recovery, landfilling with/without collection and use of landfill gases (since landfilling is still common in many countries), mechanical-biological treatment of RES accompanied by production of refuse-derived fuels with their subsequent use, and description of the relevant methods. There has been no detailed analysis of this kind so far and it may be a valuable source of information for the subsequent development of reverse logistics tasks.

Local factors have to be taken into account as well as the impact of the processing capacity on GWP of the particular treatment plants, units and operations which are shaped by concrete conditions at relevant locations (these are parameters of current heat and power sources and potential of integration of the new treatment plant). Definition of the parameter and its dependence on plant's capacity is given further in the paper.

The conclusion of the paper will summarize the results and present recommendations and methods for implementation of nonlinear dependence into optimisation tools.

2 Materials and methods

Each LCA study has to follow methods prescribed in ISO 14040:2006 [20]. Based on this standard, LCA is divided into four basic phases: definition of the goal and scope of the LCA, the life cycle inventory analysis phase, the life cycle impact assessment (LCIA) phase, and the life cycle interpretation phase. The first phase of defining the goal and scope of the LCA says for what purpose the results of LCA will be used, what the scope of the LCA is and which functional unit is to be used as a reference unit. Results of LCA then help evaluate the environmental impact of particular MSW treatment methods. A simplified version of the LCA method is employed in this paper for particular MSW treatment types: only inputs and outputs of the waste treatment process are considered. Since MSW may be treated using the three treatment methods (WTE, landfill, MBT), as discussed above, prior production or use of the products that comprise the waste has no impact on a comparison of the ecological footprint of the particular processes. One ton of waste is the functional unit. The second phase is the so-called inventory analysis phase, which is a neutral collection of inputs and outputs of the assessed system. Here, the inventory is the inputs and outputs for three basic waste treatment methods presented above. The inventory analysis is presented in detail in Electronic Supplementary Material (ESM).

System boundaries have been selected according to the aim of the paper, which is data and locality-dependent functions provision prior to complex optimisation by the reverse logistic model (see section 1.1). The following processes are to be considered: (1) The specific waste treatment process itself (see below), including the further treatment of intermediates to be disposed of including all linked material and energy, flows related to the need for materials and supplies. Intermediates, which are further utilized in technologies allocated with reverse logistic problems, have no contribution to burdens and credits. (2) Additional benefits, e.g., energy, secondary metals or slag, results from the disposal processes. Corresponding amounts of energy or products/materials do not need to be produced in a conventional way from primary processes. The environmental impacts that would be associated with the conventional manufacturing/ production each substituted primary raw material, are "saved" or "avoided".

The provision and maintenance of infrastructure (construction, service and repair of buildings, machine, industrial facilities, transport means and traffic routes) are not considered, as they are not expected to have a decisive influence.

Authors developed a computational model in MS Excel for all three methods, and basic input and output parameters were identified. These models have been already used in calculations conducted by NERUDA [4]. Definition of LCA for a WTE plant was later expanded with the monoblock, a unit designed for thermal treatment of solid alternative fuels from waste (RDF). RDF or the refuse-derived fuel is a separated fraction from MBT unit with a significant calorific value that has been sorted out of input RES, see the section 2.3. The third phase of LCA is focused on assessment of the potential environmental impact. First, elements in the inventory are assigned to relevant environmental areas based on the selected method. Assessment methods are then divided into the so-called categories which describe one environmental impact. The study described in this paper used a simplified LCA and a category of GWP and kg of CO_{2eq} was taken as the unit. Calculation of ecological burden using GWP is divided into two parts: (1) Environmental burden: production of GHG and release of their emissions into the air. (2) Environmental credit: decrease in global production of GHG thanks to the replacement of fossil fuels and primary raw materials.

2.1 WTE

There are several arrangements of WTE technologies as reviewed in [41]. However, grate combustors belong to proven and robust technologies used in most applications today. A comprehensive description of principles governing a WTE plant was presented by Stehlík in [42]. Even though an extensive environmental assessment of WTE technologies is often done (see [25]), only the subsystems and their parameters having a direct effect on GWP are highlighted in this paper. Concepts underlying WTE plants are basically identical. Incinerators consist of a thermal treatment section, heat recovery section and a flue gas cleaning system. Figure 2 illustrates basic energy inputs and outputs in a WTE plant. Typical energy balances of WTE facilities for cases with maximum electricity production and heat-power coupling can be found in [43]. These inputs are the most important elements in terms of GWP definition, as explained further in the paper. The plant is usually consisting of a waste bunker, a section for treatment and preparation of the waste and processing of

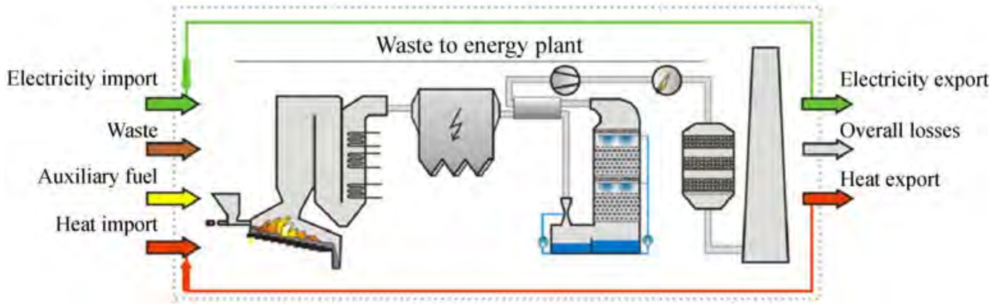

Fig. 2 Simplified diagram of main energy inputs and outputs in WTE plant

the solid and liquid products of the incineration process [42]. Best available techniques, recommendations and requirements imposed on WTE plants are listed in a thorough reference document [44].

Flue gas heat recovery in most incinerators takes place in a heat recovery steam generator (HRSG) where superheated steam is generated [44]. refers to typical parameters of the generated steam: the pressure of 4 to 4.5 MPa and temperature of 380°C to 420°C. If the steam conditions are to be higher (pressure of 6 MPa, for example), high investment costs are necessary due to the risk of corrosion and need for relevant protective measures. Effect of increased parameters on energy generation was analyzed in [45], for example.

Superheated steam is then used in a cogeneration. Backpressure steam turbines (BP) or extraction condensing steam turbines (EC) may be employed to generate power, depending on the plant owner's requirements. Current technologies need imported power only for a start-up and shutdown of the incinerator, or during emergencies [46]. Heat is exported after the BP or from one of the outlets of EC, either in the form of hot water or steam.

2.1.1 Features of particular WTEs

Processing capacities of WTE plants in Europe have extensive ranges [46]. Authors of this paper operate with two basic distinctions between the processing capacities. First, there are medium-sized and large plants processing 80–300 kt·year^{-1}. Latter plants are usually located in densely populated regions and large cities (hereinafter referred to as large WTE plants/capacities). Plants with a processing capacity of 10–50 kt·year^{-1} (hereinafter referred to as small WTE plants/capacities) are relatively common in France and Italy [42]. In terms of waste treatment, small WTE plants have been constructed as micro-regional facilities for micro-regional needs, which reduce requirements on waste logistics and related transportation costs and emissions.

If the WTE plant is of conventional design, the basic technological principles are identical regardless of the processing capacity. Heat from flue gas in HRSG is used for the production of superheated steam. This steam is then employed in heat and power cogeneration. The heat is exported either in form of hot water or steam (for example, central district heating, steam for industrial applications). In contrast to large WTE plants, small capacity units usually tend to focus more on heat generation [42]. Reasons behind this decision are high investment costs related to purchasing and running of the high-pressure steam boiler and especially condensing turbine. Further, the market availability of small condensing turbines is rather limited. Specific investment costs of reaching a high efficiency of power generation in small WTE capacities are not sufficiently compensated with high enough profits from the sale of the electricity [42]. Owners may then give preference to technical solutions with either hot-water boiler for district heating, or steam generation of low parameters and cogeneration of power using steam reduction. The power that was generated this way is usually used for power demands of the technology itself. Calculations in this paper are conducted for high-capacity plants with EC turbine and for small-capacity plants with BP turbine. If the WTE plant is to be economically sustainable and reach adequate thermal efficiency, plant owners have to find consumers for the generated heat. This is easier for small-capacity units which have lower thermal power. Flue gas cleaning system should employ ta dry cleaning method. This method consists of spraying the flue gas stream with sorbents and adsorbents which are later filtrated [42].

The so-called mono-incinerators of RDF are another type of units discussed in this paper [47]. These units are designed for incineration of RDF, and their general layout corresponds with conventional WTE units. Differences lie in the used materials, and design and operating mode of the incineration section. Mono-incinerators have a high degree of fuel utilization. Thanks to combustion of the high calorific components, the mono-incinerators have an increased specific production of energy per ton of fuel. However, the energy production is accompanied by the increased specific production of flue gas, and GHG (see section 2.1.2). Also, part of the MSW from RDF production is not utilized and is later landfilled [48].

2.1.2 Emission production (environmental burdens)

As analyzed above, the composition of the RES itself is one of the key factors when assessing the impact of a waste treatment method on GHG production, see Table 1. The most important waste parameters are the calorific value of the waste and amount of fossil-derived carbon and biogenic carbon. Amount of fossil-derived carbon in the waste, once incinerated, results in the production of carbon dioxide, a potent GHG. In contrast, biogenic carbon contained in biologically degradable parts of the waste causes the creation of landfill gas that contains methane and carbon dioxide. The natural carbon cycle is composed of two cycles: a long-term and a short-term, "biogenic". In the long carbon cycle, carbon is captured in fossil fuels and fossil fuel derived products. In the short carbon cycle, carbon naturally occurs in all living organisms. In general, released biogenic carbon is not considered to be an environmental burden and functions as a necessary part of natural cycles [49]. Another parameter important is waste calorific value. The calorific value defines how much energy is contained within the RES and, consequently, how much power and heat the waste may produce in energy recovery. A unique software tool called JUSTINE was designed at the authors' department to predict the composition of the waste and its characteristics. The software is described by Pavlas et al. in [50], for example, who studied the hazardous waste. By analogy, the method may be applied to define the composition of the RES using an approximation of the waste components [51]. Waste composition for purpose of this paper as evaluated by the approach described in [51] is displayed in Table 1.

In addition to the most important burden-producing process, that is the waste incineration itself and production of carbon dioxide, there are other GHG producing processes related to the operations of the incinerator. These processes include thermal and electrical energy supplied from primary energy sources, provided that the energy is necessary and has been purchased. Data for calculations were obtained in [46]. Others include consumption of natural gas in the combustion chamber which is necessary for the combustion stabilization, or natural gas necessary for start-up and shut-down of the boiler. Consumption of natural gas in the calculations equals 220 $MJ \cdot t_{waste}^{-1}$, see [46].

Other elements of input and output inventory pertain to solid outputs coming from the incinerator. Solid outputs are cinder from the combustion chamber and fly ash captured in the flue gas cleaning system. Metals may be recovered from the slag, the slag itself is later landfilled as an inert material or may be used in the construction industry (for construction of roads, for example). The fly ash is treated as hazardous waste and is deposited in hazardous waste landfills. Both the slag and fly ash are neutral to GWP and do not produce any additional GHG, except for the transportation, see section 2.4. Recovery of metals from cinder does have an impact on the final GWP that is a positive impact. The recovery prevents the formation of GHG that would have been otherwise created in the production of metals from primary raw materials. The following section covers other important environmental credits.

2.1.3 Energy production in WTE and related positive effects (credits)

Heat and power production in WTE plants is considered to be an environmental credit since it partially substitutes generation of power and heat from primary energy sources. It is crucial to collect basic parameters of the sources that are being replaced in order to be able to calculate the environmental credit. These basic parameters include the

Table 1 Expected average composition of residual waste in the Czech Republic

RES fraction	Content of particular components/%	Calor. value /($MJ \cdot kg^{-1}$)	Fossil-derived carbon/($g \cdot kg^{-1}$)	Biogenic carbon /($g \cdot kg^{-1}$)
Metal	2.5	0.0	0	0
Glass	5.5	0.0	0	0
Paper + beverage containers	8.0	14.6	73	317
Plastic	10.0	34.0	680	0
Electronic waste	0.4	22.9	441	0
Textile	5.5	15.0	172	218
Other combustibles	14.0	4.4	45	135
Organic waste	29.0	4.6	0	160
Hazardous waste	0.6	17.0	416	0
Mineral waste	3.0	0.0	19	0
Fraction under 40 mm	21.5	5.1	46	85
Total	100*	8.7**	104**	120**

*: sum; **: weighted average.

production of power and heat, the efficiency of the production and emissions factors of the production. However, the most important parameter is the fuel mix and its carbon content, or the fuel emissions factor. Fuel mix of the replaced source of energy has a major impact on the amount of saved CO_{2eq}. For example, the difference between the emissions factor of natural gas (55 g $CO_2 \cdot MJ_{calorific\ value}^{-1}$) and lignite (99 g $CO_2 \cdot MJ_{calorific\ value}^{-1}$) is almost a double. Emission factors are presented in [49], for example, and they are defined in Act no. 480/2012 Coll [52]. for the territory of the Czech Republic. A cumulative emission factor for fuel mix in the Czech Republic is used in this paper for the production of power, see Table 2. Two methods may be applied for heat production and its replacement: (1) If LCA is conducted and environmental impact is assessed at the local level, the emission factor of the plant whose heat production is being replaced by the WTE plant is considered. (2) If the calculation covers the whole Czech Republic, an emission factor of the energy mix for heat production in the whole country is applied, see Table 2. In future, the total energy mix for heat production should be replaced with data for particular DH networks.

An energy self-consumption data was taken from [46]. There are wide ranges of minimal a maximal heat and power self-consumption so the average data for WTE were considered. The respected values are 105 $kWh_e \cdot t_{waste}^{-1}$ for self-used power and 122 $kWh_{th} \cdot t_{waste}^{-1}$ self-used heat.

IPCC in [44] stipulates minimal energy export level of 1.9 $MWh \cdot t^{-1}$ for efficient heat supply. WTE plants should be installed in locations where they may be connected to a central district heating network. If this arrangement is not manageable, the greater production out of these two options is to be considered: (1) 0.4–0.65 $MWh \cdot t^{-1}$ for power-oriented plants, or (2) at least the same amount of power from the waste as the average annual power consumption in the whole unit with additional heat production. Reimann conducted and published an evaluation of the efficiency of energy production and other operational parameters in European incinerators [46]. The authors categorized WTE plants into three groups and identified their average efficiency of energy production: (1) Heat-production oriented plants, no power production and heat production efficiency of 77%. (2) Power-production oriented plants, the efficiency of power production of 21%, heat production efficiency of 5%. (3) CHP: power production efficiency of 15%, heat production efficiency of 37%.

A summary of WTE technologies describing the previously discussed categories is given in [42], for example.

2.2 Landfilling

The basic information about landfilling in this paragraph was taken from [55]. A landfill site is a place designated for disposal of waste where the waste is permanently stored on the ground or underground. The waste which is to be deposited on the landfill site must be divided into specific waste types and categories based on the chemical characteristics so that there is no risk of mutual interaction of the wastes and formation of harmful substances. Just like other waste treatment methods, landfilling has its own waste treatment procedures and technologies. Waste is either deposited into large open holes or is piled in heaps above the ground. Every landfill site has several protective layers. The bottom layer functions as a seal and prevents the so-called leachate and drainage from permeating the groundwater and surrounding areas. Landfills are further covered with a drainage layer; this is basically a drainage system that collects leachate into specialized sealed containers. Leachate is rainwater which falls on the landfill site and soaks the deposited waste. Landfills may further produce landfill gas, which is a mixture of CH_4 and CO_2 formed by decomposition of biological components of the waste. An extensive review of landfill leachate and gas treatment is introduced in [56]. Since these gases are GHG, amount of landfill gas released into the atmosphere is an important parameter for calculation of GWP [57].

In contrast to WTE, the actual share of the biogenic

Table 2 Fuel mix for power and heat industry in the Czech Republic, data [53] and [54]

Reference	Power		Reference	Heat	
	Share/%	CO_2 production /($kg \cdot GJ^{-1}$ of produced power)		Share/%	CO_2 production/ ($kg \cdot GJ^{-1}$ of produced heat)
Coal	51	337	Coal	59	112
Natural gas	8	187	Natural gas	24	62
Nuclear	30	0	Other gases	4	73
Water	1	0	Renewables	9	0
Solar	3	0	Heating oils	4	85
Wind	1	0	–	–	–
Biomass	6	0			
Total	100*	187**	Total	100*	88**

component is an important parameter for landfilling. CH_4 and CO are produced by anaerobic bacteria that degrade the bio-components (which make up approximately 50% of RES, such as paper, food waste, grass, wood, etc.). CO_2 emissions are not incorporated in the final GWP since they are a part of the natural carbon emissions cycle. However, CH_4 emissions are included in the GWP, despite the fact that the carbon is mostly biogenic. CH_4 is produced due to anaerobic conditions at the landfill site; these conditions are man-made (they are of anthropogenic origin) and would not otherwise occur in nature. Formation of landfill gas reaches ca. 210 $m^3 \cdot t_{waste}^{-1}$ on average [58]. This number is also used in the calculations in this paper. According to Czech legislative, landfill sites operators are obliged to collect the landfill gas on inactive sections of the site. The efficiency of the gas collection ranges from 50% to nearly 100% and is dependent on the cover type and the coverage of the collection system [59]. The US Environmental Protection Agency uses the default value of 75% for gas capture efficiency in cases where it is not exactly stated [60]. Captured gas is then combusted in a waste gas burner or used for energy recovery in a cogeneration unit [59]. Since collection efficiency is not monitored, it is handled as an uncertain parameter in the assessment (see section 3.3).

2.3 MBT

MBT installations have not been very common in the Czech Republic yet. Most data for this type of waste treatment comes from Germany, Austria and Poland. Whereas paper [48] summarizes experience with MBT in Poland, potential applications of MBT in OECD countries are evaluated in [61]. A general guide on MBT is described in [62]. MBT is a technology for RES that undergoes mechanical treatment, waste separation and subsequent biological or physical treatment. Depending on the technology, the MBT may be distinguished into three groups: mechanical-biological treatment, mechanical-biological stabilization (biodrying) and mechanical-physical treatment. MBT installations aim to decrease the amount of landfilled RES. Each of the treatment technologies varies depending on the input waste composition and demand for the output materials. Usually mechanical, physical and biological procedures are combined when the unwanted waste elements, which cannot be biologically degraded, are separated (metals, plastic, glass, etc.). Consequently, the waste is stabilized. Waste components suitable for biological degradation are stabilized using aerobic and anaerobic processes. Aerobic stabilization means composting in composting tunnels, boxes, etc. Anaerobic conversion (dark fermentation) may occur under dry or wet conditions. After the aerobic/anaerobic phase, the decomposition ends with aerobic treatment. Stabilized waste is then immune to biological decomposition at the landfill site and formation of landfill gas is thus drastically decreased. Nowadays, there are installations where there is no stabilization of the waste for landfill. These installations only mechanically separate useable waste components with high calorific value, and the rest is deposited at the landfill without any prior treatment [48]. Most modern MBT installations finish the waste treatment with a mechanical treatment phase. The undesired fractions, small combustibles, the fraction with high calorific value, and so on, may all be separated in this mechanical phase. The fraction with high calorific values may then form the refused-derived fuel (RDF). RDF has a higher calorific value (15–25 $GJ \cdot t^{-1}$) than untreated MSW (8–10 $GJ \cdot t^{-1}$).

The composition of RDF depends on the technology that created it; composition of the RDF for our calculations is listed in Table 3. It was derived based on complex modeling approach, where MSW (see Table 1) was subject to sorting and treatment process to produce RDF. MBT with a biological stabilization of the waste and production of RDF was considered. Mass balance of 100% input RES in the considered installation is as follows: (1) 41%: stabilized fraction, to be landfilled. (2) 32%: a fraction with high calorific value, transformed into RDF, for WTE treatment. (3) 19.5%: losses caused by drying and degassing. (4) 7.5%: material recovery of glass and metals. The performance was based on operational experience presented in [48]. However, the specific composition of MSW produced in the Czech Republic was taken into account. More information about the performance of MBT may be found in ESM. RDF may be combusted in units that are similar to conventional combustion plants; these plants (the so-called mono-blocks) are designed to combust fuel with high calorific value. RDF can be further co-incinerated in cement plants or in other WTE installations [63].

2.4 Transport

Waste transport precedes all waste treatment methods. The transport may be divided into two groups. First, there is the waste collection itself, that is the waste trucks collecting the waste from the garbage containers in the streets. Second, there is the transport of the collected waste from the place of its origin to the waste treatment facility. If the waste treatment facility is located far from the place of waste production, there may be various transfer stations established along the way. The conducted research study proves that impact of the waste transport on the amount of GHG emissions is negligible. For the purposes of our analysis, reference distances were identified so that the impact of transport emissions on the overall pollution from emissions may be validated. The distance covered by a waste collection truck in the analysis was 70 km and the amount of waste transported by one truck was 10 t. The transport distance to the waste treatment facility was 50 km and amount of waste transported by one truck was 24 t.

Table 3 Composition of RDF in this paper

RDF fraction	Content of particular components/%	Calorific value /($MJ \cdot kg^{-1}$)	Fossil-derived carbon /($g \cdot kg^{-1}$)	Biogenic carbon /($g \cdot kg^{-1}$)
Metal	0.0	0.0	0	0
Glass	0.0	0.0	0	0
Paper + beverage containers	22.8	14.6	73	317
Plastic	26.8	34.0	680	0
Electric components	0.9	22.9	441	0
Textile	11.0	15.0	172	218
Other combustibles	30.0	4.4	45	135
Organic waste	3.0	4.6	0	160
Hazardous waste	1.3	17.0	416	0
Mineral waste	0.0	0.0	19	0
Fraction under 40 mm	4.2	5.1	46	85
In total	100*	16.2**	243**	145**

*: sum; **: weighted average

Distances suitable for various combinations of transport types were analyzed e.g., in [64].

3 Results and discussion

This section presents concrete results of GWP calculations for the three methods of RES treatment. The most extensive analysis concerns WTE installations. At the end of the section, there is a brief comparison of all three methods and impact of their transport emissions on final results.

3.1 GWP of WTE

A simplified LCA method was used to describe WTE installation, and GWP was employed to assess the environmental impact. The results in Fig. 3 clearly show that the environmental burden originates solely from the combustion process itself and from the oxidation of the fossil-derived carbon. Waste composition is the key element here (Table 1). Environmental credits originate purely from the amount of emissions that are not exploited from the primary sources for the production of power and heat. The calorific value of the fuel (section 2.1.2), the efficiency of the whole WTE process (section 2.1.3) and the environmental burden of power and heat production in conventional fossil-fuelled energy sources (Table 2) play a major role here. Other factors may be disregarded.

The following Fig. 4 displays impact of three sub-systems (combustion, heat and power production). These sub-systems are affected only by the composition of the combusted waste. Two major parameters of the waste characteristics are its calorific value and amount of fossil-derived carbon. Amount of fossil-derived carbon is directly proportional to the environmental burden of the combustion process itself. And the amount of plastic in the RES has the major impact on the amount of the fossil-derived carbon in the waste. Figure 4 displays three profiles which differ in the share of plastic content in the waste. Profile A corresponds to the composition in Table 1, the share of plastic in profile B is lower by 2%, and share of plastic in profile C is higher by 2%. This arrangement may simulate how efficiently the primary waste producers separate their waste. Portions of other waste components were modified so that their shares remain intact. Sum of all the components must equal 100%. The other parameter important in waste is its calorific value. The calorific value may be predicted using the calorific value and share of components in the waste. High portions of high calorific value components (such as plastic, paper) lead to increase in GWP-credit for the produced power and heat. This fact (increase in calorific value and GWP-credit) in plastic goes against the previously mentioned increase in the content of fossil-derived carbon, see chart in Fig. 4 where profiles representing various contents of fossil-derived carbon converge when the heat production rises (and power production declines). Calorific value of waste in profiles is $LHV_A = 8.7\ MJ \cdot kg^{-1}$, $LHV_B = 8.2\ MJ \cdot kg^{-1}$ and $LHV_C = 9.2\ MJ \cdot kg^{-1}$.

Another interesting parameter greatly affecting the final GWP is a share of produced power and heat in the WTE installation. Most of the existing as well as the planned installations have EC turbines. As mentioned earlier, the calculations also incorporated this type of turbine for large capacity units. In Fig. 4, the impact of the EC mode is displayed. The horizontal axis (axis x) shows the percentage of extraction utilization. Zero% on axis x means a full condensing mode with heat production covering only demands of the installation itself. One

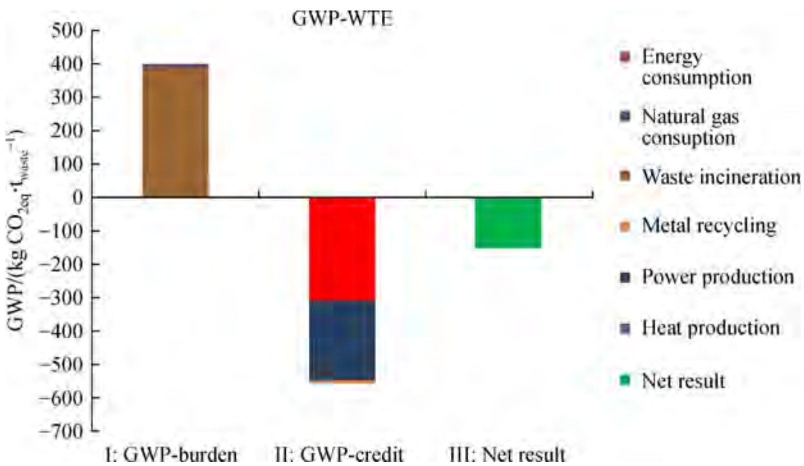

Fig. 3 WTE: Chart of average annual GWP to 1 t of waste. Capacity = 100 kt·year^{-1}, lower heating value = 8.7, heat export 4.2 GJ·t^{-1}, power export 0.39 MWh·t^{-1}

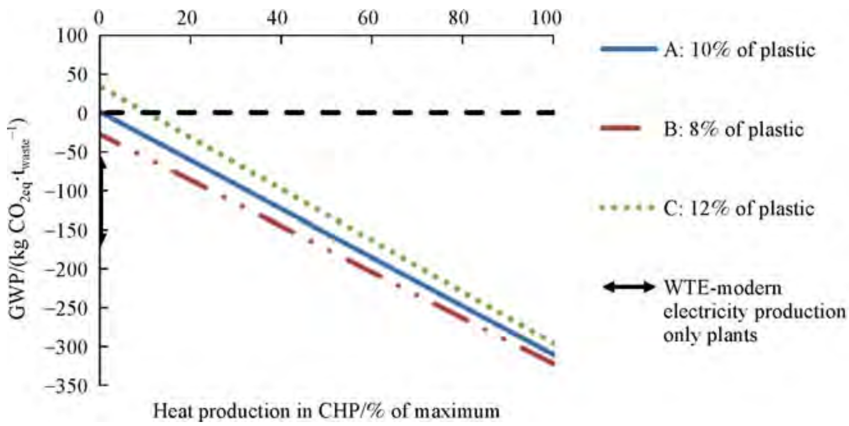

Fig. 4 WTE: GWP as a function of percentage utilization of heat production. Heat production in CHP = 0% means power-oriented operation; Heat production in CHP = 100% means heat-oriented operation

hundred% on axis x means maximum use of turbine extraction with a minimum flow of steam necessary for the condensation. This corresponds to the second and third group discussed in section 2.1.3. Figure 4 shows that increase in extraction (heat production rises) means an increase in the amount of CO_{2eq} saved. Concrete numbers for boundary points in Fig. 4 are displayed in Table 3.

Figure 4 also shows a special case for a modern WTE installation which focuses solely on power production. Power production in these installations ranges from 0.6 to 0.8 MWh·t_{waste}^{-1} [46]. The installations take advantage of measures for maximization of power production. However, these are obviously expensive installations. If there is a chance of exporting the heat, it is a preferable method of saving carbon dioxide emissions than the maximization of power production.

If we apply facts discussed above and obtained from Fig. 4 to assess a particular location defined by an annual heat demand (see Fig. 1), we may identify the impact of annual processing capacity on overall GWP. In Fig. 5, there is a dependency of installation's capacity and GWP. The calculation was conducted for a location with a heat demand of ca. 370 TJ·year^{-1}. The two profiles in Fig. 5 present an impact of the replaced fuel on the final GWP. Two potential scenarios of integrating the WTE were considered: First, in combination with a gas-fired boiler and second, in combination with a coal-fired boiler plant. The blue line shows a situation when production of heat in a natural gas-fired boiler is substituted; whereas the red line shows replacement of heat production in a coal-fired boiler. Calculations of saved CO_2 in both cases, based on Table 2, involved various emission factors of heat production: 62 kg of CO_{2eq}·GJ^{-1} for a gas-fired boiler station and 112 kg of CO_{2eq}·GJ^{-1} for a coal-fired boiler. Sudden change occurring with the 60 kt·year^{-1} processing capacity is caused by the transition from technologies designed for small capacity installations to technologies designed for high capacities. One of the main reasons there is a change

Table 4 GWP for boundary points in Fig. 4

Waste composition	GWP/(kg $CO_{2eq}\cdot t_{waste}^{-1}$)					
	Power-production oriented installations			Heat-production oriented installations		
	A	B	C	A	B	C
Burden: combustion	366	317	417	366	317	417
Credit: power production	–343	–325	–361	–145	–138	–152
Credit: heat production	–21	–20	–22	–531	–502	–560
Overall GWP	2	–28	34	–310	–322	–296

of a turbine type from BP turbine for small installations to EC turbine for high capacity installations. Main differences between the two technologies are listed in section 2.1.1.

The final profile Fig. 5 becomes a new input for reverse logistic problems (e.g., previously mentioned NERUDA [4]) and serves as an environmental criterion. A similar input principle is already used in NERUDA for an economic description of WTE, see Fig. 1(a), the profile of dependence of gate-fee on installed capacity. Results prove that rising capacity causes decrease in amounts of saved CO_{2eq}, which is a negative trend. For comparison, see the profile for gate-fee of waste processing Fig. 5 where an increase in capacity results in a decrease in the gate-fee. There the trend is positive. The comparison further shows that environmental benefits are in opposition to the economic benefits. The whole situation calls for an optimisation model covering various locations and waste transport methods.

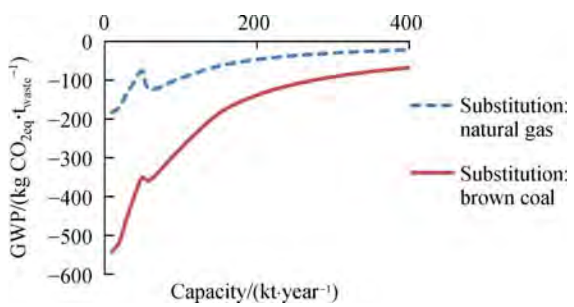

Fig. 5 Dependence of GWP and capacity

3.2 GWP of installations specialized on energy recovery from RDF

A similar calculation may be conducted for an installation specialized in energy recovery from RDF (monoblock). The following Fig. 6 displays a dependence of a GWP on the mode of the energy production, similar to the WTE installation in Fig. 4. The chart clearly shows that the negative impact of fossil-derived carbon in RDF on GWP, compared to the impact of RES, increased. The chart further displays two profiles for two options of produced steam parameters. The blue profile was compiled for

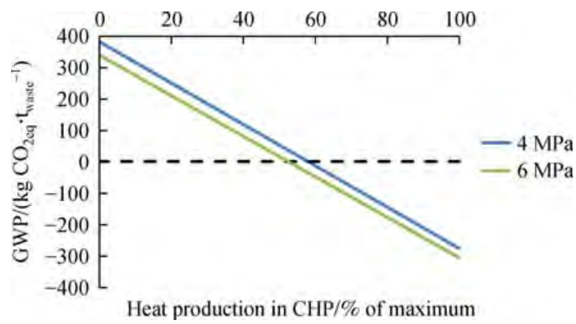

Fig. 6 Monoblock: GWP as a function of % age utilization of heat production. Heat production in CHP = 0% means power-oriented operation; Heat production in CHP = 100% means heat-oriented operation

common steam parameters (400°C and 4 MPa); green profile was compiled for increased parameters of 6 MPa. The positive effect of primary energy sources replacement is greatly outnumbered due to the increased calorific value of the fuel. GWP of the monoblocks is more susceptible to the operating mode of the installation and proportion of heat to power production. If the heat production drops below 60% of the maximum attainable production, GWP also drops below zero, which is the environmentally-neutral value, and the installation no longer saves GHG emissions. Quite the contrary, it pollutes the environment even more. The situation should also account for the negative effect of MBT which originally produced the RDF. Figure 5 shows the profile of dependence of GWP on installation's capacity.

3.3 GWP of Landfilling

Release and capture of landfill gas are the most significant parameters of landfilling which affect final GWP and the total amount of GHG released into the atmosphere. The scale of landfill gas capture greatly varies depending on the technologies available at the landfill site. The actual ratio of released and captured gas ranges from 50%–95% [59]. The example in Fig. 7 works with a constant landfill gas capture equal to 75% as recommended for not-monitored sites [60]. CH_4 makes up 50%–60% of the landfill gas, and

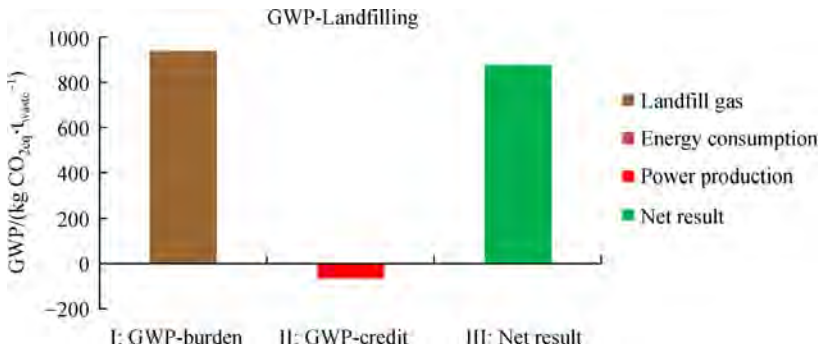

Fig. 7 GWP of landfilling (relevant for landfill gas capture 75% [60])

its GWP is 28 times more potent than that of 1 kg of CO_2. Carbon dioxide makes up ca. 30%–40% of landfill gas, and the rest are trace amounts of various gases (such as oxygen, nitrous oxide, ammonium, hydrogen, organic compounds, and others). The ratio of methane to carbon dioxide in landfill gas varies not only at a particular landfill site but also at one concrete site at a time. A constant of 55% of methane in landfill gas was entered into the calculations. The following chart in Fig. 7 shows results of calculations for positive and negative factors affecting GWP of a simulated MSW landfill.

3.4 GWP of MBT

Final GWP of a simulated MBT unit (no RDF utilization) comprises following environmental burdens and credits. The burdens include CO_{2eq}, formed by the production of energy from primary sources which cover energy demands of the unit itself. There are several configurations of the MBT unit. For purposes of our analysis, the following energy demand of MBT unit was considered [61]: 175 $MJ\cdot t_{waste}^{-1}$ of electrical energy, 60 $MJ\cdot t_{waste}^{-1}$ of heat, 30 $MJ\cdot t_{waste}^{-1}$ in the form of mechanical energy and 160 $MJ\cdot t_{waste}^{-1}$ in natural gas. Amount of GHG, in CO_{2eq}, in the output gas from biological stabilization is another burden. Output gas production is ca. 5500 $m^3N\cdot t_{waste}^{-1}$. The gas is cleaned, which decreases the amount of GWP-negative components to 5.8 $mg\cdot m^{-3}N$ of CH_4 and 6 $mg\cdot m^{-3}N$ of NO_2. Metal recycling and amount of CO_{2eq} saved in comparison to the production of the same amount of metals from primary resources are the only environmental credits. The amount is approximately 2.3 kg of iron and non-iron metals altogether. Production of other non-recyclable materials is not considered since paper and plastic are part of the fraction with high calorific value or part of the RDF. Final GWP is given in Fig. 8.

3.5 Discussion about implementing GWP in reverse logistic problems

The results from previous sections help us conduct final comparison and evaluation of parameters which are either significant or insignificant for the definition of GWP in RES processing units. The best and worst possible scenarios in terms of GWP may be outlined for the particular technologies. These scenarios are clearly displayed in Fig. 9.

The best possible scenario for WTE installation comes when heat production is maximized in small capacity units and coal-fired boilers are thusly replaced. This configuration may bring the potential GHG savings up to −500 kg $CO_{2eq}\cdot t^{-1}$. GHG savings in medium and large-scale capacity units, where heat production was maximized, and the coal-fired source was replaced, may reach over −300 kg $CO_{2eq}\cdot t^{-1}$. In contrast to this, the worst-case scenario comes when only power is produced. This

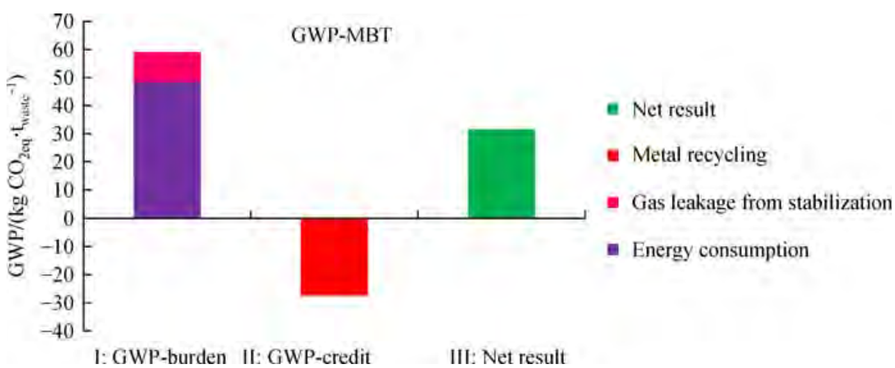

Fig. 8 GWP of MBT unit without RDF utilization

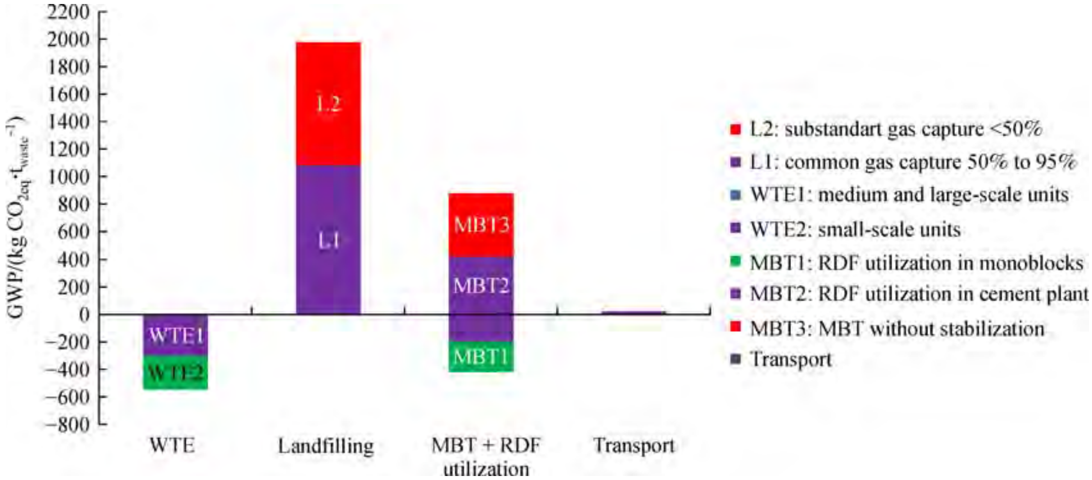

Fig. 9 Comparison of potential intervals of final GWP for particular RES treatment methods

situation may even lead to the additional production of GHG emissions instead of their saving. Results presented in this paper are valid for installations where power produced from fuel mix defined in Table 2 was replaced. Three subsystems of WTE, that is combustion, power and heat production, have more than 90% share in the final GWP. These are later used for calculation of environmental criterion in optimisation tasks.

For calculation of WTE's GWP, main inputs must be defined: (1) Waste composition; (2) WTE parameters: power and heat production; (3) Parameters of the primary energy sources that the WTE is to replace: Emission factor of carbon dioxide. Profile of dependence of GWP on WTE unit's capacity (see Fig. 5) is an input for optimisation task.

Landfilling is predominantly (by more than 95%) affected by one major parameter that is the ratio of captured *vs.* released landfill gas. The best-case and worst-case scenarios correspond to the top and bottom values of actual capture of landfill gas, as displayed in section 3.3. Maximum gas capture of ca. 95% leads us to the bottom values of GWP of ca. + 50 kg $CO_{2eq}\cdot t^{-1}$; this is, however, still an environmental burden. But once the amount of captured landfill gas reaches 50%, GWP equals ca. + 1090 kg $CO_{2eq}\cdot t^{-1}$. A facility without any capture technology yields double these values. Other factors contributing to GWP may be disregarded. Production of landfill gas is definitely affected by the composition of RES but the little differences have an insignificant impact on the final composition and are overshadowed by the previously discussed ratio of captured *vs.* released landfill gas. Inputs for the optimisation tasks thus include constant GWP, influenced by technologies.

MBT with subsequent energy recovery from RDF is the last technology analyzed in this paper. This method basically consists of the MBT unit itself, which is characterized by the constant environmental burden of GHG emissions that reach ca. +30 kg $CO_{2eq}\cdot t^{-1}$, and a unit for energy recovery from RDF, where GWP follows a similar pattern as in case of a WTE unit. This means that the best-case scenario involves the maximum production of heat and replacement of coal-fired source. GWP in this scenario reaches −300 $CO_{2eq}\cdot t^{-1}$of savings. More differences, compared to WTE, emerge at the other end of the GWP interval when heat production is at its minimum. GWP may then reach to +400 $CO_{2eq}\cdot t^{-1}$ of burden emissions. Inputs of the MBT optimisation tasks then include constant burden value and subsequent energy recovery from RDF requires similar profile as in case of WTE. This applies to common MBT unit described in section 2.3. Figure 9 shows two special examples (scenarios) on both sides of the resulting GWP. In the "MBT2" scenario the RDF is utilized in cement plant instead of monoblocks. The "MBT3" scenario shows the possible GWP production in MBT plant without stabilization of the landfilled fraction. In this case, the waste on a landfill still produces the landfill gas thus the GWP can get to +900 $CO_{2eq}\cdot t^{-1}$.

The previous part of this section discussed methods of implementing GWP into decision-making in optimisation tasks. This is followed by economic aspect, which is another benefit of using GWP for a description of environmental impact. This is enabled by European system for trading with GHG emissions (ETS). ETS was first introduced in 2005 and has entered the third stage of its existence (2013–2020). Legislation for the fourth phase is still being drafted but the basic rules have already been adopted by the European Parliament. ETS gradually developed and extended to other industries, and other than just carbon dioxide GHG have been included into the system. ETS is the "cap and trade" principle. Redundant allowances or allowances from emission-savings may then be traded on a market. Current price is just below €5 per ton of CO_{2eq}. A detailed description of ETS principles and mechanisms is given in [65]. European legislation [66] (regulation on cost-effective emission reductions and low-carbon investments) and [67] (regulation on greenhouse gas emission reductions) has taken relevant steps to revive emission allowances market. Emission production in ETS is planned to drop by 43% compared to 2005 levels, and by 30% in industries not covered by ETS. Besides that, ETS is to cover more areas and foremost of these areas is the waste management industry. Recent development in the field and measures adopted by the EU further justify the use of GWP as an environmental criterion for SCM task in WM. Economic description of GWP using prices of emissions allowances helps keep the optimisation task focused on one criterion and thus reduce computational complexity.

4 Conclusions

The research study contributes to the development of advanced reverse logistics models, where economic and environmental criteria are combined to propose an optimum infrastructure for treatment of residual municipal waste. Purpose of this paper was to investigate parameters influencing environmental impact (GWP) in case of three RES treatment technologies. These technologies were WTE, landfilling and MBT with subsequent utilization of RDF.

Since thermal treatment of RES represents a preferred method of handling this kind of waste, GWP from waste-to-energy was analyzed in more details. The effect of varying waste composition (fossil carbon content) was quantified. This was especially important for plants processing refuse-derived fuel produced in RDF plants. The increased plastics content worsens their GWP compared to WTE plant treating RES. In addition, heat delivery rate was identified as the most important aspects influencing the credits and thus the overall GWP of WTE. If there is a chance of exporting the heat, it is a preferable method of saving carbon dioxide emissions than the maximization of power production. Costly measures leading to higher electrical efficiency are justified only in cases, where heat delivery is limited.

The WTE integration in particular locality was analyzed in terms of avoided emissions from fossil-based energy producing units. The WTE capacity was increased considering fixed heat demand. Rising capacity causes decrease in amounts of saved CO_{2eq}, which is a negative trend. The relation is nonlinear. However, models employed in reverse logistics work with a linear relationship between the waste amount and emission production, which represents strong simplification.

The comparison further shows that environmental benefits are in opposition to the economic benefits of economy commonly improves with increased capacity. The situation calls for an optimisation model covering various locations and waste transport methods.

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ORIGINAL PAPER

Logistic model-based tool for policy-making towards sustainable waste management

Radovan Šomplák · Martin Pavlas · Jiří Kropáč · Ondřej Putna · Vít Procházka

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Abstract The aim of this paper is to introduce a novel approach which supports facility planning in the field of waste management. Only 23 % of municipal solid waste (MSW) was thermally treated in the EU 27 in 2011. The increased exploitation of its potential for energy recovery must be accompanied by massive investments into highly efficient and reliable incineration technologies. Therefore, the challenge is to be efficient and use the technology to its optimal level. Feasibility studies of all plants providing a service for a region create a large and complex task. Gate fee (the charge for waste processing in the facility) represents one of the most crucial input parameters for the assessment. The gate fee is driven by configuration of the technology, competition, market development, environmental taxation and costs of waste transport to satisfy the plant's capacity. Valid prediction of the gate fee thus presents a demanding task. In this paper, first, an advanced tool called *NERUDA* is introduced, which addresses logistic optimization and capacity sizing. The key idea is to focus on the problem of competition modelling among waste-to-energy plants, landfill sites, and mechanical–biological treatment plants producing refuse-derived fuel. Then, the main theoretical concepts are discussed, followed by the development of a suitable mathematical model. The goal is to obtain a minimized cost of MSW treatment for waste producers (municipalities). The application of the developed tool is demonstrated through a case study, where uncertain parameters entering the calculation are handled by a repetitive Monte Carlo simulation based on real-world data.

Keywords Supply chain · Optimization · Waste-to-energy · Monte Carlo · Gate fee · Waste management · Waste management plan

List of symbols

CEE	Central and Eastern Europe
CZE	Czech Republic
DH	District heating
EU	European Union
IRR	Internal rate of return
LCA	Life-cycle assessment
MBT	Mechanical and biological treatment
MSW	Municipal solid waste
R1	Energy efficiency, R1 factor
RDF	Refuse-derived fuel
WM	Waste management
WMP	Waste management plan
WTE	Waste-to-energy (plant)

R. Šomplák (✉) · M. Pavlas · J. Kropáč · O. Putna
Institute of Process and Environmental Engineering, Faculty of Mechanical Engineering, Brno University of Technology (UPEI VUT), Technická 2896/2, 616 69 Brno, Czech Republic
e-mail: somplak@upei.fme.vutbr.cz

V. Procházka
Institute of Mathematics, Faculty of Mechanical Engineering, Brno University of Technology, Technická 2896/2, 616 69 Brno, Czech Republic

Introduction

This paper deals with the recent salient issues of the municipal solid waste (MSW) management facility planning, and by facility planning, we mean proposing processing capacities and waste logistics optimization, which both play an important role. Individual Member States of

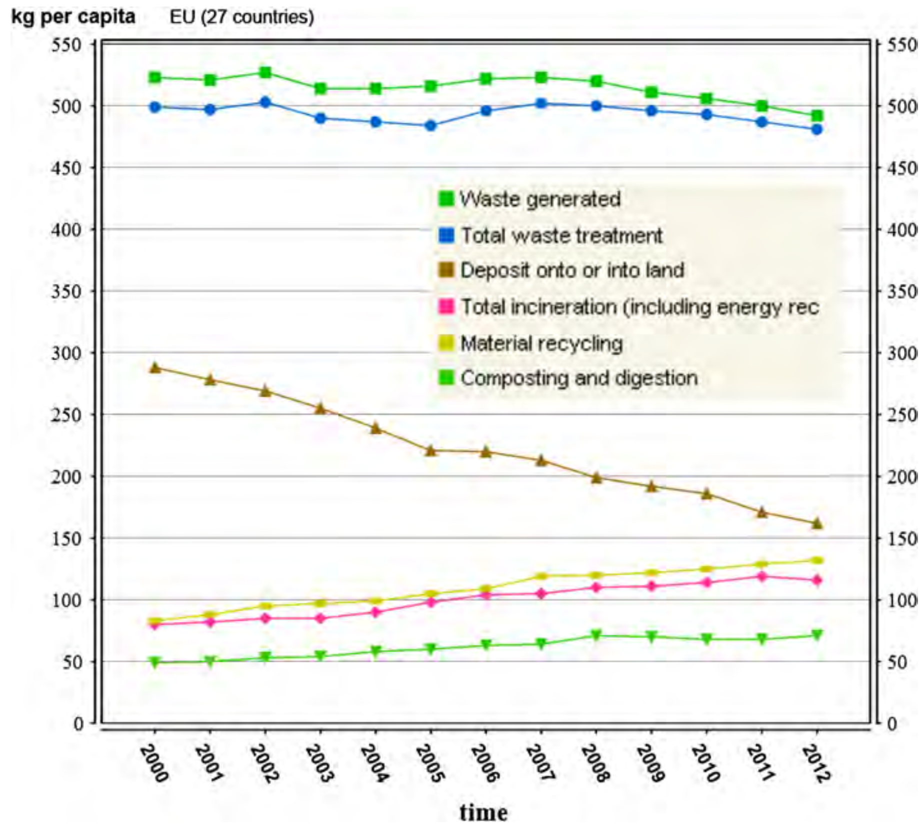


Fig. 1 Trends of municipal waste generation and treatment in the EU, by type of treatment method (Eurostat 2012)

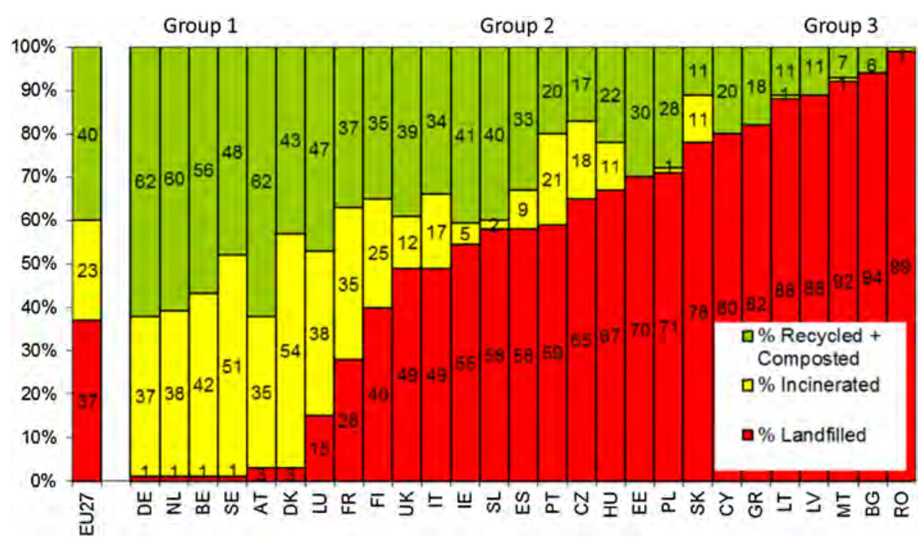


Fig. 2 Municipal waste treated in 2011 in the the EU 27, by country and treatment category (% of municipal waste treated) (CEWEP 2013)

the European Union (EU) are committed to reducing the ratio of landfilled waste, and at the same time, to treating the waste in an efficient way. Specifically, the EU issued Directive 2008/98/EC on waste and the hierarchy of waste management (WM). Waste prevention is a priority of the Directive, followed by a decrease in waste production. The reuse of certain products should also be promoted. Material recovery is at the third level in the Directive hierarchy. If all the previously mentioned levels of WM are fully exploited, energy recovery from waste should then be preferred to waste disposal, e.g. landfilling and incineration, which has no energy recovery.

In order to demonstrate the contemporary situation in the EU, a short summary of how WM is currently handled will now be given. The graph in Fig. 1 shows that the generation of MSW in the 27 Member States of the EU (EU 27) has been moderately falling. The current average of waste generation is slightly below 500 kg per capita per

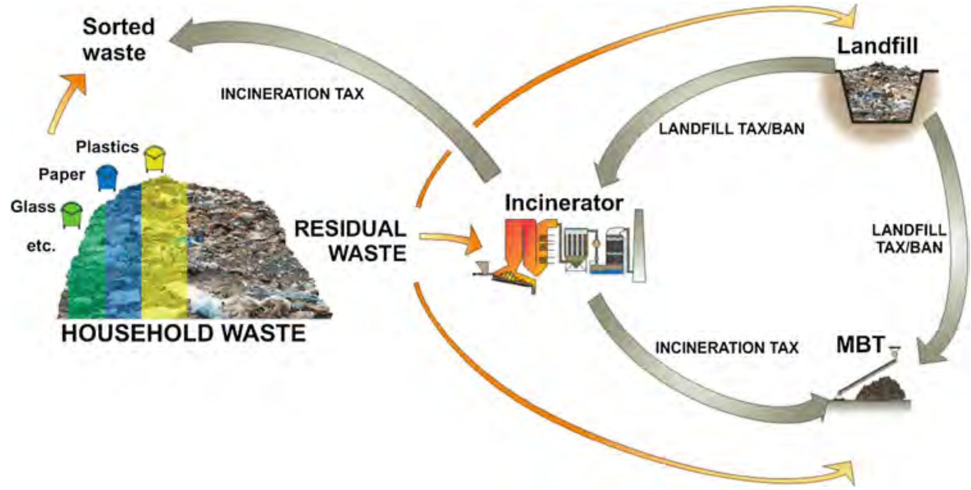


Fig. 3 Impact of landfill tax/ban and incineration tax on waste flow among key elements of MSW processing system

year. One may also notice a progressive tendency to prefer material and energy recovery to landfilling (Eurostat 2012). The latest data on the proportion of MSW processing methods (recycling, incineration, composting and landfilling) in the EU Member States in 2011 are given in Fig. 2.

Figure 2 clearly shows that the current situation and efficiency of WM vary greatly across Europe. We may distinguish between three groups of countries in this paper. Yet, there is no rigid boundary among particular groups:

Group 1 (Fig. 2 left)—we can identify countries with well-developed WM, where landfilling has been nearly eliminated. The majority of MSW is recovered for material reuse. These successful countries focus on sophisticated and effective waste collection which encompasses dozens of recyclables. The amount of residual waste, which cannot be recycled, has seriously decreased. Landfilling of this untreated and biodegradable MSW is forbidden, and therefore it is incinerated. The amount of incinerated waste is high and ranges between 30 and 40 % of the total waste generation. Incineration plants, therefore, play a significant role in these countries' WM, and the promotion of recycling is reinforced by incineration taxes (see Fig. 3). Waste prevention policy combined with demographic development may create overcapacities in the following years, and there is an ongoing discussion whether intensive recycling is sustainable for the future (Velis and Brunner 2013).

Group 2 (Fig. 2 middle)—countries where the changes towards more sustainable WM are in progress. Here, legislation is already in place, and policy is implemented in the waste management plan (WMP). There is a sufficient processing capacity but, unfortunately, processing capacity commonly refers to landfill sites, and a great share of biodegradable waste is still landfilled. These countries do not forbid waste landfilling, but they do impose landfill taxes to redirect some waste from landfilling to material recovery and/or WTE (Fig. 3). Countries in this group are experienced in waste-to-energy (WTE) plant operation. However, material recovery is insufficient, and there is still potential for its further enhancement in these countries. Overall, in these countries, more WTE projects are being prepared, and new WTE plants are being built or have building permission confirmed. The United Kingdom (UK) may serve as an example of a country on the borderline between the first and the second groups. The UK exported almost 868 kt of mechanical–biological treatment (MBT) products in 2012 (see below) (CHIWM 2013). Currently, the UK has around 18,900 kt/y of residual waste treatment capacity either 'operating' or 'under construction', which includes 44 dedicated incineration facilities and 57 other facilities. The capacity of prepared/designed projects is equal to 24,200 kt/year (Eunomia Research and Consulting 2013).

Group 3 (Fig. 2 right)—Countries awaiting the transformation of WMPs. These have insufficient capacity for processing waste, even concerning landfilling sites. Landfilling is not restricted, a low amount of waste is recycled and no WMPs are in place.

For more information about the current state in the individual EU Member States, see a detailed study issued by BiPRO (BiPRO 2012). It aims to evaluate Member States in terms of their compliance with the above mentioned hierarchy, existence and efficiency of economic tools for WM promotion, number and stage of development of waste treatment facilities, and planned projects and fulfilment of the targets for the diversion of biodegradable waste from landfilled sites.

As mentioned above, one of the key economic drivers towards efficient WM is a landfill tax or total ban on landfilling untreated waste. These restrictions influence the economy of key system elements (landfill sites, WTE, MBT, separated collection followed by material recovery, etc.) and thus the waste flow as well. This impact is summarized in a graphical form in Fig. 3.

The general relationship between the price of treating waste, landfilling, and recycling, including an analysis of correlations between the implementation stages of these strategies, is studied in (European Commission 2012). Further comments on the issue can be found in the paper (Van de Wiel 2010), where the impact of introducing these taxations for the transfrontier shipment of waste is reviewed. The recent phenomenon of overcapacity for WTE in certain countries, accompanied by legislation allowing cross-border transport of waste and different processing prices, has created a competitive environment within the EU. According to the report (Eunomia Research and Consulting 2013), if all currently planned projects in the UK, with a capacity of roughly 24,200 kt/year, are successfully implemented, there will be approximately 13,800 kt/year of overcapacity. By 2020, Germany expects incineration overcapacity to be 3,000 kt/year (Dehoust et al. 2010). Therefore, the import of waste into countries suffering overcapacity will become an important issue. Any possible imports are conditioned by energy recovery in the target country. Incineration facilities must comply with R1 (Energy efficiency, R1 factor) stipulated by the EU legislation, which allows the MSW incinerators to be classified in R category ('Use principally as a fuel or other means to generate energy') (2008/98/EC) and thus profit from this classification. An analysis and comparison of R1 factors can be found in Grosso et al. (2010) and Reimann (2012). Pavlas and Touš (2009) evaluated particular systems of MSW incinerators in terms of energy utilization and their impact on various operation modes on the R1 value. Since R1 is strongly dependent on the rate of energy generation, it has a direct relation to primary energy savings. Pavlas et al. (2010) proved that energy generated in MSW incinerators contributes to primary energy savings, as well as energy from biomass, whereas the release of emissions and pollutants is significantly lower.

Waste today has more denotations than it traditionally used to have. It is a valuable commodity—a source of energy and a source of raw materials at the same time (e.g. ferrous and non-ferrous metals). These factors lead to situations where it is beneficial to transport the waste even over long distances. This initiates the development of a unified market which is then divided into regions with insufficient processing capacities (sources of waste, groups 2 and 3) and regions where free processing capacities are available (sinks of waste, group 3). In such an environment, countries are supposed to plan, build and operate new capacities in the near future in order to meet obligations to reduce the amount of landfilled biodegradable waste (European Commission 2012). These new capacities will include not only WTE, but also MBT.

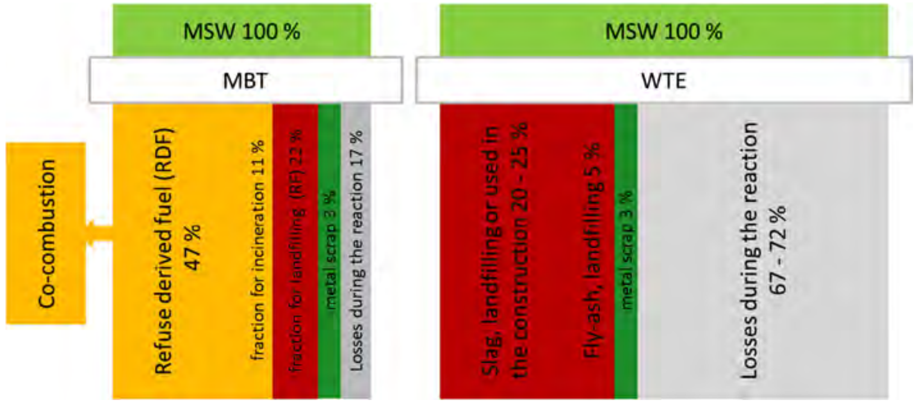
MBT spread to several EU countries in the 1990s. The process incorporates the mechanical grinding and separation of waste followed by biological processing (anaerobic decomposition and/or aerobic composting). This technology separates the input waste flow into utilizable parts. For more information about this method, see (Department for Environment, Food and Rural Affairs 2013). One MBT product is the refuse-derived fuel (RDF) with sufficient calorific value for subsequent use as fuel in combustion plants (power plants, cement plants, etc.). Finding end-users for RDF and local conditions at a particular site is vital for an efficient processing chain incorporating MBT. This line of argument is supported by various studies looking into Life Cycle Assessment (LCA) in WM. In addition, this method helped us find several general insights into the suitability of the MBT. Consonni et al. (2005) showed that when assessing all potential impacts, the direct incineration of untreated waste in an up-to-date incinerator is the most preferred strategy. Münster et al. (2013) stressed the need for the development of scenarios for the assessment of projects researching both WM and energy issues not only in the case of LCA; but Ma et al. (2010) discussed also the increased risk of corrosion due to chlorine presence in RDF. MBT was an important topic in WM debate in the 1990s and has been increasingly utilized in some countries, e.g. in Italy and Germany. Today this concept is proposed as a tentative solution for countries in groups 2 and 3.

Since the two concepts (i.e. direct combustion of MSW in WTE and RDF production in MBT) correspond to the overall balance in significantly different ways, we have summarized the key figures related to each concept in Fig. 4.

Although the sustainability of each concept should be evaluated based on both financial and environmental criteria, the final decision about pushing a specific project into realization is made by the investor. In this decision, the prediction of a competitive gate fee plays an essential role as an important economic parameter Šomplák et al. (2012a). They investigate the economy of scale related to specific WTE. They also mention the positive effect of falling per ton capital costs with increasing capacity. The cost of waste transport should be included as well, as it increases with the capacity and waste can be shipped even over long distances. At the same time, the supply chain, comprising all operations following the route of the waste from the place of its origin to its final processing place, becomes more and more complex (collecting vehicles, waste transfer stations, rail and truck transport, loading/unloading mechanisms, etc.).

In this complicated situation, it is useful to have a computational tool which can support decisions related to the following activities: (1) feasible location screening for WTE and/or MBT sites and their sizing based on residual waste availability; (2) waste flow simulation between waste

Fig. 4 A comparison of overall mass balance for WTE and MBT facilities (based on data provided by Thiel 2011)



sources and waste sinks in a rapidly extending EU waste market as an approach towards waste-availability modelling in a specific region; (3) support on supply chain planning and infrastructure improvement to remove expected bottlenecks; (4) project feasibility evaluation (risk analysis) focused on the prediction of competitive processing price (Šomplák et al. 2012a); and (5) impact evaluation of regulation and legislation (landfill taxes or ban).

Following from an extensive review published by Ghiani et al. (2013), many papers have contributed to the phenomena of WM modelling. However, the theoretical concepts and models have thus far focused on specific fields (e.g. collection itself, the exploitation of capacities of different types of technologies, transport cost minimization). In addition, they have considered some limitations and presumptions, e.g. fixed or linear cost, one technological concept included, limited number of nodes. Optimum solutions have been proposed, but a discussion about the project's feasibility, from the point of view of potential investors, is missing, and this restricts their practical application.

Therefore, our team has developed a computational tool called *NERUDA* which supports the aforementioned activities related to a new WTE project in its early stage of development (conceptual development phase). The benefits of using such a tool for analysis including hundreds of sub-regions and tens of plants is demonstrated in this paper through a case study aimed at a specific region (the Czech Republic—CZE).

The basic idea behind the *NERUDA* tool is as follows: the producer of waste (a municipality in case of MSW) makes a decision about its future MSW treatment strategy. The objective function addresses expenses in terms of cost for waste processing at individual facilities and the overall cost of the transport of waste to the facilities. Environmental taxation is included as well and reflected in the gate fee (environmental externalities can be included in the same way if necessary). For a discussion on the potential

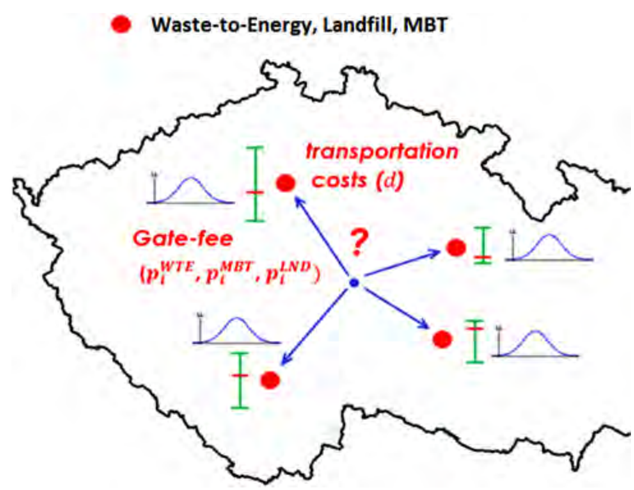


Fig. 5 A visualization of the basic ideas of transportation problems behind the developed tool

problems in the creation of models for WM planning and price estimates, see Parthan et al. (2012). The basic idea is the minimization of costs, which is presented in Fig. 5.

Although the idea presented in Fig. 5 looks simple, as soon as it is spread into the simultaneous calculation of many sub-regions, it turns into a comprehensive model (see "Mathematical model" Section) dependent on gathering and processing of real-world data. The sets of inputs can, of course, differ depending on the level of detail in the investigation. In general, the sets include information about: (1) *existing logistic infrastructure*—routes and their quality, taxation, railway corridors and their loading, distances, and expected transport times; (2) *waste-management statistics*—specific waste production, waste lower heating value, availability of separate collections systems for recyclables and their efficiency, demand for secondary raw materials, etc.; (3) *facilities*—existing landfill sites, incineration plants, new projects under consideration and/or erection; (4) *prices*—energy prices (heat, electricity, fuels), landfilling taxation, etc.

Mathematical model

First, we have to mention papers relevant to the topic, and solution methods. There are several inspiring texts dealing with sustainable supply chains design (Young et al. 2012), energy network solutions for regions (Kettl et al. 2012), descriptions and simulations by p-graphs (Süle et al. 2011), and multiple-criteria reduction in biomass energy supply chains (Varbanov et al. 2012). Concerning useful sources related to logistic models, we have to mention Ghiani et al. (2004) and Williams (2009) concerning indicator-variable integer programming techniques. There have also been several attempts to tackle the topic using an operational research approach, see (Lang et al. 2003). However, no paper has yet dealt with as an extensive case study which also assesses profitability and risks as that we shall present later in "Practical application in a selected region" Section.

We have successfully dealt with a decision-making process related to the specific WM strategy and built a specialized transportation optimization model. The key idea is to study the disposal of waste produced in villages and towns (sources of waste) and to model an approximate competitive environment. We denote sources of waste as nodes, and roads are represented as edges. Thus we minimize the overall costs as follows:

$$\min \sum_j dv_j x_j + \sum_i \sum_j a_{ij} x_j (p_i^{\mathrm{WTE}}(C_i^{\mathrm{WTE}}) + p_i^{\mathrm{LND}}) + \sum_j ev_j l_j + \sum_i \sum_j a_{ij} l_j p_i^{\mathrm{MBT}}(C_i^{\mathrm{MBT}}) \quad (1)$$

subject to (constraints are valid for all nodes i representing sources of waste):

$$\sum_j a_{ij} + o_i + \delta_i^{\mathrm{MBT}} (\sum_j a_{ij} l_j + \sum_j b_{ij} t_j) \leq C_i^{\mathrm{WTE}} + C_i^{\mathrm{LND}} \quad (2)$$

$$\sum_j a_{ij} l_j \leq C_i^{\mathrm{RDF}} \quad (3)$$

$$-\sum_j a_{ij} l_j \leq C_i^{\mathrm{MBT}} \quad (4)$$

$$\delta_i^{\mathrm{MBT}} \sum_j a_{ij} l_j = \delta_i^{\mathrm{MBT}} \sum_j b_{ij} t_j \quad (5)$$

$$\delta_i^{\mathrm{LND}} \sum_j a_{ij} x_j + \sum_j b_{ij} t_j \leq C_i^{\mathrm{LND}} \quad (6)$$

where x_j is an amount of MSW transported by arc j, l_j is the RDF amount transported by edge j, t_j is the TF amount transported by edge j, a_{ij} is an incidence matrix for MSW and RDF transportation graph, b_{ij} is an incidence matrix for RF transportation graph, d is the MSW unit transformation cost for 1 ton, e is the RDF transportation cost for 1 ton, and v_j is the length of edge j (distance between related nodes), p_i^{WTE} (C_i^{WTE}) is a gate fee for 1 ton of MSW in WTE in node i, p_i^{MBT} (C_i^{MBT}) is a gate fee for 1 ton of MSW in MBT in node i, p_i^{LND} is a gate fee landfill for 1 ton of MSW in node i, o_i is an amount of MSW production in node i, C_i^{WTE} is a WTE capacity in node i, C_i^{LND} is a capacity of landfilled site in node i, C_i^{MBT} is a capacity of MBT in node i, C_i^{RDF} is a capacity for RDF incineration in node i, δ_i^{LND} is equal to 1, if node i is of landfill type, and equals 0 otherwise, and δ_i^{MBT} is equal to 1, if node i is a village with MBT, and equals 0 otherwise.

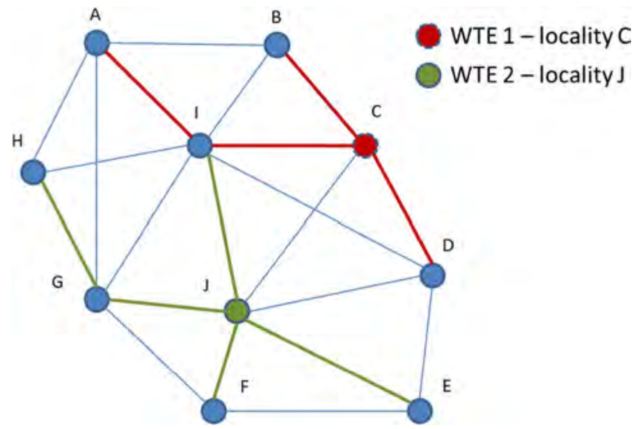


Fig. 6 Visualization of transportation network for simplified task

Calculation, simplified task

In order to provide an easy explanation of the model, we will first demonstrate the principles of calculation on a simplified task. The example here considers only a small number of nodes and edges (10 nodes, 21 edges) and does not account for the processing of waste in a MBT plant or its landfilling. Only two WTE facilities (C and J nodes in Fig. 6), which have a fixed annual processing capacity of 300 kt/year each, are considered. The overall capacity 600 kt/year slightly exceeds the total generation in all the selected nodes A to J, which is 570 kt/year (see Table 1). The gate fee is constant and amounts to 74 EUR/t and 81 EUR/t for facilities in C node and in J node, respectively. The objective function and all constrains are linear. Therefore, the solution is global. Figure 6 presents a transportation network with relevant data for this simplified optimization task. Data related to infrastructure model are summarized in Table 2.

Only road transport is considered, and the transportation price is constant, regardless of distance, amounting to 0.15 EUR/(km t). The compression of waste in transfer stations and relevant transportation price optimization are not

Table 1 Waste generation as considered in simplified task

Node	A	B	C	D	E	F	G	H	I	J
Waste production (kt/year)	50	80	85	55	75	45	35	70	35	40

considered either. Waste generation at particular nodes of the transportation task is given in Table 1.

The mathematical model is simplified to the subsequent objective function (7) and one constraint (13).

$$\min \sum_j dv_j x_j + \sum_i \sum_j a_{ij} x_j p_i^{\mathrm{WTE}} \tag{7}$$

provided that (constraint applies to all nodes and edges)

$$\sum_j a_{ij} x_j + o_i \le C_i^{\mathrm{WTE}} \tag{8}$$

Results may be easily checked, and the validity of the mathematical model may be proved thanks to the simplicity of the task. The results of the example are given in Fig. 7 and Table 3.

It is obvious that a real situation, where hundreds of subregions are optimized simultaneously, with necessary nonlinearities, makes the verification of results essentially impossible. Such an application of our tool is presented in the next section.

Practical application in a selected region

Now, we would like to introduce the benefits of our tool through its more practical real-world data-based application.

Introduction to the case study

We follow on from the discussion about future WTE potential capacities in CZE as mentioned in Šomplák et al. (2012b) and Pavlas et al. (2010). Based on the classification above, CZE falls into the second group. There are 10.2 million inhabitants in CZE, and current waste generation reaches 2.93 million tons, i.e. the specific generation per capita amounts to 287 kg/year, which is below the EU average. There are three incinerators in operation with an overall processing capacity of 645 kt/year, another incinerator is under construction, and several more are planned to be built in the future. The recent WM concept presented

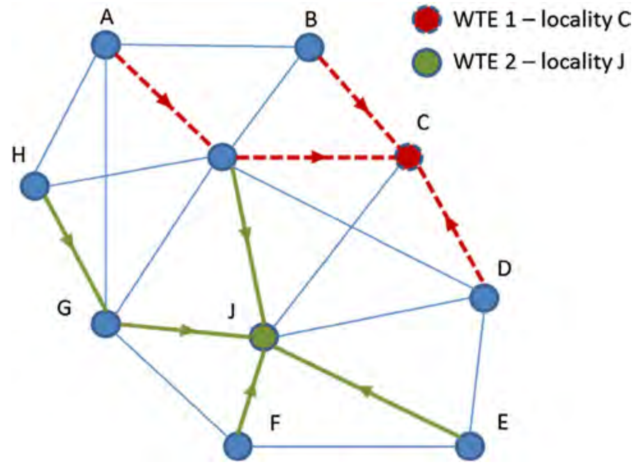


Fig. 7 Graphical representation of results of the simplified optimization task

by Pavlas et al. (2012) proposes up to 11 new WTE projects with an overall capacity of 2,200 kt/year after 2020 (see Table 4; Fig. 8). A small number of MBT plants and plants co-incinerating RDF are included as well. The total technical potential—of waste-based net power and heat production of 800 GWh/year and 14 PJ/year, respectively—is predicted for all WTE plants. The figure of 800 GWh/year may be compared with current power production from biomass, which reached approximately 1,500 GWh in 2012. The expected heat delivery may reach 16 % of the current heat delivered to end-users via district heating (DH) systems (2012 data).

In this paper, we are planning to go one step further in the analysis. We simulate the performance of this concept from an economic point of view with the help of our tool *NERUDA*.

Note: The country is characterized by a large amount of heat delivered by DH systems (88 PJ in 2012). Currently, heat is mainly supplied by coal-fired heating plants. New locations for WTE are associated with large cities where sufficient DH systems exist.

Calculations and Monte Carlo simulation

Since gate fee is the crucial input parameter in the model, we start this section with some comments on the methodology used for its generation. Constant values of gate fees are often considered in published papers and thus were also

Table 2 Definition of transportation network for simplified task–distance matrix

Edge defined by nodes	A B	A G	A H	A I	B C	B I	C D	C I	C J	D E	D I	D J	E F	E J	F G	F J	G H	G I	G J	H I	I J
Distance (km)	30	42	25	25	25	23	28	28	38	26	40	34	35	34	27	20	25	34	25	29	33

Table 3 Results of the simplified optimization task

Edge defining nodes	A B	A G	A H	A I	B C	B I	C D	C I	C J	Node with WTE plant	C	J
Amount of waste transported (kt/year)	30	42	25	25	25	23	28	28	38	Amount of waste treated (kt/year)	300	270

Table 4 Values of survival function for projects with capacities considered in the concept (scenario Sc2)

	X	**Y**	A	B	C	D	E	F	G	H	I	J	K	L
Planned capacity (kt/year) Pavlas et al. (2012)	**150**	**150**	171	220	285	96	190	180	270	95	452	220	140	163
Survival function $R(c)$ [%]	**2**	**43**	35	100	88	97	17	98	79	31	86	97	13	85

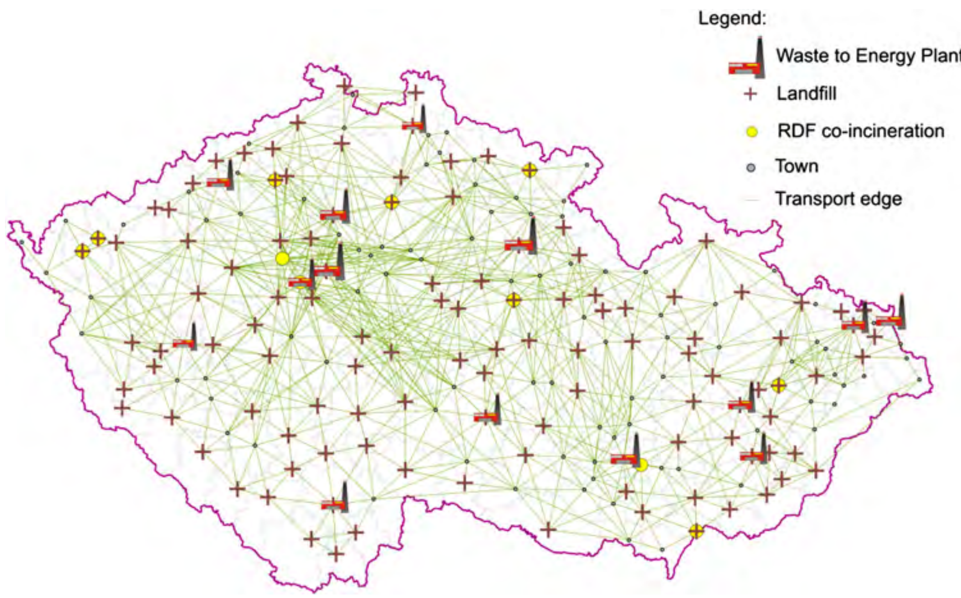


Fig. 8 Transportation infrastructure of the model with key elements for assessed concept

considered in our simplified task. In this case study, we take into account the economy of scale (see $p_i^{WTE}(C_i^{WTE})$ in Eq. 1), where the effects of falling specific capital costs with increased capacity can be observed. The gate fee function is generated separately for each project included in the assessment by external techno-economic models. The specific conditions in the locality (e.g. heat demand, heat price, existing infrastructure reducing capital cost) are taken into account as well. An example of capacity-dependent gate fee function is depicted in Fig. 9. The prices are projected onto 2020 (year of calculation) considering an annual inflation of 3 %. Let us briefly explain the meaning of parameter IRR in Fig. 9.

The sustainability and financial attractiveness of each new project are determined by many uncertain parameters (energy prices, waste quality, maintenance, unexpected power outages, etc.). All of these parameters have their own positive or negative effects on the project's cash flow and subsequently on the project's profitability, which is often expressed by internal rate of return—IRR. The sensitivity of IRR (under varying futures in uncertain parameters) can be tested under the assumption of a fixed gate fee with the use of complex techno-economic models. Vice versa, if IRR is fixed, we can investigate the sensitivity of the gate fee. We considered the same average IRR of 10 % for each competitive project in our case study, which is considered to be adequate revenue related to this industrial sector and expected by a private investor. To address the uncertainty, we as well set its minimum and maximum values to 8 and 12 %, respectively. The corresponding gate fee intervals are determined in the next step (see Fig. 9 as an example).

The optimization of the aforementioned objective function (Eq. 1) was repeated thousands times for varying combinations of gate fees at individual facilities. The gate fee for each calculation was generated by the Monte Carlo

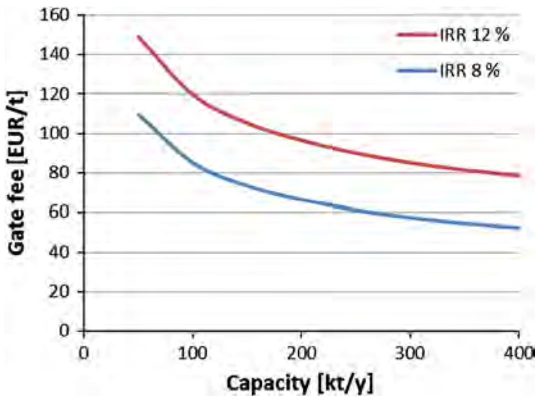


Fig. 9 An example of capacity-dependent gate fee function generated for one specific project. Uncertainty of future development in key economic parameters is addressed by varying internal rate of return (IRR)

method using the gate fee interval with the truncated normal probability distribution function. This stochastic approach, which may be considered a wait-and-see approach by terminology of stochastic programming (Birge and Louveaux 2011), allows for the subsequent statistical analysis of results.

Results

There is too limited space here to give a detailed description of all benefits of our *NERUDA* tool, and therefore we will now present only few examples of our results.

The first result is related to risk analysis, where two WTE projects to be located in different locations (denoted as X and Y) are compared. Figure 10 shows that they perform in a manner completely different from each other. The risk is expressed by survival function (see Fig. 10):

$$R(c) = P(\{C > c\}) = \int_c^\infty f(u)\mathrm{d}u = 1 - F(c). \qquad (9)$$

where $F(c)$ is the cumulative distribution function, and c is plant capacity. Function $F(c)$ is obtained from the results of a Monte Carlo simulation. In each run, one capacity c for the project was proposed as optimally reflecting the current gate fees of all competitors. The survival function $R(c)$ (complementary cumulative distribution function or reliability function) then expresses the percentage of experiments resulting in a capacity higher than capacity c. Moreover, two different scenarios related to legislation development were included (Sc1—promoting WTE only; Sc2—promoting both WTE and MBT). Under the assumption that the same capacity of 150 kt/year for both projects was proposed by the concept specified in Table 4, we conclude that project Y is less sensitive to future competitors, whereas project X is very risky and probably feasible only under specific circumstances resulting in a lower gate fee and subsequently in lower IRR.

One can speculate about the effect of an even higher landfill tax 80 EUR/t expected in our calculation in Sc1 and Sc2. This situation is depicted in Fig. 11 where the relationship between the risk and landfill tax is shown. The project in locality X remains high-risk even under conditions of a high landfill tax. Other methods to enhance its competitiveness have to be investigated (e.g. establish if it as a municipal project with lower return on investment expectations).

The survival function $R(c)$ was evaluated for each plant. The results for one scenario are presented in Table 4. The calculation also proposes collection areas for each facility, and therefore, maps the expected future flow of waste in

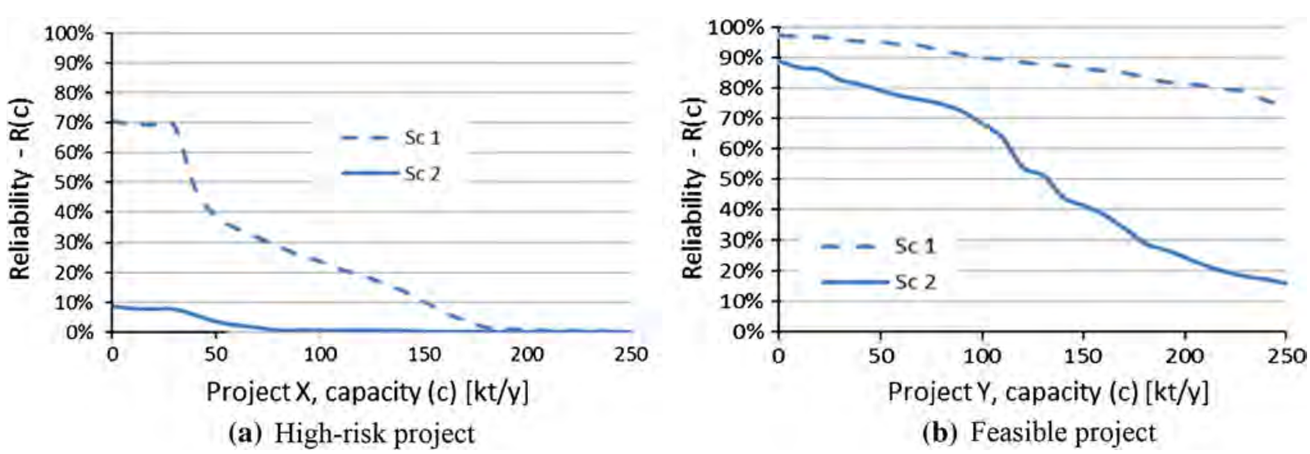


Fig. 10 Risk-analysis related to the reliability of capacity fulfilment performed on two projects in different locations for two different scenarios of future legislation development

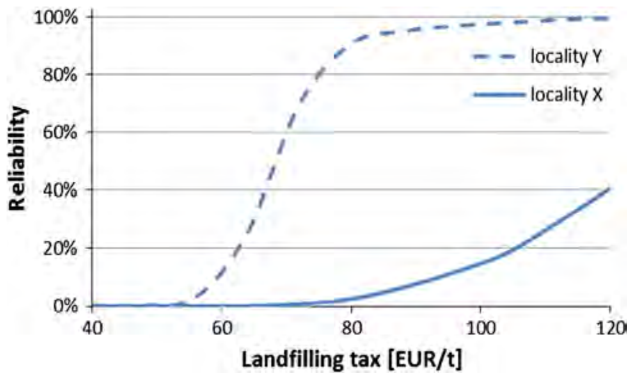


Fig. 11 Risk-analysis related to the reliability of capacity fulfilment performed on two projects under different landfill taxation rates

the region. This information is crucial for a survey of the traffic load and missing infrastructure planning. A graphical illustration of collection areas is depicted in Fig. 12. The layout fully corresponds to the proposed concept of WM; almost all WTE facilities are in operation. The majority of waste is incinerated directly; only a small portion goes through a MBT process and/or is landfilled. These streams are excluded to keep Fig. 12 clear.

The results prove the complexity of the task which has to deal with all locations simultaneously. We have demonstrated a sensitivity analysis of environmental taxation (Sc1 and Sc2). In the same way, waste calorific value, fuel prices, transportation costs and limitation, the situation in neighbouring countries (cross-border transport of waste) and other uncertain parameters can be included as well. There are two approaches available. We can model scenarios, or we can generate values from an interval. The first method was used for Sc1 and Sc2, the latter for gate fee modelling in our case study. For the each of further applications, the task can be adjusted with respect to the required targets of the calculation.

Further research and other *NERUDA* applications

Previous sections presented a logistic task and application of the model on a specific region and one type of waste. The task must be interpreted as motivational. The model is universal and may be modified depending on the assignment. Modifications include various locations and types of waste (the so-called multi-commodity problem), discussed in detail in (Ghiani et al. 2004). In general, the model may be applied to altogether different commodities. Several potential subjects may benefit from the developed tool, and they are given in Fig. 10. It is clear that end-users of the results (e.g. state administration, representatives of government, potential investors interested in new plants, operators of existing plants) will differ in their motivation and objectives and that the application must be always tailored to their needs. Future development of our tool (reflecting current demands) is expected as follows:

- Previous parts of the paper discussed a stochastic approach based on repeated calculations with adjusted input data according to defined scenarios. Reliability functions are generated subsequently (see Fig. 10). Obtained functions indicate risky and/or attractive

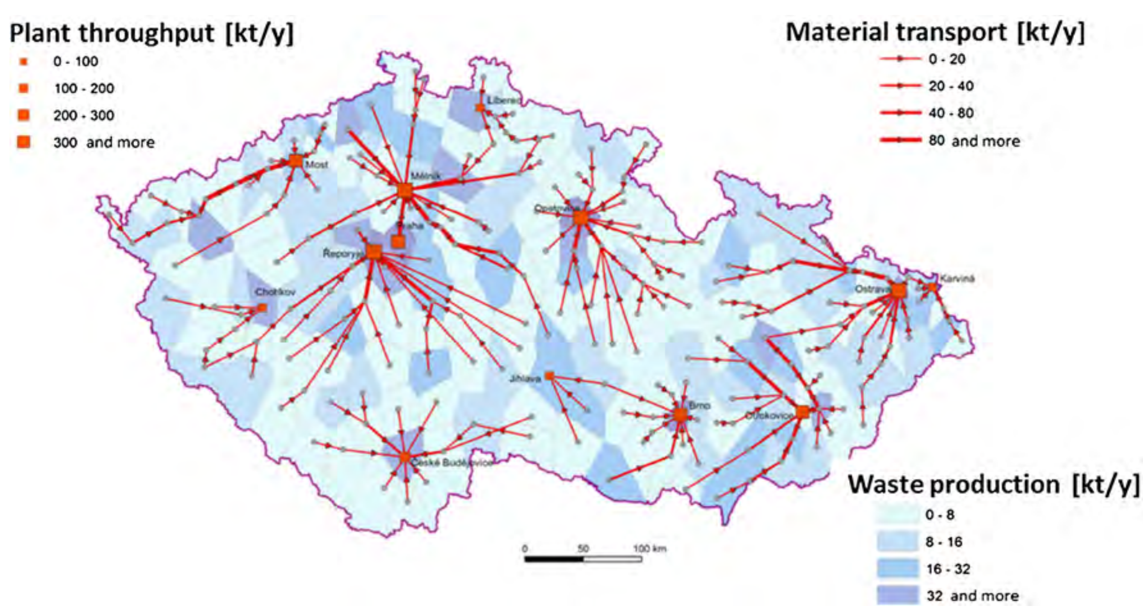


Fig. 12 Visualization of results of the transportation model for one particular scenario—high landfill tax introduced, energy produced in WTE supported by subsidies

projects. This approach is called a wait-and-see approach. We further plan to focus on the generalization and modification of our model to involve uncertain parameters in a more complex way, see (Huang et al. 2001; Birge and Louveaux 2011). This will lead to an improved methodology for risk assessment under uncertain future conditions.

- The calculation model described in this paper allows for simulation only for a single time-frame, i.e. a year. Our new and improved model will include sequences for several years, where calculation results from previous years constitute inputs and constraints for future years. Therefore, particular years of the simulations interact. This also enables modelling of long-term contracts between producers and operators.
- In all the previous points, the tasks are related to analyse waste flow on an annual basis. Such a calculation provides us with a conceptual insight into the problem. Once the promising patterns of the sender and the receiver are identified, a detailed analysis is expected. The whole logistic chain is optimized in terms of selecting the best transportation system and sizing it. The result is sensitive to many local aspects (fluctuation in waste production, local infrastructure, transport routes, loading and an increase in freight transport duration times due to transport accidents). These local factors must be considered in a task simulating a short time-frame (shipment on a daily basis). A typical application includes finding a location for transfer stations within metropolises and/or regions.

Conclusion

In the paper, the tool *NERUDA* for conceptual planning of new WTE capacities was introduced. By using the calculations results, WM policies can be implemented through legislation amendments. In addition, it is also possible to determine the attractiveness of potential sites for the construction of new facilities. Therefore, the proposed optimization model contributes to effective WM.

The model represents a transportation problem implemented in WM. Its practical application was demonstrated through a case study related to a specific region (the Czech Republic). A risk analysis of two WTE projects located in different areas was performed.

Another challenging task is the application of our tool for simulation and/or optimization of a developing and ever-growing EU waste market. The introduction of the model in large areas exceeding the borders of one country will inevitably increase the requirements/demand for input data.

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Research paper

A waste-to-energy project: A complex approach towards the assessment of investment risks

Tomáš Ferdan*, Radovan Šomplák, Lenka Zavíralová, Martin Pavlas, Lukáš Frýba

Brno University of Technology, Faculty of Mechanical Engineering, Institute of Process and Environmental Engineering, Technická 2896/2, Brno 61669, Czech Republic

HIGHLIGHTS

- Some regions of the EU will have to invest into thermal treatment in the coming years.
- Feasibility studies with risk analysis are major parts of the pre-project phase.
- New methodology for risk analysis based on a competition modelling proposed.
- Waste availability is one of the most important risk factor.

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ABSTRACT

This paper presents a complex methodology towards investment risk quantification in a waste-to-energy (WTE) project. It focuses on risks related to the supply of waste. A novel approach is proposed, where waste availability is assessed based on a complex simulation of future competition in the waste market.

The methodology takes advantage of complex calculation performed by the system NERUDA. NERUDA is a logistic-based optimization tool, which allocates processing capacities and proposes waste flows between producers and processors within modelled region. One original feature of the methodology is how the assessment is formulated, whereby the optimum collection areas are compared with a project's capacity. The new term waste availability factor is defined and used in the assessment. The practical implications of such an approach are demonstrated through a case study.

The results of this work support decision-making processes involved in new WTE projects. Since one of the major risks is a lock of waste availability, its evaluation represents an integral part of feasibility studies for WTE projects.

1. Introduction

Waste production, and its environmentally-friendly treatment, has become a worldwide challenge. The European Union (EU) has established a hierarchy of waste management based on the classification of various waste treatment methods with the prevention of waste is the foremost aim. Recycling methods and material recovery fall next in the waste treatment hierarchy. However, these methods are rather costly and do not allow for processing all municipal waste. Furthermore, the higher are the yield of these methods, the higher are the costs. Energy recovery from waste, i.e. recovery through incineration with subsequent use of the energy for production of electricity and heat, is employed if the above mentioned methods cannot be applied. Waste disposal without energy recovery and landfilling are the last resort.

It has been estimated that approximately 1.7–1.9 $\times$ 10^9 tonnes of municipal solid waste is produced annually worldwide. Only about 70% of this amount is actually collected within organized waste management (WM) systems, and only 20% is utilized (through energy or material recovery) in compliance with the EU waste treatment hierarchy [1]. However, some countries in Western Europe, such as Germany, Switzerland, the Netherlands, and Belgium, rank highest in the share of waste utilization, with numbers reaching as high as 80–90% [2].

WM in the EU has and will undergo major developments. Many countries have experienced a positive trend in the so called process

* Corresponding author.
E-mail address: ferdan@upei.fme.vutbr.cz (T. Ferdan).

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of decoupling, when an economy is able to grow without burdening the environment [3]. However, individual EU Member States are at different levels in their approaches to waste treatment.

Many EU countries, especially from Central, Southern and Eastern Europe, have agreed to decrease the amount of landfilled biologically degradable waste by 2020. This represents 50–60% of municipal solid waste produced in an area, and an increase in the share of material recovery from waste. The shift towards more efficient utilization requires the design of intelligent regional strategies together with investors' willingness to build and operate new incineration plants.

1.1. Modelling approaches toward efficient waste management systems

Many studies have discussed the topic of how sustainable particular WM solutions are, and compared them extensively.

One subsection of studies commonly deals with conditions in specific regions, and their conclusions are therefore locally-dependent. Evaluation methods for various WM technologies include supply-cost curves analyses [4] or life cycle assessments (LCA). Beccali in Ref. [5] applied LCA on a comparison of three WM systems; Kočí and Trečáková in Ref. [6] compared seven model systems using the LCA method. Margallo in Ref. [7] then introduced normalization and weighting procedure for the results of LCA studies.

Another group of the published studies present theoretical models and procedures aimed at finding the optimum arrangements integrating more technologies. An extensive review of modelling optimization techniques was published in Ref. [8]. Waste treatment optimizations are often calculated for large regions, and then try to propose the best location for WM facilities in a given area. However, this effectively tackles only waste transportation and the only criterion is the cost. An example of a multi-criteria objective function is given in Ref. [9] where two approaches are presented, which deals with sustainable system synthesis. Another example is using multi-objective mathematical calculations for decision making support in Ref. [10]. Interesting multi-objective optimization of WM in Mexico is used in Ref. [11] where it is used to maximize the net annual profit and minimize the environmental impact.

From a practical point of view, the currently available models dealing with these issues are often insufficiently interconnected, and very limited in their practical implementation. Researchers are now facing the task to make the computational methods more sophisticated and simpler. Lam et al. [12] reduced the connectivity in a biomass supply chain in order to lower the computational time. In a similar manner Ng [13] presented a clustering approach for optimizing industrial resources.

The recycling targets of the EU, should they be applied to all EU countries, are rather ambitious. The aim of the EU is to move all Member States up the waste treatment hierarchy, which is above all costly and of course unwelcome by the general public, especially if they should bear the costs. However, acceptance is one of the pillars of sustainability, as was resolved at the World Summit on Sustainable Development in Johannesburg 2002. In this context, WTE is a sustainable solution for many regions (in low-income countries) as it presents less ambitious targets and may be the first step in moving higher up the waste treatment hierarchy. WTE systems may bridge the gap in WM in Eastern European countries as well as create the chance for developing markets worldwide [14]. Even though those future obligations exist, it looks as though the current motivation driving investors' activity to move the projects from planning to their implementation phase is missing.

1.2. A successful waste-to-energy project – the basic requirements and feasibility studies

The construction of a WTE plant is a rather costly, complicated, and prolonged endeavour. Investment costs of a WTE plant and technologies range from 700 to 1000 EUR/t of annual capacity [15]. The preparation phase lasts 5 years at best but is usually longer [16]. Moreover, the life cycle of these plants lasts 20–30 years. To help future investors, several guides and manuals have been issued e.g. the World Bank presented general guide for evaluation of WTE plant [17] or more specific guide from Themelis [18] that deals with situation in Latin America. Despite the fact that the manuals were drafted for various countries over different periods, the basic principles and conditions remain the same, and are as follows:

- A stable planning environment (15–20 years), relatively stable and preferably foreseeable cost of spare parts, consumables, etc.
- Energy delivery contracts
- A relatively stable market and energy costs
- A reliable supply of suitable waste for the waste incineration plant
- The annual mean lower heating value of the waste cannot drop below 7 MJ/kg
- The support of stakeholders
- The acceptance of the plant from the general public and municipalities – good public awareness
- Support from the Government/legislators – landfill taxes/bans, bonuses, tax relieves, etc.

If all of these conditions and principles are met, a situation for the building of a WTE project is ideal. If any of these needs fall short of what is required, the project team has to rely on a detailed analysis that will prove the economic and technical feasibility of the project from the investor's point of view. The project has to be acceptable from the stakeholders' point of view.

Prefeasibility and feasibility studies are major parts of the pre-project phase. The contents of both of these studies are basically identical, but differ in input data and structure (see Table 1). The prefeasibility study is drafted using generally available data and references. The feasibility study must work with accurate information and data from a given location so that the project team may estimate relevant factors, evaluate project financing and identify a financing strategy as accurately as possible.

The risk analysis is one of the most important parts of the feasibility study. The risk analysis refers to the identification of the greatest risk sources, the risk's impact on the project's stability and financing, and/or measures taken to minimize the risk. An extensive risk analysis for WTE, established and run as a PPP project, is given in the study by Song [19] who identified various associated risks and classified them in ten major groups. These are: government decision-making risk, government credit risk, legal and policy risk, technical risk, contract change risk, environment risk, public opposition risk, waste supply risk, payment risk and revenue risk. Song [19] further describes a potential correlation of risks when a poor governmental decision-making process results in the selection of an inadequate plant location. This in turn may cause a failure to comply with environmental requirements, the dissatisfaction of local authorities, and the rescission of certain contracts.

1.3. Identifying and assessing investment risk

The basic structure of expenses and income given in Fig. 1 gives us a clear idea what the risk analysis should focus on. The particular parameters affecting expenses and income of the project significantly change throughout the life of the plant, and each parameter

Table 1
Content of WTE pre-feasibility and feasibility studies [18].

Pre-feasibility study	Feasibility study
• The potential location of the plant • The outline of waste collection areas, and basic information about the average composition of waste coming from different producers • Basic demographic information • Basic information about plant size, capacity and technology • A basic environmental assessment • An estimate of investment and operational costs and gains • Project organisation	• The potential location of the plant • The identification of the waste collection area, and detailed information about the composition of the waste • Demographic data for the given location • A stakeholders' analysis • Detailed energy market research: consumption, cost, competition • Plant design (size, capacity, technologies, etc.) • Full environmental assessment • Project organization – others • The identification of the plant's organization and management • Risk analysis and control

has a different impact on the final return on investment (ROI) of the project.

Expenditures do not usually fluctuate much and there is little risk unless the plant encounters a serious accident or has to face unexpected expenses. Risk is therefore associated with the revenue of a plant. Revenue includes income from the sale of electricity and heat (supplies into a system of central heat source or integration of the WTE facility with other commercial facilities). These sales are affected by price trends, and by the amount of the produced and exported commodity. However, the processing of waste is the most important income. This main revenue is then set by the gate fee price.

Song [19] discusses only information about the mere existence of the risks. Unfortunately, his work provides no quantification data on particular risks and/or the quantification of the risk's impact on the project returns indicators, e.g. the internal rate of return (IRR) and payback (PB) [20]. Pereira [21] and Li [22] both present quantitative data related to the risk, and analyse the risks using a Monte Carlo method applied on photovoltaics and wind farms, respectively. Various indicators help assess the quality of an investment project [20]. The outcome of the first article [21] is a net present value (NPV), and dynamic payback period (T_d) and IRR in the second article [22]. In both cases, energy is converted from renewable resources of energy (wind, sun). However, the availability of wind and sun is rather random, which affects production costs and interferes with the competitiveness of the plant. Therefore, statistical planning and scenario analyses must be employed in the assessment. A similar analysis of a WTE was outlined by Ferdan [23] who modelled the gate fee (price for waste processing) using variable input parameters; see Section 3.

1.4. The objective of the paper

High investment costs, uncertainty of profit (the availability of waste, price of waste processing, energy cost, etc.) along with competition from landfills, make WTE projects an ideal area for utilizing advanced simulation and evaluation techniques. Such a tool could provide the investor and stakeholders with all the necessary information for their decisions. All studies dealing with project planning and constructing WTE plants (e.g. the aforementioned Refs. [17–19]) list particular risks but do not mention any methodology for calculating input data for the risk analysis.

This paper presents the required methodology for a complex assessment of an investment project risk associated with future waste delivery and waste processing price. Regarding the gate fee, the intended project has to be competitive with the current treatment method. Future environmental taxation is also taken into account. In addition to this, the plant has to be competitive with any other intended projects in the area. With increased plant capacity, the collection area becomes larger and it can interfere with the collection areas of other projects (see Fig. 2). To secure the waste available within the collection area a competitive price should be proposed.

The objectives of the paper are: (1) evaluate the availability of waste – a key aspect in the project's success, (2) identify risks associated with waste shortage and assess. The proposed methodology contributes to resolving questions such as: the size of the waste collection area, and availability of the waste and its cost.

2. Methodology based on a competition modelling approach

The methodology proposed in this paper is focused on waste availability modelling and its evaluation. It is based on an innovative computational approach involving complex simulations of future competitive environments. For this a network flow optimization tool NERUDA is used. The approach comprises three interconnected steps (see Fig. 3). Step 1 and step 2 exploit the findings of our previous work which was recently published (see Sections 2.1 and 2.2). The main objective of this paper is step 3 – a newly developed simulation analysis focused on quantifying risks from a limited supply of waste (Section 3). The new term *waste availability factor* is defined within the framework of our methodology and used in the assessment. Competition modelling concerns several competing plants, whereas the subject of this analysis is one particular WTE plant.

Since the methodology takes advantage of the repetitive use of the NERUDA tool, let us first summarize its main features and

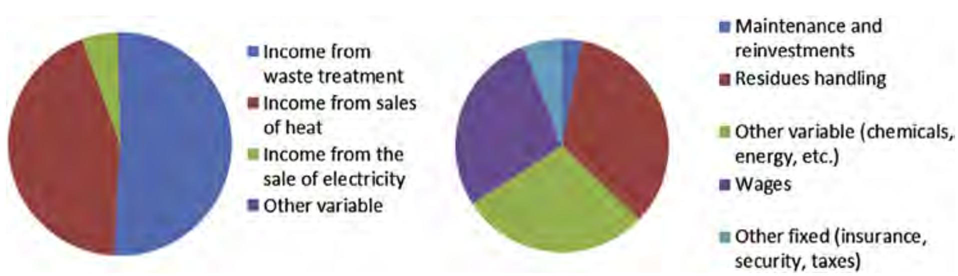

Fig. 1. An example of structure of incomes (left) and expenses (right), [%] [15].

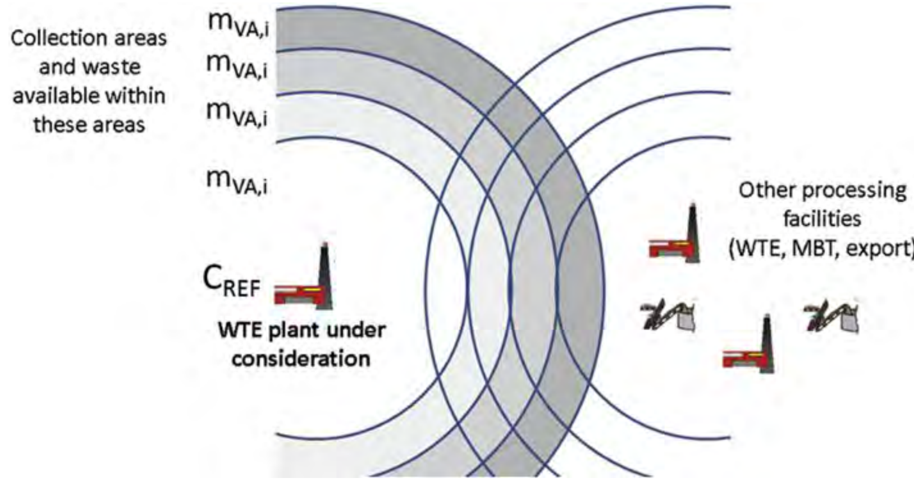

Fig. 2. Interference of collection areas resulting in a limited waste availability.

provide more details for predicting gate fees in relation to the objective of this paper.

2.1. NERUDA introduction and its basic features

NERUDA is a network logistic-based computational tool which simulates and optimizes waste flow from waste producers to processing facilities within a particular geographical area (region, country, etc.). These regions are then divided into many sub-regions represented by nodes. A detailed description of the tool, its main principles and equations forming the mathematical model, is provided by Šomplák et al. [24]. In the same paper, the model is first explained with a simplified example covering only a few nodes and then an extensive case study with more than 200 nodes is solved.

The tool contains data about basic waste producers (municipalities) within the sub-regions, the waste transportation network between nodes, and existing plants processing waste. The calculation is performed for all nodes (producers) simultaneously. The results of the calculation provide information about waste flows and allocate processing capacities. The tool is currently able to compare three types of waste treatment methods – WTE, mechanical-biological treatment, and landfilling, and the tool is open for further extensions. Moreover, the simulations take into account transfer stations where waste volume is reduced by pressing into containers. This decreases the costs of transportation over long distances. So far, road and rail transportation has been integrated in the software.

The tool further allows for us to evaluate investment projects and the competitiveness of new and existing waste processing facilities. NERUDA helps producers (municipalities) in a given region optimize waste treatment by employing the basic principle of minimizing the cost of waste treatment in this region. Generally, the application potential of NERUDA (see Fig. 4) is as follows:

- The design and optimization of waste management concepts at various levels of public administration

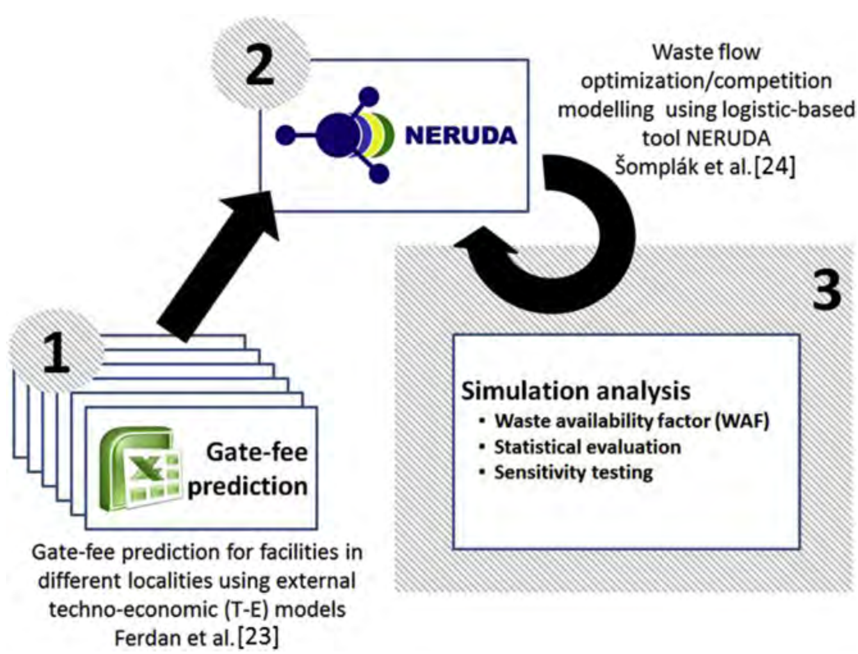

Fig. 3. The components of our waste delivery risk analysis methodology.

Fig. 4. Scheme of NERUDA software and components included.

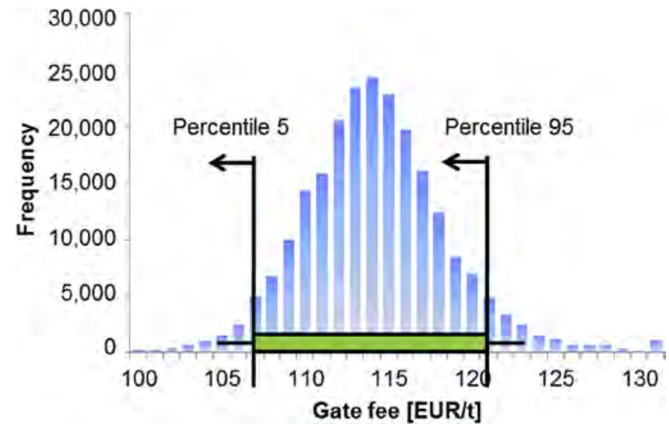

Fig. 5. A histogram of the gate fee distribution for a given capacity C_{REF} [23].

- A feasibility study of plant investments
- The optimization of waste transportation
- The complex modelling of waste market.

Calculations in NERUDA are influenced by a number of uncertain parameters which can be predicted only with difficulty. However, these parameters influence waste availability, plant economy, plant competitiveness and energy production, and therefore have to be considered and integrated in the simulations. This is done with a stochastic approach and scenario generation.

Following Fig. 3, calculations in the NERUDA software are an intermediate step in our methodology. Before the calculation, an interval of a suitable fee at a WTE gate is identified for all facilities included in the assessment. The desired return on investment is considered as well. Since we deal with the project preparation phase and future predictions, changes in key parameters, which affect the project economy, should be considered. This phase is called the "gate fee prediction" and it is introduced in the next section.

2.2. Gate fee prediction

Estimating the facility gate fee, using the desired returns given by IRR, is the foremost part of the whole methodology. We developed a "Flexi model" to help us here. A flexi model is a technical-economic model of a WTE plant which integrates an adjustable balance model of technology and a complex economic model. The flexi model allows us to set various configurations of technologies employed in modern incinerators, and then simulate the economic outlook for the whole duration of the project, see Ref. [23].

In order to identify the dependency of gate fee vs capacity, it was useful for us to apply a scenario-based approach. We used various scenarios to outline the development of major parameters which affect the project economy (energy costs, maintenance costs, etc.). The scenarios are generated using geometric Brownian motion. Real historic data, relevant to the location of the planned plant, are used for the scenario generation. Individual parameters are assumed to correlate with each other. We performed that many simulations to guarantee convergence. It was measured by several characteristic parameters of probability distribution (mean value, variance, kurtosis, skewness). Results were used to construct a histogram which displays the gate fee distribution. Fig. 5 gives a concrete example for a particular capacity.

The results of most of the proposed and simulated scenarios (C_{REF} = 150 kt/y) show that the gate fee ranges from 107 to 121 EUR/t. These values correspond with 5 and 95 percentile, and are displayed in Fig. 5.

The simulations were repeated for various C_{REF} capacities ranging from C_{MIN} to C_{MAX} (e.g. 50–400 kt/y in Fig. 6). A dependency graph of gate fee vs capacity is constructed using point estimates (Fig. 6).

The decreasing gate fee, together with an increasing capacity, reflects lower specific investments cost per ton of processed waste. This positive effect outweighs the negative effect of falling income from heat delivery (if measured in GJ per ton of waste incinerated). Our simulations in NERUDA also have to consider zero capacity (i.e. the NERUDA tool will not recommend building the plant). Problems with integer programming (switching between zero capacity and C_{MIN}–C_{MAX} interval) are overcome by an extrapolation close to zero capacity with extremely high gate fees. Therefore capacities in the range of 1–50 kt/y are never proposed.

Whereas two gate fee values related to 5 and 95 percentile for specific C_{REF} and IRR were presented in Fig. 5, these points are converted into two capacity-dependent curves in Fig. 6. There is a relationship between the gate fee and project profitability. Therefore, we present two sets of results. One result where the lower IRR of 8–10%, represented by the value 9%, is requested by a public investor (e.g. municipal project), and the other for meeting a private investor's requirements (IRR of 10–12%), represented by the value 11%.

The results presented are valid for one location (one facility). In order to simulate the competitiveness of the plant, the gate fee of competing plants must be specified, i.e. a similar prediction must be done for all locations. We introduced a financial plan for each location, considered specific local aspects, and then generated the gate fee curves. These enter the NERUDA calculation later on, when we incorporate additional payments and fees, such as landfill tax

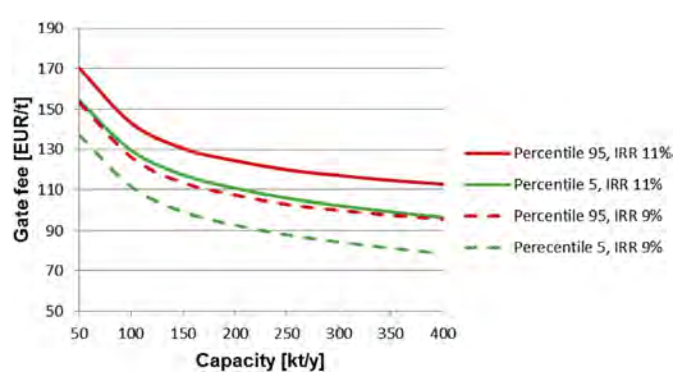

Fig. 6. The dependency of the gate fee and capacity–gate fee curves.

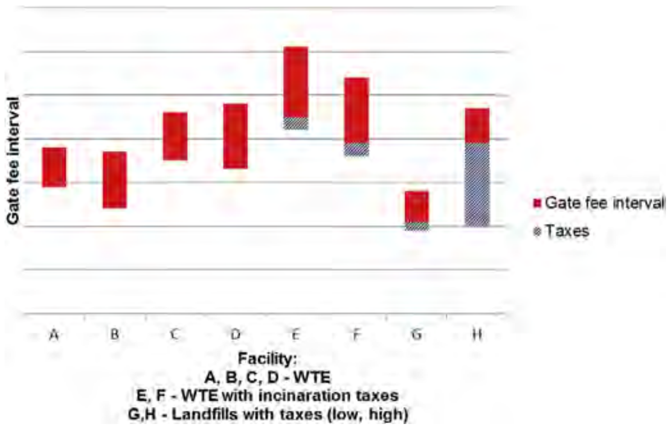

Fig. 7. Gate fees at various locations and environmental taxation – basic inputs for the NERUDA tool.

and incineration tax (see Fig. 7), by which market competition in waste management is simulated. The dependency of the gate fee against the capacity is a result of the first step and serves as an input for the competition modelling phase.

3. A simulation analysis for evaluating waste availability

Previous sections discussed conditions for the sustainable operation of a WTE plant and gave an overview of associated risks. One of the major risks is an adequate and constant supply of municipal waste, i.e. waste availability. Waste availability is mentioned in every paper which deals with risk analyses and WTE project evaluation. However, none of these papers actually present a principle for determining waste availability. This is obviously a precondition for a quantitative risk assessment and any identification of a risk's impact on the project's finances (using, for example, an IRR indicator).

3.1. Waste availability and waste availability factor

We decided to formulate a new criterion called *waste availability factor (WAF)*, and to incorporate it in our methodology. This new criterion helps quantify and display the effect that changes to various parameters (such as capacity, landfill fee, and IRR) have on waste availability.

Before we proceed to explain the calculation of the WAF, we want to clearly define the parameters which are evaluated by the NERUDA software:

- C_{REF} – reference capacity. The capacity of the plant which is subject to a risk analysis.
- C_{MAX} – maximum project capacity. The maximum capacity is identical with the value of CREF before individual iterations, and is relaxed during the simulation analysis described in the following section.
- C_{OPT} – optimum capacity – the calculation result obtained in every calculation step. This is the sum of waste transported to the plant from several subregions.
- m_{WA} – waste availability – amount of waste produced within a specific geographical area. This amount may be a subject-matter of future negotiations between producers and processor. Both the producer and the waste processor must agree on the cost of waste processing (the gate fee), and only then can they enter into a contract. The facility operator offers the cost of waste processing, and the waste producer opts for the best price on the market. In other words, waste availability is a sum of municipal waste production in the municipalities which find the proposed gate fee as the cheapest alternative.
- Waste availability factor (WAF) – the ratio between waste availability and planned reference capacity C_{REF}; defined by equation (1). The calculation of WAF is discussed as a simulation analysis in the following section.

$$W_{AF} = \frac{m_{WA}}{C_{REF}} \tag{1}$$

An example of the calculation is shown in Section 3.3 in addition to a graphical representation of the parameters used to calculate the WAF. The capacity C_{REF} is set before the calculation and the capacity C_{OPT} is the optimum obtained from the NERUDA calculation for each scenario.

3.2. The basic principles for determining WAF

The simulation analysis is based on the tool NERUDA and provides us with a quantification of waste availability and/or WAF criterion. Šomplák [24] gives the basic principle of calculations in NERUDA. A shortened description is as follows: The capacity of existing projects is given. The optimum capacity C_{OPT} of all new projects in locations (i) must be identified; the gate fee is related to capacity via functions similar to Fig. 6. This principle is presented in Fig. 8. The capacity of individual projects may be limited by C_{MAX}.

We slightly modified the basic principle to accommodate the risk assessment. Waste availability is analysed for a given capacity (C_{REF}). The basic principle is governed by the following maxim: waste is available if the waste producers have no cheaper alternative for processing their waste.

Calculations are commonly carried out as a stochastic simulation, but for now we will not consider any scenarios. We present a procedure for a simulation run (further marked as a point in Fig. 10) which consists of the following steps:

- The capacity of an evaluated location is given as $C = C_{REF}$. The gate fee (GF_{REF}) is assigned to this capacity. The fee is fixed throughout the calculation.
- The gate fee is dependent on capacity ($GF = f(C)$) in other locations (competing projects). Capacity C_{OPT} is unknown (it is a variable) and the gate fee is given by a gate fee curve as in the basic calculation (see Fig. 6). The waste processing cost was estimated using a technical-economic model for all waste processing projects (see Section 2.2).
- Waste availability at a fixed cost GF_{REF} is analysed later. For now, the capacity is unknown, the C_{MAX} limit is relaxed (the capacity is theoretically unlimited), and we search for the optimum amount of waste mw that is available at this price. This optimum

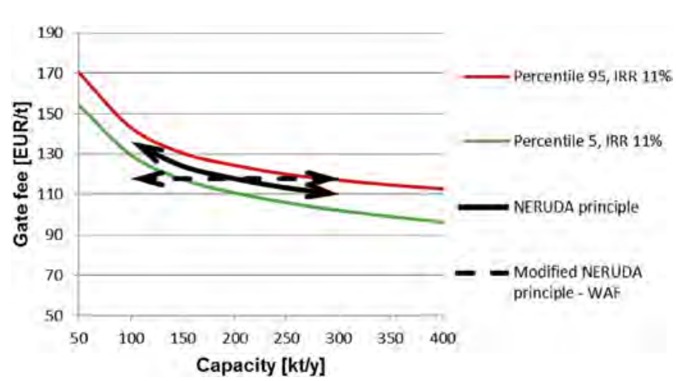

Fig. 8. NERUDA principles.

amount is then defined as waste availability m_{WA}. The calculation scheme is illustrated by horizontal arrows in Fig. 8.
- The WAF is evaluated using equation (1).

If the waste availability m_{WA} is higher than the reference capacity (C_{REF}), the project is sustainable and complies with the requirements for profitability, and the WAF is higher than 1. If the waste availability is lower than the reference capacity, the facility does not have an adequate amount of waste at GF_{REF} fee (WAF is lower than 1, see Fig. 9 and for more details Table 2). In order to obtain enough waste, investors should expect a lower gate fee, which decreases their income and consequently the returns too (IRR). We calculated WAF for various IRRs so that we can demonstrate the dependency of waste availability on project returns. This solution allows us to simulate various types of ownership arrangement.

3.3. An example of WAF calculation

To clearly demonstrate how the calculation of WAF works with NERUDA, we present a simple case study. The whole geographical region (country, state, etc.) is divided into 41 nodes (municipalities, cities, etc.), see Fig. 9. Each sub-region is characterized by its residual waste production, which at the same time represents waste available for thermal treatment with WTE. The plant (the subject of the risk analysis) is placed in node 8 in this particular case, see Fig. 9. Its competitors are not displayed for simplicity. The computation in NERUDA was carried out and we obtained results from 500 simulations (various gate fees for other projects). We present the results for two particular scenarios, see Fig. 9. The data for those 2 scenarios are presented in Table 2.

In each scenario, the NERUDA tool proposed a collection area (see Fig. 9). Waste from other sub-regions is treated in different facilities. Following this, we the amount of waste transported to the facility. This is amount is identical with the optimal capacity C_{OPT}, which was provided by NERUDA. The WAF is then calculated using the equation (1). The total waste transported to the facility in scenario 1 is lower than the reference capacity, therefore WAF is equal to 0.80. In the other scenario the amount of waste exceeds the reference capacity and WAF is 1.28. The results are displayed in Table 3.

3.4. A stochastic simulation to determine WAF

Compared to the previous simplified example, we now wish to present a more complex analysis here which incorporates various

Table 2
Input data for calculating WAF as received from the simulation analysis using NERUDA tool.

Node	Waste delivered to the facility		Transportation cost	Scenarios
	Amount [t/y]	Price [EUR/t]	[EUR/t]	
1	1,742	67.72	7.4	Scenario 1; Reference capacity C_{REF}; Scenario 2
2	10,620	67.72	4.9	
3	2,783	67.72	3.1	
4	7,801	67.72	6.1	
5	10,470	67.72	2.9	
6	5,323	67.72	6.2	
7	4,120	67.72	5.6	
8	12,521	67.72	0.2	
9	5,398	67.72	4.5	
10	51,384	67.72	3.7	
13	4,534	67.72	6.7	
15	2,825	67.72	10.7	
11	1,827	67.72	10.1	Reference capacity C_{REF}; Scenario 2
14	5,678	67.72	10.3	
16	1,523	67.72	10.8	
17	5,225	67.72	11.4	
19	14,350	67.72	11.9	
20	1,874	67.72	12.5	
12	3,898	67.72	10.5	Scenario 2
18	5,347	67.72	12.5	
21	4,674	67.72	12.6	
22	599	67.72	13.3	
23	6,946	67.72	12.6	
24	17,210	67.72	14.8	
25	3,120	67.72	12.0	

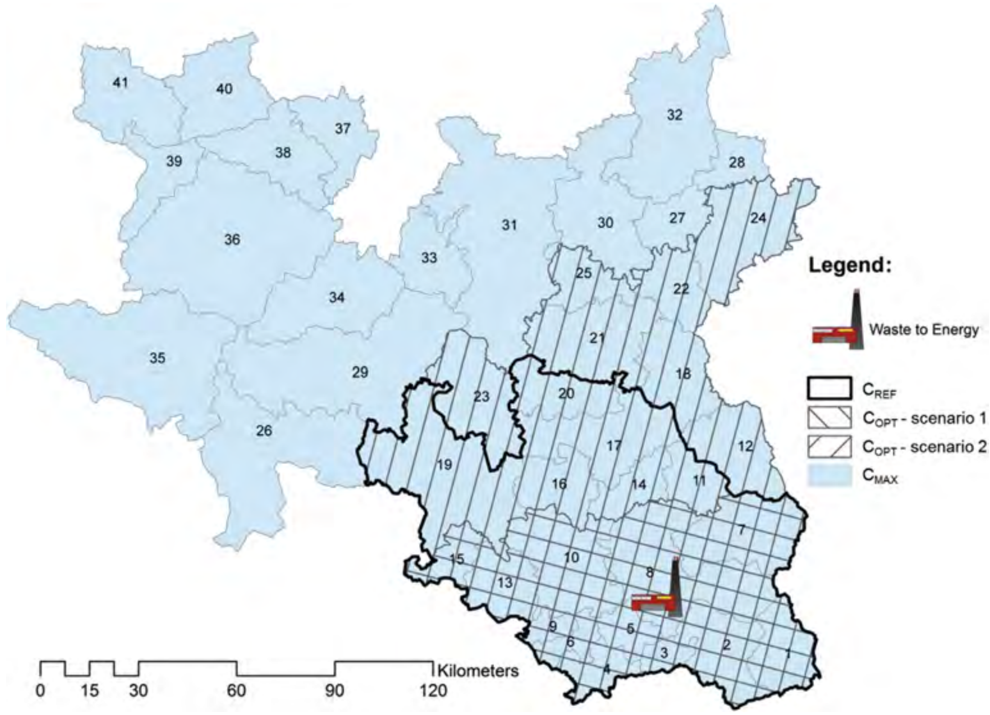

Fig. 9. A graphical illustration of two proposed collection areas for two different scenarios.

Table 3
Waste availability factor calculation.

Parameter	Total waste [t/y]	Reference capacity [t/y]	WAF [−]
Scenario 1	119,522	150,000	**0.80**
Scenario 2	191,795	150,000	**1.28**

uncertainties embodied in the scenarios. The capacity of the project may not be decided at this stage of the project development, and, therefore, it may be useful to analyse WAF for different reference capacities C_{REF}. We simulated the scenarios where C_{REF} ranged from 100 to 350 kt/y (six scenarios, each with a 50 kt/y increment). Likewise, legislation trends on landfill fees are also unclear as the fees may range from 37 to 81 EUR/t (seven scenarios, each with an 8 EUR/t increment). In total, we simulated 42 scenarios (i.e. combinations of various capacity solutions and various landfill fees). We simulated 500 situations for a particular scenario; the gate fee from a predefined interval was randomly generated for all projects (see Section 2.2).

Fig. 10 displays the sensitivity of average WAF to the changing capacity C_{REF}. The results are valid for a 75 EUR/t landfill fee. Two options for desired returns were evaluated: IRR ranging from 10 to 12%, and 8–10%. The results are presented further.

The project with lower IRR requirements (an IRR of 8–10%) produced better results for all capacities compared to requirements for higher returns (an IRR of 10–12%). The waste availability factor rises along with the rising capacity for both IRRs, see the graph in Fig. 10. The project has enough waste, obtained at a gate fee corresponding to 8–10% IRR, if capacities exceed 150 kt/y. However, a further increase in capacity does not result in an increase in WAF. The advantages of higher gate fee are outweighed by the need for a larger waste collection area and higher transportation costs. Competition from other plants also becomes fiercer as the waste collection area enlarges. Compared to the reference capacity (C_{REF}), the project has a capacity reserve of roughly 25–30% for capacities exceeding 150 kt/y. If the investors require higher returns (IRR of 10–12%), the analyses prove that the waste availability at a given reference capacity (C_{REF}) is inadequate for all scenarios. A facility with capacities exceeding 200 kt/y has only 80% of the required waste available.

Since the calculations were carried out in a stochastic model, we may analyse the results in greater detail. Let us now focus on capacity $C_{REF} = 150$ kt (see the black points in Fig. 10). Fig. 11 displays a histogram of the amount of available waste (m_{WA}) which was calculated in particular simulation runs. The results of waste availability at IRR = 10–12% clearly show that most of the simulations (95%) estimate that the waste availability for C_{REF} of 150 kt/y will be lower than the reference capacity; only 5% of simulations estimate sufficient amounts of waste. These values correspond with an average waste availability factor of ca. 0.4 (see Fig. 10).

We constructed a similar histogram for IRR = 8–10% (see Fig. 12). Most of the simulations (81%) proved that there is enough waste available. The rest of the simulations (19%) showed a lack of available waste. Incidentally, the two scenarios mentioned in

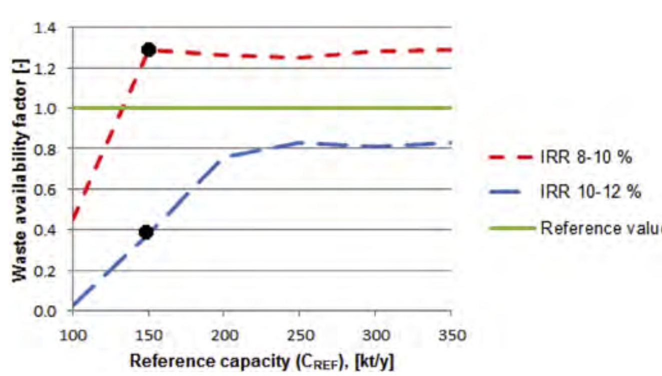

Fig. 10. The dependency of average WAF and reference capacity.

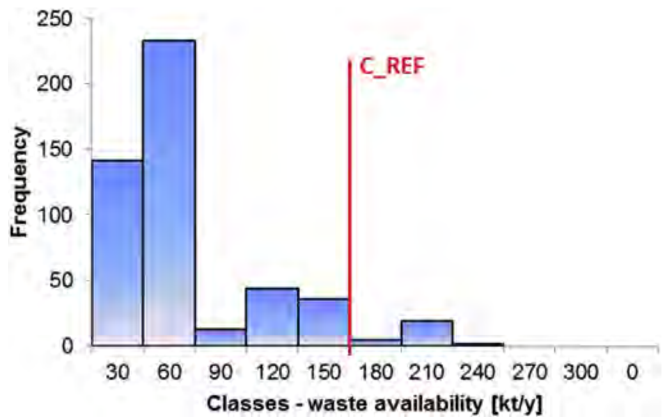

Fig. 11. A histogram of waste availability for IRR of 10–12%.

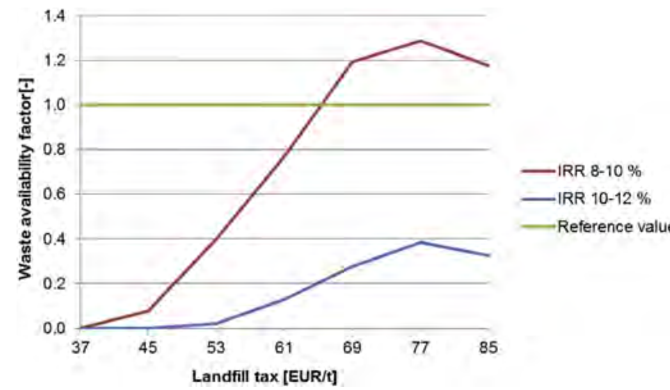

Fig. 13. The dependency of WAF and landfill tax.

Section 3.3 are displayed in Fig. 9 as well. Here we may analyse risk factors and/or a set of boundary conditions affecting the results.

The results proved that if the plant had insufficient amounts of waste (WAF lower than 1), a relatively small decrease in gate fee (lower requirements on return of investments) significantly increased the probability of meeting the capacity (i.e. having sufficient amounts of waste). This gate fee – waste availability dependency is unique for each project, and reflects concrete locations and competition in the close vicinity of the plant.

3.5. The impact of other parameters on WAF

An assessment into the impact of a particular parameter is a different type of simulation results analysis. Fig. 13 displays the dependency of waste availability and landfill tax. The results were calculated for a reference capacity (C_{REF}) of 150 kt/y. Again, we analysed two options for potential returns: an IRR of 10–12%, and IRR of 8–10%. The decrease in waste availability for 81 EUR/t landfill tax is caused by tough competition from other projects, especially those based on mechanical-biological waste treatment technologies. The results presented in Fig. 13 are average values of all simulations with relevant boundary conditions (scenarios).

For returns higher than 10%, waste availability is very low (max. factor of 0.4) even for a landfill tax fee of ca. 75 EUR/t. If returns drop below 10%, waste availability is satisfactory for a landfill tax rate of ca. 63 EUR/t. If the landfill tax equals 75 EUR/t, the project has a ca. 30% waste reserve above the reference capacity C_{REF}. The

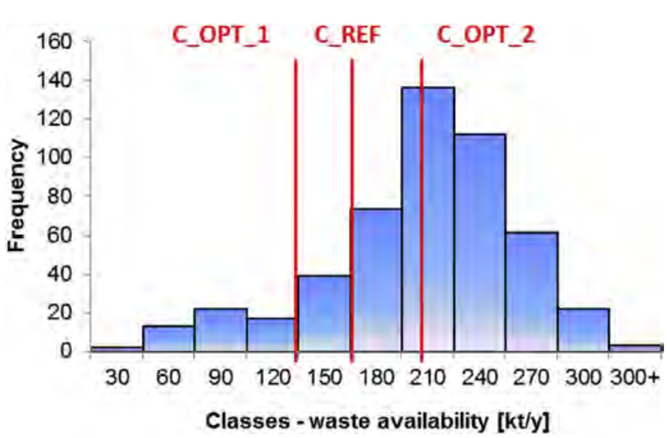

Fig. 12. A histogram of waste availability for IRR of 8–10%.

results may again be analysed in greater detail (as for Figs. 11 and 12). We may identify the factors which impose a risk on waste availability and economic sustainability. We shall deal with these issues in the following section.

The previous parts of the text discussed the relationship between the gate fee and waste availability. Many other risks are associated with the gate fee. The project must be successful, and for example an increase in operational costs must be compensated with an increase in income. The gate fee, therefore, reflects a certain scenario and must provide the project with a sufficient amount of waste. The scenario is a combination of developing parameters (risk factors) which may impose a risk on the project.

4. Conclusion

In this paper a novel methodology was proposed for a complex analysis of risks associated with limited waste delivery. The formulated methodology comprises three steps, which are logically linked and make up a thorough system.

The first step in this methodology is identifying the dependency of the gate fee in relation to the capacity for several facilities. These are derived from complex techno-economic models addressing technology- and locally-dependent parameters.

A major element and important computational tool is the software NERUDA, which is used for simulating waste flows, allocating processing capacities and determining collection areas (step two). The subject of the calculation is a particular region. Regarding its application, the basic features of NERUDA were introduced.

The last step in our proposed methodology comprises a simulation analysis. The algorithm of the analysis was formulated in Section 3. It is based on the repetitive use of NERUDA tool in order to properly simulate the waste market competition. The collection areas were proposed for relaxed project capacity. The new term waste availability factor was defined, which is later used as the main criteria for risk evaluation. The evaluation of this factor is first comprehensively demonstrated for two particular scenarios. Finally, the results of a complex stochastic-based analysis are provided which incorporated various uncertainties embodied in the scenarios. This was done in order to justify the practical implications of this approach.

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Contribution to Global Warming Potential by waste producers: Identification by reverse logistic modelling

Radovan Šomplák [a, *], Martin Pavlas [a], Vlastimír Nevrlý [b], Michal Touš [b], Pavel Popela [c]

[a] Sustainable Process Integration Laboratory – SPIL, NETME Centre, Faculty of Mechanical Engineering, Brno University of Technology – VUT Brno, Technická 2896/2, 616 69 Brno, Czech Republic

[b] Institute of Process Engineering, Faculty of Mechanical Engineering, Brno University of Technology, Technická 2896/2, 616 69 Brno, Czech Republic

[c] Institute of Mathematics, Faculty of Mechanical Engineering, Brno University of Technology, Technická 2896/2, 616 69, Brno, Czech Republic

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An overview of relevant literature shows how supply chain and network flow models represent useful tools in the area of clean energy generation and processing related waste. This paper deals with a specific network flow problem where the mixed municipal waste as a secondary and partly renewable energy carrier is transported from waste producers (municipalities), through pre-processing facilities, to its final treatment in waste processing units and in which the optimal flow is desired. The results obtained for the minimum total costs, including treatment and transportation, correspond to production and savings of a certain amount of CO_2 and other greenhouse gases which is described by Global Warming Potential (GWP). The average cost was 74 EUR/t and average GWP was 37 kg CO_{2eq}/t. The GWP contribution varies among the waste producers as a result of treating waste in different places and various technologies. However, to identify the individual contributions, the detailed waste flow identification is required. The flow distribution is unknown due to the effect of merging and splitting waste streams in the network. For this reason, a consequent network flow problem for exact waste flows identification is proposed. The model follows the principle ideas of multi-commodity network flow modelling and it reveals the variability of cost and GWP contribution for all producers in the investigated area. The proposed method has been tested through a case study considering treatment of mixed municipal waste. The results obtained by the original implementation in GAMS are presented and discussed in detail. The GWP contribution varied between −173 and 880 kg CO_{2eq}/t and significant waste producers were identified in the network regarding GWP. The results are important for setting the target for emission reduction in individual regions and for particular producers. The principle can be applied in general to any commodity and network flow problem.

1. Introduction

Applied research in waste management can be considered as a current and rapidly developing theme in process engineering. Related problems have been studied in different areas, such as dealing with municipal solid waste in Bidart et al. (2013); cost-effective waste collection using routing problem solver tool of ArcGIS in Khan and Samadder (2016); sustainable supply in Young et al. (2012); distribution of waste and treatment technologies within the mega-city in Thikimoanh et al. (2015); efficiency of energy recovery in Grosso et al. (2010); recycling validity in Velis and Brunner (2013); Life Cycle Assessment and mathematical programing is used for highest environmental impact prevention from food waste in Cristóbal et al. (2017); waste-to-energy facility planning in Pavlas et al. (2010); the economic, environmental, and social perspectives for a municipal solid waste management is modelled in Habibi et al. (2017); the sustainability requirements with the same criterions were studied in Asefi and Lim (2017) while the multi-objective approach was carried out using ε-constraint; a systematic approach for an integrated recycling and disposal network for municipal solid waste is analysed in Harijani et al.

Abbreviations: WTE, waste-to-energy; MBT, mechanical-biological treatment; W, waste; CW, compressed waste; RDF, refused derived fuel; RL, railway; CWRL, compressed waste via railways; LND, landfill; TR, transfer station; RDFP, refused derived fuel plant; GWP, global warming potential; GHG, greenhouse gases.

* Corresponding author.
E-mail address: Radovan.Somplak@vutbr.cz (R. Šomplák).

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(2017). The paper Kurdve et al. (2015) study how operations management and environmental management can be integrated on an operational level including the waste management supply chain. Challenges related to optimizing waste management are discussed in Juul et al. (2013). An important topic in waste management is the transport of waste. A comprehensive review was published by Bing et al. (2016) which focused on logistic issues, applied modelling techniques and research opportunities. The transport of waste from its producers to processing facilities is categorized as a reverse logistics problem, where the optimal results are named as a convergent network structure (i.e. waste generated by many producers is shipped to a small number of processing plants). Novel ideas of reverse logistics are also mentioned by Ferri et al. (2015).

This paper presents detailed information about recent improvements of a large-scale reverse logistics optimization tool (see section 2.1). It deals with the phenomena of tracking waste flows and related greenhouse gas (GHG) emissions from a single producer to the final processing location. It extends the ideas of the paper by Šomplák et al. (2015) which discussed the fundamental principles and by Pavlas et al. (2017) where the forecasting of waste is performed, while this paper improves and enhances the results and analysis further.

The effort is put on the analysis of produced emissions in particular nodes of the network. The Global Warming Potential (GWP) has been selected as an indicator used in this study. However, also other criteria may be used, see Čuček et al. (2012). The focus is on emissions produced by specific producers in logistic tasks considering the allocation of waste from individual edges. Such an analysis is important for identification of bottleneck waste producers in the network regarding GWP contribution. The results are important for setting the target for emission reduction in individual regions and for particular producers.

2. The problem statement

2.1. The flow and capacity allocation problem

The strategic decision making in the field of waste management is a useful tool. Such an approach was introduced by Šomplák et al. (2014), where the basic idea was presented in a mathematical model with application on waste-to-energy (WTE) plant location and its capacity allocation within a specific geographical region. In another work by Ferdan et al. (2015), it was used for a comprehensive evaluation of a proposed plant in terms of waste availability and associated investment risks. The tool follows and improves network flow modelling ideas applied to waste management, see, e.g., Gottinger (1986) for references to its beginnings. The main part of mathematical modelling in waste management belongs to a class of specialized reverse logistics models, see Ghiani et al. (2014) for detailed survey. These models can simulate a competitive environment among producers or facilities in waste management, see Bazaraa et al. (2010) for an overview of utilised concepts from the area of network flows and linear programming. In this way, also waste treatment strategies can be optimised in a specific region from a waste producer's point of view (including economic and environmental aspects), since the region is divided into numerous nodes. The energy concept of cities is also integrated through demands on heat in district heating systems in candidate locations and their profiles during the year. The network can combine roads and railways. Various waste treatment technologies were analysed and the uncertainty was included.

From a process engineering point of view, the use of various mathematical programming approaches allows to develop and extend computational modules. However, the extensive supply of input data is needed. These modules need various technological and economic data, such as: (1) geographical information systems, and related logistic data; (2) landfilling data; (3) waste-to-energy processing data; (4) waste separation related data; (5) recycling based data; (6) MBT units data; (7) transfer stations related data; (8) scenarios based on legislation requirements; (9) economic parameters (prices, taxes, specific funds, etc.); (10) ecology impact evaluations; and (11) quantified European strategy of waste management development. The data are transferred from databases into computational modules, thus feasibility studies and subsequent optimal local strategies are computed and visualised.

Recent practical applications have also revealed the need for further extensive analysis of processing costs and emission produced. Especially the GWP contribution as a modern indicator should be further analysed. This problem is first introduced in section 2.2. Next, there is a related discussion and developed modelling approach enabling tracking the waste on its way from producer to treatment facility in sections 2, and 3 described in detail, respectively. The final part in section 4 demonstrates the practical implications of such an approach through a case study.

2.2. Identification of producer-facility waste flows within the network

The next challenge is linked to the problem that involved producers and treatment facilities compete among themselves. The results of this competition can be evaluated by a comparison of overall waste treatment costs, i.e. the sum of processing costs and transportation costs for each producer. However, the important aspect is not only the cost, but also the identification of the emission footprint from individual waste producers – GWP contribution. Of course, it is based on the mean of transport or the waste treatment method. It is obvious, that the environmental milestones are very often in contradiction with the economic point of view.

However, the results from the aforementioned flow and capacity allocation problem provide us with only information about the total waste flow along edges, capacities of the treatment facility (amount of processed waste), gate fees and the emissions produced in particular facility. Regarding the particular producer, information about a waste flow through the network is not available due to reasons stated later on. This is acceptable within the framework of a global and/or regional analysis, e.g., for governmental purposes. It is obvious that the solution to the facility location problem does not necessarily represent such information because the waste flows from different waste producers can merge and split again (see in Fig. 1). Thus, the information about the original source of the specific waste flow can be lost.

The real industry solutions and so the waste flow follow currently the economic aspects and legislation rules. Such an approach is also used in the illustration. The resulting production of emission is calculated hereupon and it is just a consequence of the economic decision. This problem is demonstrated by using a simple network shown in Fig. 1. The cost and emission terms used in this

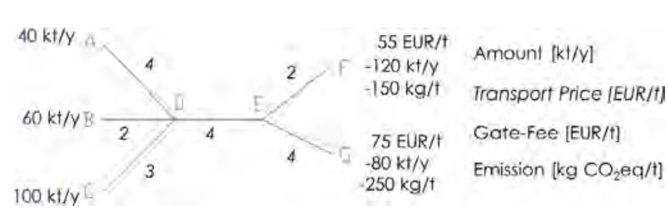


Fig. 1. A simple network to demonstrate difficulties in identifying flows.

illustrative case and also in Section 4 are inspired by the values and ranges reported in detailed analysis by Šomplák et al. (2015) (treatment cost ranges for WTE), Gregor et al. (2017) (waste transportation cost) and Ferdan et al. (2017) (GHG emission from treatment and transportation of waste).

Waste from producers A (40 kt/y), B (60 kt/y) and C (100 kt/y) flows separately to node D (at a transportation cost of 4 EUR/t, 2 EUR/t, and 3 EUR/t) and then together to node E (costing 4 EUR/t). In node E, the waste flow is split up and the first part goes to node F (costing 2 EUR/t), the second part goes to node G (costing 4 EUR/t) to satisfy their allocated capacities of 120 kt/y and 80 kt/y in nodes F and G, respectively. Additionally, the gate fee for processing the waste is paid in F and G with unit costs of 55 EUR/t and 75 EUR/t. Regarding transportation, the GWP is considered as constant 0.06 kg CO_2eq/km·t. At node E, the information about waste flow direction from a particular producer is lost (A, B or C). From the solution of this simple transportation problem, we only get the obvious information about total waste flows along the edges (the flows from A, B and C comes to 200 kt/y at edges D-E and they split into 120 kt/y and 80 kt/y amounts at E). Therefore, we do not know at what ratio the waste from a particular producer is split up into the node E. There are various possibilities, see Fig. 2 for two of them.

For the first one, producer A delivers waste to F and pays 2.6 mil. EUR/y and GWP is 5976 kg CO_2eq/y, which is the average price and specific GHG production of 65 EUR/t and −149.4 kg CO_2eq/t, respectively. For the second one, producer A delivers waste to G and pays 3.48 mil. EUR/y and produces 9971.2 kg CO_2eq/y, which is 87 EUR/t and −249.28 kg CO_2eq/t. In both cases, the overall objective function (overall processing cost for the examined system) is fixed at 14.54 mil. EUR/y and overall GHG production is −26,892.6 kg CO_2eq). In fact, there is an infinite number of such flow options, so the total cost and flow are the same while the cost, emissions and flows for the producers vary.

2.3. Applications for real problems

It should be emphasized that our artificially developed situation from the previous section occurs for the real world data. Fig. 3 illustrates the resulting network for a specific region (the Czech Republic and selected neighbourhood areas) and model dealing with complex waste management planning. There are several situations locally similar to Fig. 1 in Fig. 3, specifically, see the thick blue edge in the detailed view of the northern part.

For this reason, the arisen situation motivates us to further deal and handle the challenge through our original utilization of multi-commodity network flow ideas combined with suitable post-processing in the next sections.

Problems related to the above-mentioned solution's uniqueness have been studied in different engineering application areas, see (Xu, 2010) for maximum flow problem with multiple solutions. However, none of the so far published papers considered the general flow problem with splitting and merging. This paper developed an approach for handling the complex problem and it is considered

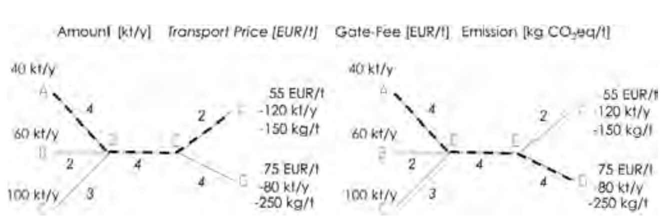


Fig. 2. Different solutions for producer A in a simple network.

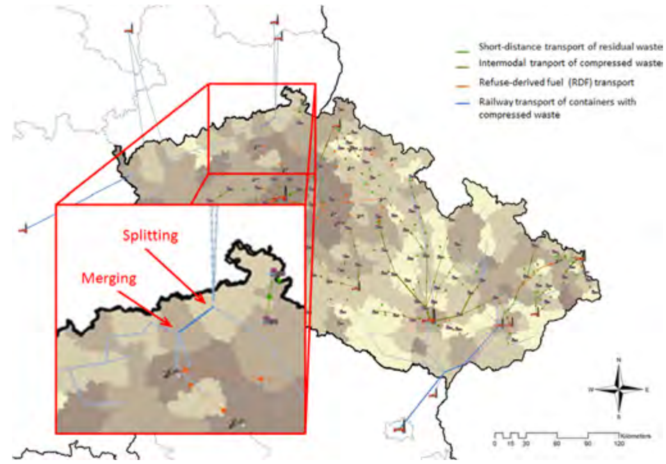


Fig. 3. The network for producers in CZE and a detail of a fragment allowing various solutions for a producer.

to be a novel one not only within engineering waste-management tasks. This approach follows up on the previously published papers, where the lack of detailed flow information formed a research gap, e.g. in (Lo et al., 2018) for the application in the source allocation, in (Pradel et al., 2018) for the flow in manufacturing processes or in wood logistics by Taskhiri et al. (2016).

First, various approaches to identify a producer-facility pattern and trace the waste have been assessed. Each approach is accompanied by specific limitations, which can be summarized as follows:

- Simple post-processing, based on a sequential algorithm which performs the node balancing needs expert-based decisions about splitting nodes and is applicable for small networks due to a lot of manual work; otherwise, output flows have to be divided equally.
- The optimization approach, based on using a different type of graph (e.g. bipartite complete graph, where each producer is connected directly with treatment facility by edges) requires a large amount of computational time, see Pavlas et al. (2015). Furthermore, the solution uniqueness for producer-facility flows is still not guaranteed.
- Multiple criteria optimization needs the specification of weights, but minimum costs for all regions are not guaranteed;

Therefore, in the presented approach, it is focused on multi-commodity network flow model ideas and partially on the utilization of the experience summarized above. The ideas already introduced in Šomplák et al. (2015) are followed as well.

3. The flow identification problem and waiting list of producers

Regarding the aim, the waste flow for a treatment facility(ies) for each municipality has to be identified, i.e., to solve flow identification problem. This principal idea is based on the assumption that municipalities need to make a contract with each treatment facility(ies) separately. The municipality is represented by a mayor. If the mayor is a responsible person, he/she begins negotiations with waste treatment facilities as soon as it is possible, if another mayor does not care about the future too much he/she postpones this step. Through this idea, a waiting list of municipalities/waste producers is created. The waste flows along the edges and the capacities of treatment facilities are given by the solution of the previous advanced transportation and location problem. These flows and capacities cannot be exceeded by any producer. It is obvious that the later a mayor makes a contract, the more limited his options of waste treatment are. The first mayor has the best position since all capacities of all edges and treatment facilities are fully available. The mayor second has a little bit worse position because the first mayor decreased the available capacity of a particular treatment facility(ies) and the available waste flow capacity of particular edges. The last mayor is in the worst position since there is only one, and probably very expensive option as the capacities are already taken by the other mayors.

There are two options on how to implement a waiting list. First, the problem for each producer can be solved separately following the waiting list order. For each producer, the capacity of treatment facilities and edges decrease according to the solution for previous producers. This leads to high demands on the pre-processing of input data (the results have to be processed and implemented into inputs for the next calculation addressing another producer).

The other option is preferred instead. It consists of an introduction of weights in the objective function. These weights represent the order of producers on the waiting list. In this case, the problem is solved for all producers simultaneously. By this, a multi-commodity nature has arisen into the problem – waste from each producer represents a commodity.

This multi-commodity network flow problem is characterized as one with a limited capacity of edges and treatment facilities, see Ghiani et al. (2014), for related network flow models with logistic applications and Bazaraa et al. (2010) for solution techniques.

The original model, described by Šomplák et al. (2014), is extended by a new index related to producers, and their productions are understood as various commodities. Therefore, new constraints linking commodity flows through edges with the total flow variables must be defined. For this reason, as the number of variables increases, computation time also increases significantly and multiple optimal solutions such as those in Fig. 2 may still appear.

Note that this could be implemented directly into the original logistic model (in stage I.), however, it enlarges the original model significantly, see Fig. 4.

Therefore, from our point of view, it is better to split the enlarged combined model into separate models designed for the facility location problem (stage I.) and flow allocation problem (stage II.) separately, see the dashed vertical line in Fig. 4. Separated models have fewer variables and constraints than the combined model. Considering related steps, such as sensitivity analyses and/or Monte Carlo simulations, the separated models are favoured due to their computational time (furthermore, analyses of costs and emissions for producers are not needed every time, as mentioned above). It has to be emphasized that the split models may lead to worse solutions from the various aggregated points of view of producers. However, after tuning certain parameters of both disconnected models, optimal solutions can be the same as for the enlarged combined model because it can be considered as one satisfying a general greedy algorithm functionality assumption.

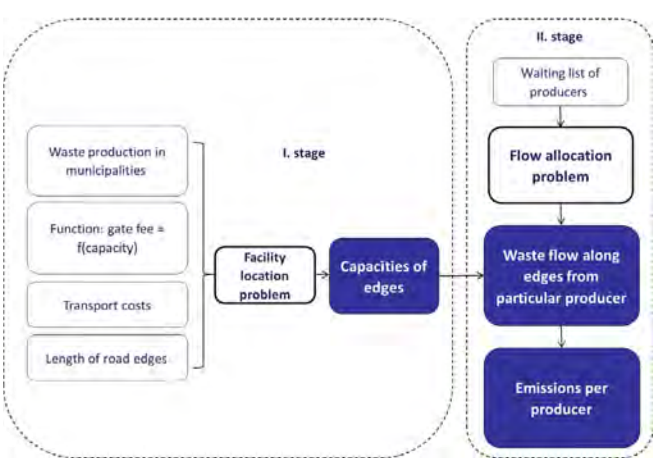


Fig. 4. Modelling of a facility location problem and flow allocation problem.

4. Mathematical model

In this section, the presented idea is converted into a mathematical model. It features a road (RD) network and also a railway (RL) network. There are different types of processing units. These are transfer stations (TR), MBT plants, WTE plants, landfill sites (LND), combustion plants utilizing calorific outputs from MBTs. The first group of units (TR, MBT) represents pre-processing facilities, where the input flow is transformed into another form. For example, an MBT plant produces refused derived fuel (RDF), a transfer station compresses the original waste (W) into containers for subsequent shipment at a reduced cost via roads (compressed waste, CW) or via railways (CWRL). The latter group (WTE, LND, RDF plant (RDFP)) consists of facilities where the final treatment is performed. Handling output streams from these facilities is out of the scope of this calculation. Let us introduce the key elements of the mathematical model. At first, it has to be emphasized that above-mentioned abbreviations are used as superscripts in the listed symbols to identify the related structural element.

Sets, indices, and parameters

$k \in K$ set of all nodes (producers and treatment facilities together)
$j \in J, \; J \subseteq K$ set of municipalities (waste producers)
$m \in M, \; M \subseteq K$ set of waste treatment facilities (transfer stations, incinerators)
$n \in N, \; N \subseteq K$ set of treatment facilities producing CW (transported to WTE)
$i \in I$ set of edges, representing road infrastructure
$l \in L$ set of edges, representing rail infrastructure
$a_{k,i}$ node-edge incidence matrix element of the road network
$b_{k,l}$ incidence matrix element of the rail network (CW transport only)
s_i capacity of an edge i on roads for W, CW and RDF, used as superscripts
t_l capacity of an edge l for CWRL on rails
w_j amount of waste W produced in a municipality j
δ_j weight coefficient for a producer j
p_k gate fee at a node k (if not a facility, gate fee is equal to 0), where WTE, LND, MBT, TR are used as superscripts
c transportation cost for W, CW, RDF, and CWRL, used as superscripts
d_i^{RD} length of the road edge i
d_l^{RL} length of the rail edge l e GWP for transportation, where CW and CWRL are used as superscripts
e_k GWP at a node k (if not a facility, GWP is equal to 0), where WTE, LND, MBT, TR are used as superscripts
α^{RDF} yield of RDF at a MBT plant, transformation of W into RDF
F GWP related to waste handling at rail stations
Q costs related to waste handling at rail stations

Variables

$u_{i,j}$ flow of waste along the edge i produced in a municipality j (for W, CW, RDF, and CWRL, used as superscripts)w

$v_{k,j}$ amount of waste from a municipality j processed in the node k (for W, CW, RDF, and CWRL, used as superscripts)

E_j total GWP for municipality j By using the introduced symbols, the objective function minimizes the total treatment cost for all producers as follows:

$$\min\sum_{j\in J}\frac{\delta_j}{w_j}\left[\left[\sum_{k\in K}-\left(v_{k,j}^{W}+v_{k,j}^{CW}+v_{k,j}^{CWRL}\right)p_k^{WTE,LND}\right.\right.$$
$$\left.-\alpha^{RDF}v_{k,j}^{RDF}p_k^{MBT}-v_{k,j}^{CW}p_k^{TR}\right]-\sum_{n\in N}v_{n,j}^{CWRL}Q+\sum_{i}d_i^{RD}\left(u_{i,j}^{W}c^{W}\right.$$
$$\left.\left.+u_{i,j}^{RDF}c^{RDF}+u_{i,j}^{CW}c^{CW}\right)+\sum_{l}d_l^{RL}u_{l,j}^{CWRL}c^{CWRL}\right],\tag{1}$$

where the previously mentioned abbreviations are used as superscripts in the objective function terms to specify processes applied to treated waste. The total treatment costs are defined as the sum of various accumulated processing costs and separately specified transportation costs. Minus signs in front of waste processing related terms indicate the correct directions of the local flows to avoid possible misinterpretations of partial costs, as profits from the computational point of view. Parameter p_k^{MBT} includes both the MBT and RDFP related cost. Then, δ_j is a weight specified for a producer j. The weights have to be ordered and no two weights are equal. The first producer in the waiting list has the highest weight and the last one has the lowest weight. The weights artificially increase the total costs. Considering the minimization problem, this means that total costs for a producer with a high weight have corresponding impact on the value of the objective function.

Let us show this as an example based on Fig. 1. If we assume that the order of municipalities in the waiting list is A, B, C, we could, for example, assign weights to the municipalities in the following way: $\delta_A = 6$, $\delta_B = 3$, and $\delta_C = 1$. The effect of the costs (separately related to municipalities on the value of the objective function for municipality A) is two times stronger, and six times stronger than the effect of costs for municipalities B and C, respectively. Therefore, the model puts the strongest emphasis on the total costs for municipality A, weaker emphasis on B and the weakest on C.

So far, the only objective function was discussed. Now let us have a look at the constraints. The first constraint, Equation (2), says that the sum of waste flow along an edge produced by different municipalities is equal to an edge capacity (given by the solution of location problem). The next constraints, Equation (3), represents the condition that the waste produced in all municipalities is further processed (the values of variables describing production has the sign that is opposite to the values of variables specifying processing). Equation (4) says that the waste produced in a municipality has to be loaded and then transported. Equation (5) provides the constraints that guarantee the waste flows through a network. Equation (6) is a node related balance; simply what flows in or is produced in the node has to flow out or to be processed in the node. Equation (7) is a pre-processing constraint (MBT or transfer stations), i.e. the amount of raw waste pre-processed in a node has to leave the node in a different form (in our simplified example, this is only related to transfer stations as collected waste W becomes compressed waste CW). According to Equation (8), the waste produced in a municipality has to be transported to a treatment facility(ies). Equation (9) says that the waste transported from all producers to a treatment facility has to be processed. Equation (10) reflects the calculation of total GWP contribution by the municipality. Parameter e_k^{MBT} includes both the MBT and RDFP related GWP. Equations (11)–(14) are introduced to keep sign rules (production is positive, processing is negative). Equations (15) and (16) say that the edge variables are nonnegative. The whole model Equation (1) to Equation (16) is implemented in GAMS modelling language and solved by the CPLEX solver.

$$\sum_{j\in J}u_{i,j}^{W}=s_i^{W},\sum_{j\in J}u_{i,j}^{RDF}=s_i^{RDF},\sum_{j\in J}u_{i,j}^{CW}=s_i^{CW},\sum_{j\in J}u_{l,j}^{CWRL}$$
$$=t_l,\quad\forall i\in I,\forall l\in L,\tag{2}$$

$$\sum_{k\in K}v_{k,j}^{W}=0,\sum_{k\in K}v_{k,j}^{RDF}=0,\sum_{k\in K}v_{k,j}^{CW}=0,\sum_{k\in K}v_{k,j}^{CWRL}=0,\quad\forall j\in J,\tag{3}$$

$$w_j+v_{j,j}^{W}+\alpha^{RDF}v_{j,j}^{RDF}+v_{j,j}^{CW}+v_{j,j}^{CWRL}=0,\quad\forall j\in J,\tag{4}$$

$$\begin{aligned}&\sum_{i\in I}\left(a_{k,i}u_{i,j}^{W}-v_{k,j}^{W}\right)=0,\sum_{i\in I}\left(a_{k,j}u_{i,j}^{RDF}-v_{k,j}^{RDF}\right)=0,\\&\sum_{i\in J}\left(a_{k,j}u_{i,j}^{CW}-v_{k,j}^{CW}\right)=0,\sum_{l\in L}\left(a_{k,l}u_{l,j}^{CWRL}-v_{k,j}^{CWRL}\right)=0,\end{aligned}\quad\forall j\in J,\forall k\in K,\tag{5}$$

$$\sum_{i\in I}a_{k,i}\left(s_i^{W}+\alpha^{RDF}s_i^{RDF}+s_i^{CW}\right)+\sum_{l\in L}b_{k,l}t_l-\sum_{j\in J}\left(v_{k,j}^{W}+\alpha^{RDF}v_{k,j}^{RDF}\right.$$
$$\left.+v_{k,j}^{CW}+v_{k,j}^{CWRL}\right)$$
$$=0,\quad\forall k\in K\tag{6}$$

$$v_{n,j}^{W}+\alpha^{RDF}v_{n,j}^{RDF}+v_{n,j}^{CW}+v_{n,j}^{CWRL}=0,\quad\begin{aligned}&\forall n\in N,\\&\forall j\in J:n\neq j,\end{aligned}\tag{7}$$

$$\sum_{m\in M}\left(v_{m,j}^{W}+\alpha^{RDF}v_{m,j}^{RDF}+v_{m,j}^{CW}+v_{m,j}^{CWRL}\right)$$
$$=\sum_{m\in M}\left(\sum_{i\in I}a_{m,i}\left(u_{i,j}^{W}+\alpha^{RDF}u_{i,j}^{RDF}+u_{i,j}^{CW}\right)\right.$$
$$\left.+\sum_{l\in L}b_{m,l}u_{l,j}^{CWRL}\right),\quad\forall j\in J,\tag{8}$$

$$\sum_{j\in J}\left(v_{m,j}^{W}+\alpha^{RDF}v_{m,j}^{RDF}+v_{m,j}^{CW}+v_{m,j}^{CWRL}\right)$$
$$=\sum_{j\in J}\left(\sum_{i\in I}a_{m,i}\left(u_{i,j}^{W}+k^{RDF}u_{i,j}^{RDF}+u_{i,j}^{CW}\right)\right.$$
$$\left.+\sum_{i}b_{m,l}u_{i,j}^{CWRL}\right),\quad\forall m\in M,\tag{9}$$

$$E_j = \sum_{k \in K} \Big[- \left(v_{k,j}^{W} + v_{k,j}^{CW} + v_{k,j}^{CWRL} \right) e_k^{WTE,LND} - \alpha^{RDF} v_{k,j}^{RDF} e_k^{MBT} - v_{k,j}^{CW} e_k^{TR} \Big] - \sum_{n \in N} v_{n,j}^{CWRL} F + \sum_i d_i^{RD} \left(u_{i,j}^{W} e^{W} + u_{i,j}^{RDF} e^{RDF} + u_{i,j}^{CW} e^{CW} \right) + \sum_l d_l^{RL} u_{l,j}^{CWRL} e^{CWRL}, \quad \forall j \in J \tag{10}$$

$$v_{j,j}^{W} \leq 0, \quad \forall j \in J, \tag{11}$$

$$v_{k,j}^{W} \geq 0, \quad \forall k \in K, \; \forall j \in J : k \neq j, \tag{12}$$

$$v_{n,j}^{RDF}, \leq 0, v_{n,j}^{CW} \leq 0, v_{n,j}^{CWRL} \leq 0, \quad \forall n \in N, \forall j \in J, \tag{13}$$

$$v_{m,j}^{RDF} \geq 0, v_{m,j}^{CW} \geq 0, v_{m,j}^{CWRL} \geq 0, \quad \forall m \in M, \forall j \in J, \tag{14}$$

$$u_{i,j}^{W} \geq 0, \; u_{i,j}^{RDF} \geq 0, \; u_{i,j}^{CW} \geq 0, \quad \forall i \in I, \forall j \in J, \tag{15}$$

$$u_{l,j}^{CWRL} \geq 0, \quad \forall l \in L, \forall j \in J. \tag{16}$$

An application of the model will be presented in the next section. A simple example involving only several producers and treatment facilities will be solved in detail to provide a comprehensive understanding of the problem.

5. Model applications – example featuring a small network

5.1. Task definition

The example is introduced for explanatory purposes. It features a network consisting of 7 nodes and 8 edges connecting the nodes. A network visualization is presented in Fig. 5 together with the necessary input data, such as lengths of edges (in kilometres) and the amount of produced waste (kt/y).

The network also contains different processing units which are attached to the nodes. Therefore, there are auxiliary edges connecting nodes and processing facilities listed in the latter group for modelling reasons. The network scheme is illustrated in Fig. 5, where the edge length, waste productions and facility distribution is displayed. There is only one exception to the connection between node 3 and nearby WTE. It is a railway connection with a significant distance. There are 2 WTE plants located close to nodes 6 and 7; 2 landfill sites attached to nodes 6 and 7; 3 transfer stations (TR) in nodes 1, 4 and 6; 2 MBT plants in nodes 2 and 4; and 1 RDF plant close to 5.

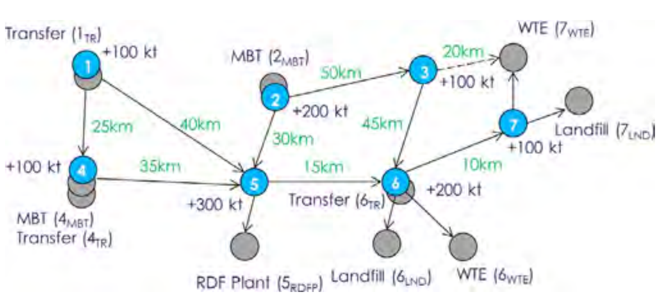


Fig. 5. Simple example specification.

The amount of produced waste is specified for each node (waste producer) in Table 1 together with the flow balance reflecting facilities being operated in the nodes. It should be noted that RDF produced in the MBT plant represents only a portion of the amount entering the plant. The optimal waste flow for each edge is stated in Table 2.

Regarding Fig. 4, the following illustration represents the result of NERUDA, where the green numbers are capacities of edges for all considered waste types, see Fig. 6.

Considering the network from the illustration, the average cost of the whole treatment process was 74 EUR/t and average GWP was 37 kg CO_{2eq}/t. The weights δ_j then determine the order in which the producers decide the place and method of processing their waste. This implies the unit cost/GWP of the waste processing of individual producers. In the next step, the weights are generated randomly for producers to get an insight into the variability of GWP for each producer when their agreement related activities are not coordinated and they act spontaneously. A simulation based approach can help us to estimate the interval of varying GWP, their variance, and their mean value for each producer and hence to derive conclusions about GWP stability for each producer under scenario based circumstances.

5.2. Cost related analysis

Let us recall the main goal of the calculation, which is to gain information on where the waste from a particular producer will be processed. Additionally, the total processing costs are under interest with respect to the choice of generated weights δ_j.

The following analysis reflects the calculation that was performed in two scenarios. In the scenario 1, weights were set the same $\delta_j = 1, \ \forall j$. Whereas the following weight set up $\delta_1 = 7, \delta_2 = 6, \delta_3 = 5, \delta_4 = 4, \delta_5 = 3, \delta_6 = 2, \delta_7 = 1$ was carried out in scenario 2. In this specific case, waste producer 1 chooses among the waste treatment possibilities without considering about others. Then, producer 2 realizes his choice is under restriction caused by producer 1. The further producers continue to realize their choices subsequently as more and more restricted in their possibilities by previous producers.

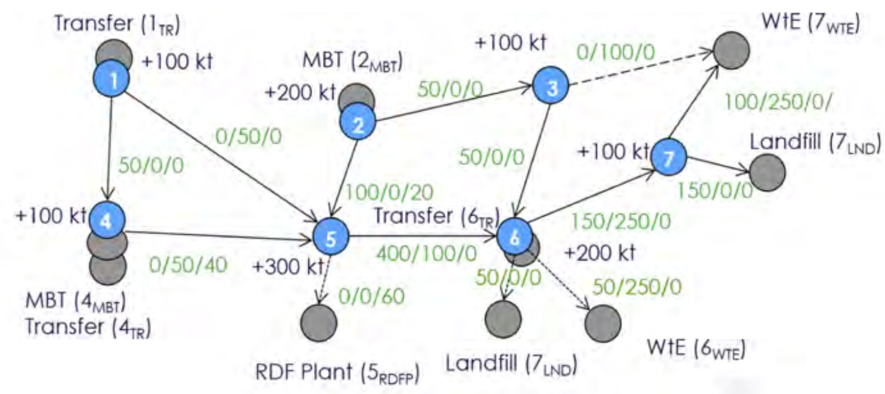
Input data about costs: RDF treatment fee in a RDF plant: 55.6 EUR/t; WTE and landfill sites related fees (varying across facilities due to economies-of scale and local conditions): 6_{WTE}: 48.1 EUR/t, 7_{WTE}: 83.3 EUR/t, 6_{LND}: 85.2 EUR/t, 7_{LND}: 74.1 EUR/t; processing cost

Table 1
Waste production in nodes and facility balances.

Producer	1	2	3	4	5	6	7
Facilities	TR	MBT		TR, MBT	RDFP	TR, LND, WTE	LND, WTE
W produced [kt/y]	100	200	100	100	300	200	100
W treated [kt/y]	−50	−50		−100 (MBT) −50 (TR)		−50 (LND) −300 (WTE)	−150 (LND) −450 (WTE)
CW produced [kt/y]	50			50			
RDF produced [kt/y]		20		40			
RDF treated [kt/y]					−60		

Table 2
Total optimal waste flows for identified edges; [kt/y].

Edge	1–4	1–5	2–3	2–5	3–6	4–5	5–6	6–7	6-6_{WTE}	7-7_{WTE}	6-6_{LND}	7-7_{LND}	5-5_{RDFP}
W	50		50	100	50		400	150	50	100	50	150	
CW		50				50	100	250	250	250			
RDF				20		40							60



Note: The sequence of parameters describing the flow along edges and representing roads, is as follows: W/CW/RDF. For railway transport only, CW is allowed

Fig. 6. Visualised results for the simple example.

at transfer stations: 1_{TR}: 0.67 EUR/t, 4 $_{TR}$: 1.11 EUR/t, 6 $_{TR}$: 0.93 EUR/t; transportation costs for W using the roads: 0.19 EUR/(t.km); RDF transportation costs specific for roads: 0.13 EUR/(t.km); costs for compressed waste (CW) roads: 0.13 EUR/(t.km); costs for compressed waste transportation on railways (only relevant for edge 3–7_{WTE}): 0.11 EUR/(t.km).

The results of scenario 1 for previously mentioned input data are in Table 3.

The previous tables specify the flows to processing plants for the waste of each producer. For example, let us discuss the flow of producers 1 and 2:

For waste producer 1: 50 kt of W is transported directly by a vehicle along edge 1–4 to node 4, where an MBT plant produces 20 kt of RDF, which is subsequently shipped along edges 4–5 and 5-5_{RDFP} to an RDF plant in node 5_{RDFP}. The remaining 50 kt of produced W is directly processed via the transfer station in node 1, and then transported in containers to two different WTE plants, 6_{WTE} and $7_{WTE,}$ for its final treatment. The beginning of the paths for both consignments is the same. They go along edges 1–5 and 5–6. The first consignment, accounting 14.6 kt W, is processed here at a WTE plant in node 6_{WTE} and the further remaining 35.4 kt W continues along the edge 6–7 and is finally treated at a WTE plant in node 7_{WTE}.

Waste producer 2: 150 kt of W is first transported by collecting vehicles where 100 kt of this amount is moved by edges 2–5 and 5–6 to node 6, where it is compressed in the transfer station. The first part of the 68 kt of CW is then transported along edge 6–6_{WTE} to be processed at a WTE plant in node 6_{WTE}. The second part of 32 kt of CW is transported along edges 6–7 and 7–7_{WTE}, where it is further processed at a WTE plant in node 7_{WTE}. The remaining 50 kt of W is moved along edge 2–3 into node 3, where it is located on a railway and moved by edge 3–7_{WTE} for processing at a WTE plant in 7_{WTE}. The next 50 kt of CW is directly processed in node 2 at an MBT plant and 20 kt of RDF is produced and further transported along

Table 3
The results of scenario 1 for flows identified by the waste type [kt/y].

Edge\producer	1	2	3	4	5	6	7
1–4	50/0/0						
1–5	0/50/0						
2–5		100/0/20					
2–3		50/0/0					
3–6			50/0/0				
4–5	0/0/20			0/50/20			
5–6	0/50/0	100/0/0		0/50/0	300/0/0		
6–7	0/35.4/0	0/32/0	0/0.5/0	0/48.3/0	0/133.8/0	150/0/0	
5-5_{RDFP}	0/0/20	0/0/20		0/0/20			
6-6_{WTE}	0/14.6/0	0/68/0	49.5/0/0	0/1.7/0	0.5/116.8/0	0/48.9/0	
7-7_{WTE}	0/35.4/0	0/32/0	0/0.5/0	0/48.3/0	0/133.8/0	100/0/0	
6-6_{LND}					48.9/0/0	1.1/0/0	
7-7_{LND}						50/0/0	100/0/0
3-7_{WTE} (rail)		0/50/0	0/50/0				

Note: The sequence of parameters describing the flow along edges is as follows: W/CW/RDF.

Table 4
Cost-related results – two scenarios.

Producer	Scenario 1 The same weights for the producer			Scenario 2 different weights for producer		
	Weight Symbol δ	Unit price [EUR/t]	Total price [103 EUR/y]	Weight Symbol δ	Unit price [EUR/t]	Total price [103 EUR/y]
1	1	72.080	7208	7	58.380	5838
2	1	74.265	14,853	6	68.110	13,622
3	1	74.270	7427	5	74.740	7474
4	1	74.270	7427	4	57.420	5742
5	1	74.267	22,280	3	77.697	23,309
6	1	74.265	14,853	2	85.685	17,137
7	1	74.270	7427	1	83.530	8353

2–5 and 5–5_{RDFP} towards the final treatment into an RDF plant in node 5_{RDFP}.

The previously mentioned results are related to edges and waste types. As soon as the patterns producer-facility and associated waste flow within the network are identified, the total treatment cost for each producer can be evaluated. Transportation costs are aggregated taking into account all the edges the path consists of and their related transportation costs. The processing prices at the facilities (both pre-treatment and final treatment) are added. The unit and total costs for each producer are presented in Table 4. The changes in the costs for individual producers are evident when comparing both scenarios.

It is obvious that the resulting costs do not include the values of weight parameters as they served only to model the order of the producer's choices. The choice of having equal weights models an example of an agreement between producers where nobody has an advantage due to coming first. Additionally, they have reached the smallest possible average overall cost. Therefore, the unit costs displayed in Table 4 are the same for most producers. The price is slightly lower only for producer 1 since this could be achieved with a balanced adverse effect on the other producers.

In the second simulated case (Scenario 2), the computed costs differ from the previous one. Lower costs are reached by producers who started to choose treatment facilities before the others. There are exceptions, as producer 7 has lower unit expenses than producer 6, who had the opportunity to make his choice before him. Such exceptions appear in the case of specific differences between regions (such as distances, reachability, available edges, and so on). Producer 7 has a better position with respect to the considered scenario (see the weights and original flows) although his choice is only made after producer 6. However, the other set up of the weights may lead to qualitatively completely different results.

5.3. GWP related analysis

This section covers the insight into the GWP changes regarding particular waste producer for randomly generated weights. The two previously mentioned scenarios are analysed as well. The following Table 5 contains the input data of GWP for all treatment facilities and means of transport.

In the same way, as for the cost analysis, the results for two selected scenarios with different weights are proposed. The values for GWP are summarized in Table 6. It is important to note, that the results are based on the calculation of location problem, where the objective function considers only cost criterions. The following table compares the changes in GWP.

For some producers, the change was insignificant (e.g. producer 2), while in the case of producer 7 it was enormous. The simulation based on changes in weights can give us information about the sensitivity of specific GWP per particular waste producer with respect to scenario changes. Moreover, the risk of higher GWP can be estimated in some regions in the case of a passive wait-and-see approach to waste management challenges. Fig. 7 depicts the sensitivity analysis for 1000 scenarios with randomly generated weights. These weights were generated from the uniform distribution δ_j~U(1,10).

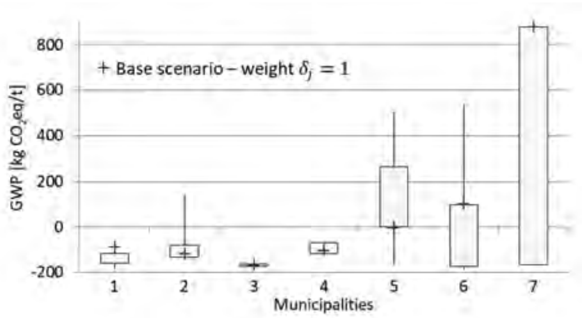
Table 5
GWP input data.

Facilities	1_{TR}	1_{MBT}	4_{MBT}	4_{TR}	5_{RDFP}	6_{WTE}
CO_2eq produced [kg/t of W]	0.2	0	0	0.2	−70	−185
Facilities/edges	6_{LND}	6_{TR}	7_{WTE}	7_{LND}	**Road [km]**	**Rail [km]**
CO_2eq produced [kg/t of W]	880	0.2	−165	880	0.06	0.004

Note: Heat utilization for 6_{WTE} and 7_{WTE} are 80% and 60% respectively, for 5_{RDFP} 70%, based on Ferdan et al. (2017); GWP for CW transportation is assumed with coefficient 0.7; emissions of MBT are included in RDFP value.

Table 6
Emission related results – two scenarios.

Producer	Scenario 1 The same weights for the producer			Scenario 2 Different weights for producer		
	Weight Symbol δ	Unit emission CO_2eq [kg/t of W]	Total emission CO_2 [t/y]	Weight Symbol	Unit emission CO_2eq [kg/t of W]	Total emission CO_2 [t/y]
1	1	−117.94	−11,794	7	−181.8	−18,180
2	1	−128.16	−25,632	6	−131.59	−26,318
3	1	−173.39	−17,339	5	−173.15	−17,315
4	1	−116.16	−11,616	4	−69.4	−6940
5	1	−1.21	−363	3	529.66	158,898
6	1	97.40	19,480	2	−164.54	−32,908
7	1	880.06	88,006	1	−164.94	−16,494



Note: The box plot displays the distribution of data based on the four characteristics summary: first decile, first quartile, third quartile, and ninth decile.

Fig. 7. Sensitivity analysis – Box plot for GWP of municipalities.

The base scenario where $\delta_j = 1$ is depicted by a red cross. The characteristics of the results were stable after the selected number of simulations. Municipalities 1–4 have a very low variability in GWP. They are all in negative numbers and so positive from the environmental point of view. The lowest interval (first and ninth decile) for GWP contribution has producer 3 with the length of 9 CO_{2eq} kg/t. While the GWP of municipalities 5–7 is much more variable. Results of scenarios with low weight impact the environment with the highest GWP indicator. The large range in case of municipality 7 is given by two different boundary values, which regardless of the weights occur. The most frequent GWP contribution lies in the range of 1045 CO_{2eq} kg/t, see Fig. 7. The resulting values are influenced mostly by the location of treatment facilities. Such computational approaches can motivate the rational behaviour of decision makers relating to waste producers, and hence support the establishment of new projects in the future.

6. Conclusions and further research

The presented approach shows an option how to track the commodity flow from the producer to the treatment facility in a logistic problem where this information is lost due to the merging and splitting streams in vertices. This task is called a "flow identification problem" and it is essential for a comprehensive emission and cost analysis, addressing a single producer. This is beneficial for governments, producers, investors and operators of processing facilities due to decreasing target of GWP contribution regarding treatment of waste. It is an integral part of pre-feasibility and feasibility studies (assessment of the emission impact for individual producers, return of investment, risk analysis, and so on). Due to these factors, it is possible to set real-time targets for the emitted emission with a link to a specific region. In case of non-fulfilment the obligation, consequences in the form of penalties might be applied.

Several straightforward approaches were studied and their limitations specified, including a simple sequential balancing algorithm, its effects and the benefits of implementing different types of networks. The uncertainty of getting solution uniqueness was identified as the most important aspect.

A new approach towards flow identification was proposed, combining a multi-commodity network flow model with a Monte Carlo simulation. It is based on a multi-commodity approach enriched with the idea of the waiting list of producers. Hence, it is applied to a waste logistic problem.

It is proposed to keep this model separated from the original facility location problem for practical reasons and an acceptable computational time. On the other hand, there is an interconnectivity between both models, since the first problem provides the desired constraints for the flow allocation problem. The flow identification problem represents a certain form of post-processing the result obtained from facility location problem.

The newly developed approach was demonstrated through the example involving several producers for cost and GWP analysis. The average total processing cost in the subjected area was 74 EUR/t and the average GWP was 37 kg CO_{2eq}/t. However, significant local dissimilarity was stated, where some producers would suffer from considerably increased treatment costs and GWP contribution. For some producers, a limited number of preferred options could be identified, where acceptable costs can be expected. The GWP contribution varied between −173 and 880 kg CO_{2eq}/t. This analysis enables identification of significant waste producers in the network regarding GWP. On behalf of this analysis, the response in the form of planning and support of new projects can be performed. The results allow not to generalize the overall environmental impacts, but it is possible to effectively focus the attention to problematic locations and effectively reduce the impact on GWP contribution. The mathematical model is stated in general and thus it is suitable for solving large-scale tasks. The applicability of the presented approach is broad, especially within the process, logistic and manufacturing fields. Further research will consider a case study with real network and hundreds of nodes.

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Spatially distributed production data for supply chain models - Forecasting with hazardous waste

Martin Pavlas [a, b, *], Radovan Šomplák [a, b], Veronika Smejkalová [c], Vlastimír Nevrlý [a], Lenka Zavíralová [a], Jakub Kůdela [c], Pavel Popela [c]

[a] Institute of Process Engineering, Faculty of Mechanical Engineering, Brno University of Technology, Technická 2896/2, 616 69 Brno, Czech Republic
[b] Sustainable Process Integration Laboratory – SPIL, NETME Centre, Faculty of Mechanical Engineering, Brno University of Technology, Technická 2896/2, 616 69 Brno, Czech Republic
[c] Institute of Mathematics, Faculty of Mechanical Engineering, Brno University of Technology, Technická 2896/2, 616 69 Brno, Czech Republic

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ABSTRACT

This paper introduces a novel approach to forecasting future commodity production in hundreds of nodes, which represents a key input for many applications of supply-chain models. A mathematical model was proposed to handle the problem of forecasting with spatially distributed and uncertain data. It is derived from the principle of regression analysis and extended by a data reconciliation technique. Additional areal constraints guarantee mass conservation in a tree-like structure, which reflects the organisational arrangement of an investigated region. The proposed model was tested through a case study, where future production of hazardous waste suitable for thermal treatment was forecasted in 206 base-nodes, 14 superior nodes and one apex. Based on an extensive investigation of historical data, it was revealed that extrapolations carried out at different levels of the hierarchical organisational structure lead to inconsistent forecasts. The differences between forecasts reached up to 50%. In addition to this, mass conservation was violated. Significant corrections were performed by computations utilizing the formulated model. The corrections ranged from between 0% and 12% for 90% of nodes. There were 17 nodes, where massive adjustments of up to 30% were inevitable.

1. Introduction

This contribution addresses issues of quantitative input data processing prior to a supply chain model (SCM) calculation. As is explained later on, it tackles the interconnected problem of extrapolation and subsequent data reconciliation. The paper focuses on prognosis with the preservation of hierarchical and waste code aggregations in the field of hazardous waste management. For this reason, this article starts with a short review of recent achievements which are relevant to the topic of the paper.

1.1. Quantitative data and their forecasted values as key inputs for supply chain model applications

SCMs represent an effective concept to optimise processes where resources and raw materials are first transformed into desired products and then moved on to the customers. SCM are employed at several stages of process development covering both strategic and tactical issues, i.e. investment planning and operation.

Any SCM requires spatially distributed production data (related to the region of interest). The higher the level of detail, the more nodes which are included in the calculation network and the more data which are needed. Many research articles relevant to SCM and devoted to the various areas of transporting raw materials, fuels, waste, and so on have been published in the last few years. This confirms a broad range of applications for this supportive approach handling various commodities. For example, Balaman and Selim (2016) presented a comprehensive decision model for the sustainable design of biomass-based renewable energy supply chains. The aim was to locate and size facilities. The proposed model was based on mixed integer linear programming (MILP).

A P-graph is another interesting approach related to SCM. In the paper Varbanov and Fiedler (2008) a procedure for the evaluation of energy conversion systems is presented. In Vance et al. (2015), the effort is extended with another sustainability metric, emergy. A

* Corresponding author. Institute of Process Engineering, Faculty of Mechanical Engineering, Brno University of Technology, Technická 2896/2, 616 69 Brno, Czech Republic.
E-mail address: pavlas@fme.vutbr.cz (M. Pavlas).

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Monte Carlo simulation was used in Tan et al. (2017) to evaluate the robustness of a network to variations in system parameters.

Among other areas, SCMs are also relevant to waste management (WM). Since this contribution is dedicated to hazardous waste, the paper focuses on this field in particular. In Ghiani et al. (2014), the reverse problem was proposed, where the product, which is now the waste of different types and its individual fractions, is first collected and then transported to places of its intermittent or final treatment. The transport of residual solid waste was optimised by Chatzouridis and Komilis (2012). One of their key questions was whether a transfer station should be built or not. A complex problem was presented in Šomplák et al. (2014) which described the competitive environment in the field of waste management and where the collection phase was excluded. The issue of collecting and processing hazardous waste was dealt with by Zhao et al. (2016). Their case study described the situation in Sichuan province in China and used an approach based on multi-objective MILP. Samanlioglu (2013) described a task focusing on the location of processing plants and determined the flow of hazardous waste in selected areas in Turkey. The problem was described by a multi-objective location-routing model, where the objective was to minimise the cost and risk to the population.

The mentioned papers perform economic optimisations of the processes, where the operational cost (or annualised cost in the case of investment planning of an overall system) is minimised.

In this context, our review revealed that a typical paper published in this area dominantly focuses on the introduction of the mathematical model, highlighting new contributions and features. The practical impact is typically presented through case studies. Whereas the region of interest is commonly well described (the network may be reconstructed by using online maps and more advanced geographical information systems), the quantitative data addressing the production of the commodity in each of the nodes are often only briefly mentioned. Typically, current commodity availability is provided based on the latest reported data or an average value from the few last years at the highest regional level. This value is distributed down to all nodes of the network, for example using a socio-economic parameter (e.g. population, in the case of household waste). Based on our knowledge, none of the papers dedicated to SCMs and its applications stressed the issues of simultaneous forecasting a commodity's availability in the future for all nodes in the investigated network. This may be acceptable in the case of stable commodity availability. The use of current or average data represents a strong simplification because data develop over time and future investments are planned by the SCM. On the other hand, forecasting, especially based on short-time series (a typical case in SCM applications, not only in waste management), represents an independent problem (see Section 1.2) which was studied by many authors in different fields. The complexity of the problem, even if applied to one time series, is enormous, which hinders its routine use as demanded by SCM.

1.2. Short-time series forecasting

From a mathematical point of view, there are several approaches toward estimating beyond the observed data which can be called a basic time series analysis (TSA). Frequently used techniques are provided by regression analysis, so in the context of this paper, TSA represents regression analysis based techniques for extrapolation, where the sole explanatory parameter is time.

Andow and Kiritani (2016) studied the population dynamics of 17 species of saproxylic beetles in a specific location by using classical autoregressive integrated moving average (ARIMA) models. It is a frequently used technique for data fitting or predicting which generalises an autoregressive moving average model (ARMA), see Hamilton (1994). These techniques are not appropriate for a short TSA.

The waste management area usually suffers from a rather short available dataset (regarding time and one year as a basic time interval). This has a negative impact on prediction quality, especially when using traditional methods. Forecasting is often devoted to municipal solid waste (MSW) and its fractions.

The work presented by Ghinea et al. (2016) used a small dataset prognostic tool, regression analysis and time series analysis for forecasting MSW generation in Iasi (Romania) in 2023, when data from 2001 to 2013 were used. This study also focused on predicting the amount of solid waste fractions (paper, plastic, metal, glass, biodegradable and other waste). A different methodology was used in the study Intharathirat et al. (2015), which presented an analysis of possibilities for determining the prediction interval for MSW production. This was over a long-term period and used optimised multivariate grey models. Only 13 samples were available here. Another approach for forecasting based on a set of limited samples was presented in Xiang and Daoliang (2007), where grey fuzzy dynamic modelling (combining two forecasting techniques - grey dynamic model and the fuzzy goal regression model) was used for the prediction of solid waste generation in a fast-growing urban area - Beijing (China).

Since the time series (the available data for each node) encompasses only a few points (seven in our case study), any attempt at a rigorous time series analysis of such data is going to result in a heavily skewed estimate of the real underlying trend.

From the previously mentioned points, a current SCM developer and user working in the waste management area has to cope with short-time series. From a statistical point of view, the accuracy of extrapolation models is rarely guaranteed with a high level of confidence if the series consists of only a few points. This limits the direct use of the obtained forecasts in SCM applications. On the other hand, these models still provide important information about the trend. They are acceptable from an engineering point of view as no other models are available and they offer an improvement to existing approaches which rely on only the most recent reported data.

All of these approaches forecast data for a single node and commodity in terms of SCM terminology. Moreover, none of these extrapolation techniques reflects mass conservation, where, for example, the sum of values in regions equals the value in a higher territorial unit. As a result, this leads to inconsistencies (see Section 2). For this purpose, the utilization of a reconciliation technique appears promising.

1.3. Data reconciliation

Data reconciliation is a frequently used technique for data balancing and identifying gross errors. It primarily uses mathematical programming techniques, where the weighted least square errors are minimised, while balance constraints are satisfied. One of its first applications was in the field of chemical engineering, where the data reconciliation problem was presented by Crowe et al. (1983). A further extension of his research was proposed in Crowe (1996). Many other works have attempted to apply this method in various industries.

The energy system application in Yong et al. (2016) considers complete heat exchanger networks within the data reconciliation scope. Two methods are compared: i) an iterative method using local non-linear programming (NLP) and ii) a simultaneous method applying global NLP. In Weiss et al. (1996), an iterative gross error detection method was proposed, followed by data reconciliation using weighted least squares on a non-linear and on a linearized model of an industrial pyrolysis reactor. Jiang et al. (2014)

presented another mathematical method to evaluate the minimum isolable magnitude with a required probability for data reconciliation based on gross error identification. The importance of adequately treating the possible heteroscedasticity of measurement errors was demonstrated in Vocciante et al. (2014). A two-step approach for error detection and data reconciliation is provided by Sun et al. (2011). A simultaneous calculation of reconciled values and gross error detection was described in Korpela et al. (2016) using the Welsch-estimator and NLP methods. Martins et al. (2010) proposed a water balance tool for data reconciliation in industrial processes. They presented a new method based on the idea that an estimated assumption can be made for any flow rate based on the best available information (the quality of information). Valdetaro and Schirru (2011) used a metaheuristic (inspired by naturally occurring events) to simultaneously tune the model objective function, detect outliers and compute the data reconciliation. Zhang et al. (2010) propose sequential sub-problem programming strategies for data reconciliation and parameter estimation with multiple data sets. Based on objective and model parameters, the construction of a series of sub-problems is performed to solve the optimum of the original optimisation problem. A paper from Manenti et al. (2011) describes the integrated solution of different model-based optimisation levels to face the problem of inferring and reconciling online plant measurements practically. This was under the condition of poor measure redundancy in measurements due to the lack of instrumentation installed in the field. The question of choosing an adequate objective function for gross error detection and data reconciliation in chemical processes was studied in Özyurt and Pike (2004).

To sum up, articles in this field mostly focus on presenting new approaches for optimisation tasks, specifically reducing the computational complexity of the models or gross error detection. A common feature of data reconciliation papers is a fully defined covariance matrix which reflects the accuracy of the measurement devices. In this case, a covariance matrix which reflects the regression's quality is needed. Moreover, multiple values for a particular node must be allowed, where each of these values can have a different contribution in the matrix.

1.4. Contribution and novelty

The user of the SCM tool has to frequently cope with short-time series. Each of the mentioned approaches for extrapolation is interesting and have their strengths and weaknesses. In general, they provide only rough estimates instead of precise values and they are of very low practical relevance. Low confidence intervals, in addition with the complexity of extrapolation even when done for one time series (i.e. one node and one commodity, see Section 2.2), represent an obvious hindrance to effective forecasting in SCMs, where such extrapolation is needed in hundreds of nodes.

This paper introduces an approach towards improving forecasting in SCM applications. It is considered to be a pre-processing phase, prior to the main SCM calculations. The principle proposed is structured as follows:

1. Extrapolation – Non-linear regression is applied to all nodes of an investigated area to obtain initial estimates on future commodity production. As follows from Section 1.1 and 1.2, such an approach has not been published yet nor has it been practically applied to SCM. In this paper, we propose an extrapolation model which was tested for a particular waste type – hazardous waste. An iterative calculation is formulated with altered starting values, overcoming the problem of local solutions.
2. Reconciliation – the results of the extrapolation are handled as initial estimates, which are subject to further adjustments. Our method proposes exploiting mass conservation equations associated with a tree-like organisational and code aggregation structure in the reconciliation process. First, the problem of inconsistent forecasting and mass-balancing in a tree diagram is introduced. Then a mathematical model for data reconciliation is formulated and explained (see Section 3). The application of reconciliation in the field of reverse flow models and data forecasting is considered to be novel.

The whole procedure is tested through a complex case study, where hazardous waste produced in many small particular regions is forecasted, balanced and analysed. This paper was motivated by an extensive project for the Ministry of Environment of the Czech Republic carried out by the authors in 2015. The task was to allocate future capacities for hazardous waste treatment in the Czech Republic using the application of an advanced network flow model, called NERUDA (Ferdan et al., 2015). This waste is mainly produced by the industrial sector. Detailed historical data on production in particular micro-regions was provided by the authorities.

2. Extrapolation and inconsistent forecasts

In this section, specific aspects of simultaneous forecasting in a tree-like structure are introduced for locations of a large geographical area divided into many sub-areas and their parts.

2.1. Areal aggregation within a hierarchical organisational structure

Generally, the geographical area of the investigated region is organised according to a tree-like structure. It is illustrated in Fig. 1 and the real administrative arrangement for the Czech Republic may be derived from supplementary materials. The diagram, if based on real data, describes the relationship between nodes located at different levels of a hierarchical structure.

The idea, further explored in this contribution in more detail, is to utilise relationships within this tree-like structure to produce more convenient forecasted values, especially for those nodes where there are poor results from extrapolation regression models.

Following the tree diagram, the historical base data (i.e., data for nodes located at L2 level according to Fig. 1) may be aggregated to generate production at higher levels. This is highlighted by the sums in Fig. 1 for the apex node (L0) and one L1 level node. This summation is later labelled as “areal aggregation”. This areal aggregation is commonly used in practise where data for higher organisational levels (regions, country, see L1 and L0 level in Fig. 1, respectively) are reported as sums of production in all subordinate nodes. It also means that mass is conserved in the system around the particular node and its descendants as highlighted by the boundaries in Fig. 1. In Section 3, there is only one set with all nodes and tree structure is included in hierarchical matrix.

Whereas base level data often fluctuate, this variability is often suppressed by areal aggregation at a higher level (compare Fig. 2 a) and b) for instance).

2.2. Extrapolation

The creation of extrapolation models for all territorial units (i.e. L2, L1 and L0 levels) represents the initial step in the procedure. Trend analysis applied to historical data was used for non-linear regression model building and subsequent forecasting of the amount of waste produced. The model used is generally defined as:

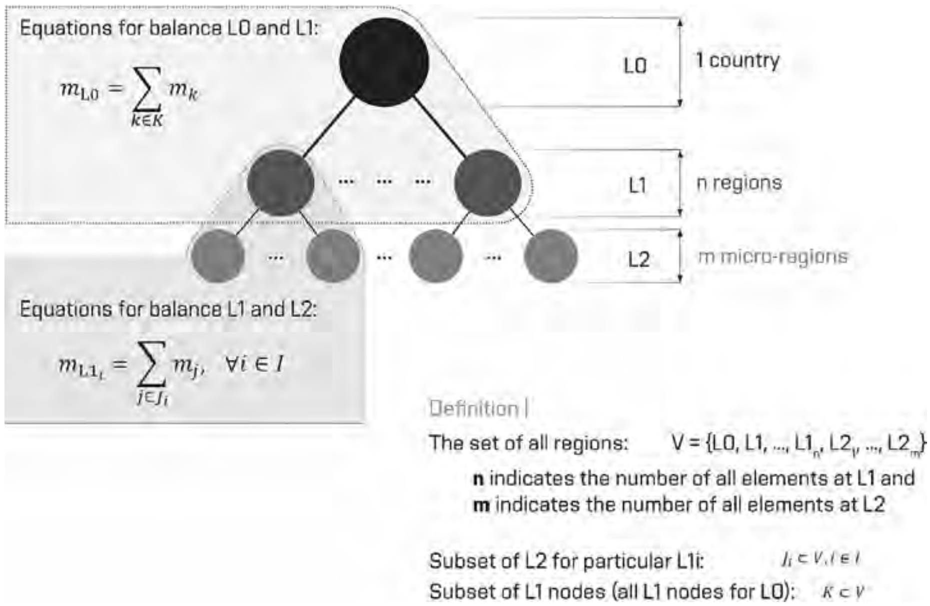

Fig. 1. Locations represented by nodes and organised in a tree structure with several levels, where mass conservation is required.

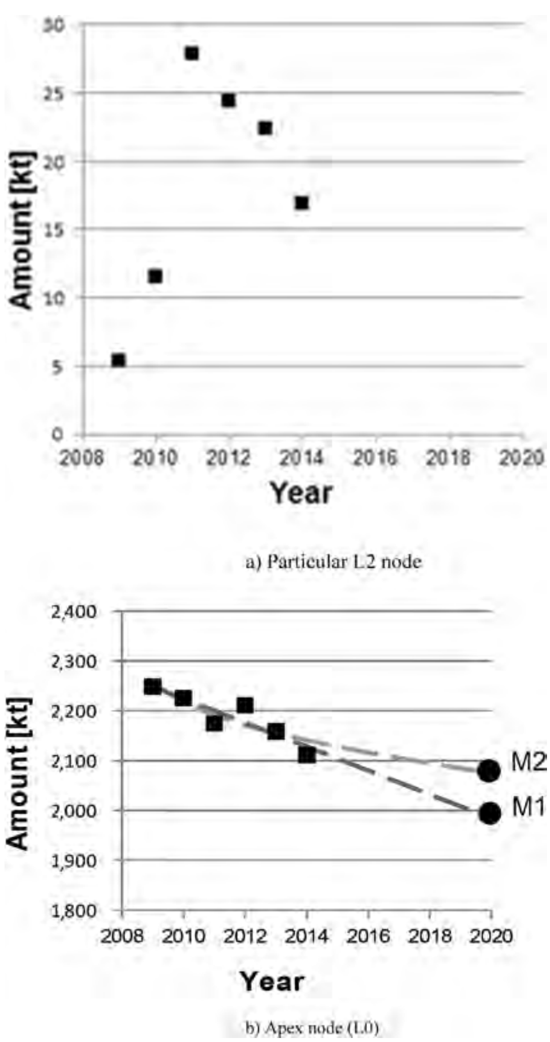

Fig. 2. Various data quality based on the level of detail, an example for particular waste stream. a) Particular L2 node. b) Apex node (L0).

$$M = a + bt^c, \tag{1}$$

where t is an independent variable whose values are the year(s) of waste production, M is the dependent variable giving the amount of produced waste in year t, and a, b, c are regression parameters to be estimated. Additionally, $M \geq 0$ is valid.

This type of model was judged to be suitable for the studied area of hazardous waste and input data is summarised in the supplementary materials. However, an alternative model could be more convenient for other types of data. For example, logistic function is very suitable for streams were a surge in the amount is observed as a response to recently introduced incentives and new legislation.

2.2.1. Setup of the algorithm's starting values

The minimization of the sum of square errors (looking for the least sum of squares) in the non-linear regression model (1) does not guarantee convexity of the objective function. Only a locally optimal solution can be found. Some pre-processing effort has to be made to achieve suitable starting values for the locally convergent Marquardt-Levenberg similar algorithm to find a globally optimal solution, see, e.g., Bazaraa et al. (2014). Therefore, the extrapolation was repeated in several iterations. Parameter a was established on the basis of the most recently reported data (in our case it was from the year 2015, see supplementary materials). Parameter b was set to zero. A uniform probability distribution of U(-3,3) was used to generate c values. This interval was estimated by our investigation to be the most suitable since it covers most observed trends in WM. The mentioned scheme was utilised to repeatedly generate the algorithmic starting values of c. For each of the s iterations, the quality of the regression was measured in a standard way as the sum of least square errors ε_{is}:

$$\forall i \in I: \qquad \varepsilon_{is} = \sum_{t=2009}^{2015} (m_{it} - M_{its})^2 \tag{2}$$

where t is the year based on the utilised regression model, m_{it} is historical input data for years t (2009–2015) and nodes i, and M_{its} is a computed value of waste production in the year t, node i and specific iteration s.

The results were compared and an extrapolation model (coefficients a, b, c), experiencing minimum ε_{is} denoted as $\varepsilon_{i,opt}$ is awarded as an initial estimate for the next calculation by the reconciliation model proposed in Section 3.

For future computations, this pre-processing can also be optimised to improve the regression models as their number can be quite large for SCM applications and hundreds of nodes. Due to the extreme time requirements, the selection of initial estimates and number of iterations may be subject to further enhancement. For example, the initial values can be obtained by choosing three typical points and a solving system of non-linear equations to get the solution values (not necessarily unique) of three regression parameters.

2.2.2. An evaluation of the extrapolation model's quality

To evaluate the quality of the extrapolation model, we proposed the following parameter Q_i:

$$Q_i = \frac{\frac{1}{N}\sum_{t=T1}^{T2} m_{it}^2}{\varepsilon_{i,opt}} \tag{3}$$

where T1 and T2 represent the first and last year, respectively, where the time series is available, $N = T2 - T1$, because it is the number of years for which data are available.

The quality of an individual extrapolation model is expressed by $\varepsilon_{i,opt}$ and Eq. (2). These absolute values are not suitable for comparing nodes with completely different production. Therefore, normalisation expressed by Eq. (3) is implemented, where the average of square productions serves this purpose. The higher the Q_i,, the better the extrapolation model which was achieved.

2.3. Discussion on aggregation and forecasting

At this point, extrapolating models on future production are available not only in micro-regions (L2), but also in all regions (L1) and for the whole country (L0). There is less data variation at L1 and L0 levels and extrapolation provides models with a better fit (for example, expressed by Q_i). In other words, TSA for larger geographical areas provides more robust predictions. This is illustrated later in the case study.

The mentioned areal aggregation may be applied not only to historical data but also to extrapolated values. This opens up alternative ways how to build extrapolation models for nodes situated at higher hierarchical levels in the tree structure.

This idea is illustrated in Fig. 3. The starting point, located in the origin of our coordinate system, is established by the historical data for nodes at level L2 (micro-regions). There are three basic moves possible in the direction of the three axes (see edges highlighted in red). These moves are associated with two types of actions: i) forecasting ($\rightarrow$ symbol) and ii) aggregation ($\sum$ symbol). A move upwards along the vertical axis represents aggregation for various types of waste. This type of aggregation is mentioned in Section 4, where the procedure of grouping waste codes was applied to define investigated streams. There are two alternatives left: For example, we can take the local forecasts first (base level extrapolation, L2) and follow the horizontal edge. Then, we can move in parallel with the depth axis to aggregate the L2 forecasts with the hierarchical spatial structure. The displayed situation is relevant for aggregation towards the country level (L0) forecasts, which means that all forecasts for all L2 nodes were summed. The alternative path starts with the aggregation of region-related information and is followed by the forecasting model computations at country level data. In

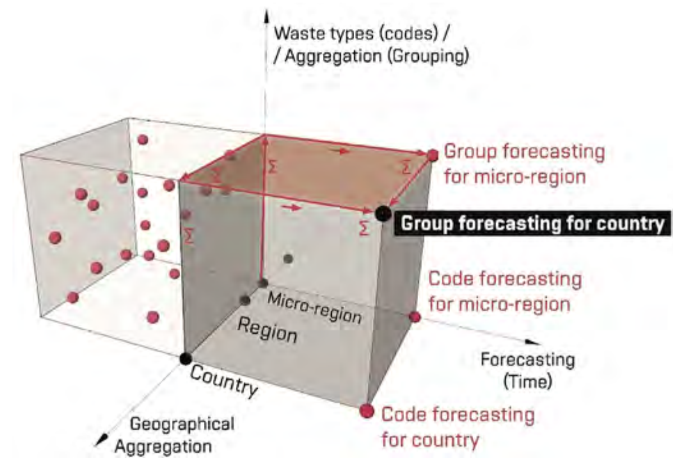

Fig. 3. Visualisation of the consistent forecasting procedure, where the order of aggregation ($\sum$) and forecasting ($\rightarrow$) operations do not influence the result.

general, the moves may be ordered arbitrarily. In addition to the previous steps, intermediate levels (e.g. L1) can be included as points where the direction is changed. This leads to many combinations and possibilities how to build the final model.

Fig. 3 also illustrates the desired state where the same forecasted value is obtained irrespective of the movements along the box's edges. The group forecast we require for a country is depicted by the vertex highlighted in bold. It also means that the final forecast is subject to the areal constraint that represents a mass conservation, as introduced above.

Unfortunately, it is not possible to guarantee that all models will be equivalent from a mathematical point of view. This is due to the treatment of uncertainty in computations, the necessity to use the non-linear regression models and non-commutative properties of aggregation and forecasting steps discussed above. This is also illustrated in Fig. 2 b), where two different extrapolation models were obtained, resulting in values M1 and M2 for the year 2020. Model M1 starts at bottom level data and forecasts for all L2 nodes are performed. Following the mass conservation (applied to future forecasts), we aggregate the extrapolation's results to obtain a forecast at L0 level. Alternatively, forecasting on top level data was performed for M2.

We conclude that the result may depend on the order of the operations, geographically-based sums and level–related extrapolation, because the different models differ by their presence, realisations, and treatment of random errors, which are interpreted as a source of uncertainties. This finding was considered to be a key-driver to develop a reconciliation technique, where results from extrapolation are treated as initial estimates.

2.4. Forecasting improvements by implementing the reconciliation technique

A variety of spatially distributed forecasts (sub-models) for production at every considered node were obtained separately by the mentioned basic TSA (based on non-linear regression models). For nodes at higher organisational levels (i.e. L0 and L1 in Fig. 4), the forecasted values may obviously differ for the various sub-models (see M1 and M2 in Figs. 2 and 4 for instance). They are considered to be initial estimates from now. In the next step, they are subject to further processing by the reconciliation-based model, leading to consistent and unified, final forecasts (see red stripes and R in Fig. 4).

From a computational point of view, the balancing itself is

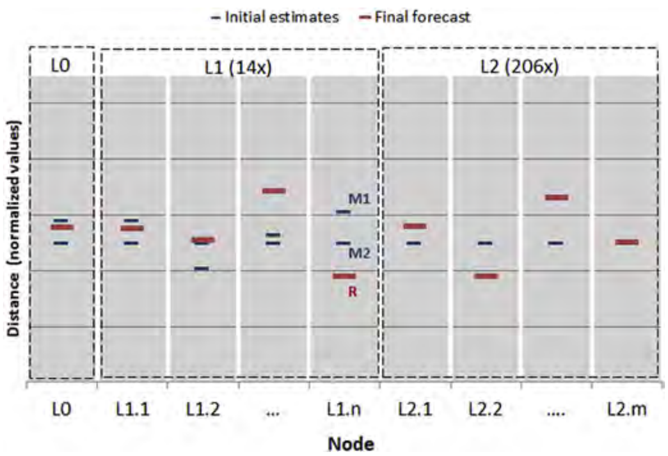

Fig. 4. The principle of model adjustments and final forecasted values.

inspired by the frequently used engineering principle of least squares of differences. The same technique is used in many other areas as summarised in Section 1.3.

A common denominator for the studies mentioned in this section is that the process they describe is a steady state, the topology of the model, mass and energy conservation equations (linear or non-linear) and that the covariance matrix of the measurement errors is directly known or can be determined from historical process data. The problem addressed in this paper differs in these regards. Instead of a rigorous process and an identified precision of measurements, a several forecasts are prepared for future values (possibly from different models/approaches) and the mass balance-like constraints correspond to certain consistency requirements (i.e. that the resulting forecasted values for higher hierarchical structures should equal the sum of the forecasts of its components). The variability of error for the different forecasts (i.e. in the data coming into the model) is unknown to us, hence the introduction of different weights is proposed.

Furthermore, weight parameters are derived and utilised to equalise the differences between nodes together with an area-hierarchical relationship approach. We have to emphasise that this approach allows us to also use other (e.g., more robust) optimisation criteria and structural modifications to the related constraints. This will be presented in forthcoming papers.

In the mentioned articles about data reconciliation, weights for each measurement are usually determined on the basis of the quality of the data measurement and collection, which is generally not always available. In our case, there are multiple models for one node. The data are tied to each other and each change affects all the other elements of the system for industrial processes. For each of measurements, errors are additionally present and the assumption is their mutual independence.

In the case of this paper, the production of waste is predicted, while the value is estimated separately in each location and it has no effect on other elements of the system. These values are tied up in the final model, where the data reconciliation is performed. The aim is to obtain the maximum from the historical data, while the desire is to exploit a suitable regression model for predicting a trend (usually non-linear). The key input parameters for the entire balance task are weights and their choice. This respects the character of the historical data with regard to their predictability (the existence of trends in historical data with minimal variability in the data). For this purpose, a new approach for evaluating the quality of the models is proposed.

3. Reconciliation model

Since extrapolations performed for all nodes are inconsistent in terms of mass conservation in a tree-like structure, reconciliation represents the next logical step. Data reconciliation is basically mathematical programming and it has been found by the authors to be a proper approach to deal with the initial estimates and their adjustments.

3.1. Mathematical model

Before building a model, the following notation is provided with a description:

sets and indices

$i \in I$ index of territorial units (nodes)
$d \in D$ index of particular data set (extrapolation models)
$h \in H$ index specifying particular area-hierarchical constraint

parameters

A_{hi} matrix reflecting the hierarchy of territorial units (nodes) and waste codes grouping
M_{id} two-dimensional parameter containing data for node i and data set d (values from extrapolation models for all nodes)
p_{id} $\{0,1\}$ indicator of data availability for node i and data set d
w_i^I weights for node i
w_d^D weights for data set d

variables

R_i amount waste for node i
e_{id}^+ positive part of an error in data for node i and data set d
e_{id}^- negative part of an error in data for node i and data set d

With this notation, we have built the following mathematical model:

$$\min_{\{e_{id}^+, e_{id}^-\}} \sum_{i \in I} \sum_{d \in D} w_d^D w_i^{I^2} \left(\left(e_{id}^-\right)^2 + \left(e_{id}^+\right)^2 \right) \tag{4}$$

Subject to

$$\sum_{i \in I} A_{hi} R_i = 0 \qquad \forall h \in H \tag{5}$$

$$p_{id}\left(M_{id} + e_{id}^+ - e_{id}^- - R_i\right) = 0 \qquad \forall i \in I, \forall d \in D \tag{6}$$

$$e_{id}^+, e_{id}^- \geq 0 \qquad \forall i \in I, \forall d \in D \tag{7}$$

$$R_i \geq 0 \qquad \forall i \in I \tag{8}$$

Eq. (4) represents the objective function, which summarises all positive and negative squared errors with weights w_i^I for each node and weights w_d^D for data set d, which are used to balance differences. The use of the square of the weight w_i^I and their construction is explained further on in Section 3.2.

Eq. (5) follows the idea that some lower nodes i (from L2 or L1) are part of a bigger node (from L1 or L0 respectively) and can also connect waste codes into groupings. This feature is included in matrix A_{hi}, where h defines a row and corresponds with a particular area-hierarchical constraint. Each row consists of numbers $\{-1; 0; 1\}$, where -1 defines a bigger node for an index i_L and $\{0; 1\}$ number indicates if it belongs to it or not for the rest of nodes with corresponding indices.

There is Eq. (6) which connects the input data M_{id} with the decision variable R_i and the respective error between them, which is separated into a positive and negative part (e^+_{id}, e^-_{id}). The error is separated to allow easy implementations of the other forms of criteria, such as the sum of absolute values of errors. The binary indicator parameter p_{id} determines whether Eq. (6) with indices i and d is used or not, which is based on the parameter's data availability M_{id}, see Eq. (9).

Eq. (7) defines non-negative bounds on variables e^+_{id} and e^-_{id}.

Eq. (8) states the variable R_i as non-negative.

The binary indicator parameter p_{id} is defined as follows:

$$\forall i \in I, \forall d \in D: \quad p_{id} = \begin{cases} 0, & \text{if } M_{id} \text{ not available or incorrect} \\ 1, & \text{otherwise.} \end{cases} \tag{9}$$

Use of the least square method is motivated by expert based advice and by experience with computer science heuristics in engineering. The least square method in its traditional applications, results in a description where the sum of the square distances between each of the input data (and the related forecasted or model-based value) is minimised. The application is illustrated in Fig. 4 for our case. The initial models (see M1, M2 and all other blue points in Fig. 4) obtained from TSA and RA are split into groups related to the points specified by year and location. In other words, each of the groups which is represented by a grey vertical bar in Fig. 4 is associated with one unknown parameter, which describes the point-related waste production. For example, M1 and M2 stand for initial estimates for production in a particular node. Considering each of the vertical bars, the initial estimates have to be balanced (corrected) to provide a final forecast, labelled R (the thicker red segment of the horizontal straight line). However, the task cannot be solved in a decomposed way for each of the bars due to the additional area-hierarchical constraints and related reasons mentioned above. It is handled by the above-mentioned optimisation model involving both balancing and the discussed constraints (Eq. (5)). In this context, Fig. 5 shows a simplified example of the unknown “hazardous waste amount”, previously displayed as the first bar on the left in Fig. 4. The final corrected forecast (the R point on the horizontal axis) is obtained by balancing values from the two initial models (points M1 and M2). The result, R, is shifted to the left from M1 and M2 due to the effect of the area-hierarchical constraints. In our complex interconnected system, the correction in the first bar introduces secondary deviations in all the other bars. This effect is illustrated by the visualisation of a “penalty function based constraint relaxation” for the model in Fig. 5.

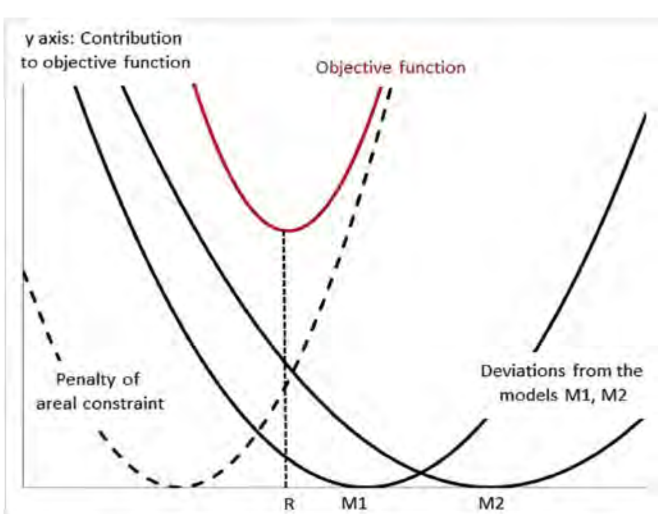

Fig. 5. The balancing principle illustrated as an optimisation task for specific node.

One important task is to discuss whether the optimal solution obtained by classical locally convergent algorithms for the model Eqs. (4)–(8) is a global one. It is a non-linear optimisation model. Because the node-related non-linear regression models are separated from the optimisation model in this text as the related computations are realised in advance, we can enlist the following facts:

Each optimisation problem can be characterised from the viewpoint of linearity and convexity. In the introduced model the sum of squared errors is minimised. These errors are the differences between the input data and the resulting modelled forecast. The minimised objective function is a quadratic convex (see Fig. 5 for an example). In addition, the areal constraints are linear.

For the above reasons, the minimization of a convex quadratic objective function (on a convex set specified by linear constraints) assures the global optimum, which was proved in Giaquinta and Modica (2012), for instance. Well-developed algorithms from the field of quadratic programming can be utilised to solve this problem.

3.2. Locality-dependent weights

With respect to the fact that territorial units have different areas, populations, and different waste productions, the estimated errors influence the objective function with various significance from a waste management specialist's point of view. The model without weights gives preference to the reduced error in bigger territorial units in order to minimalize square errors. Errors in smaller territorial units may increase, which is the impact of heteroscedasticity. For this reason, it is necessary to design a system of weights for individual errors in order to be able to minimise the impacts of these errors almost uniformly.

Based on these requirements, the goal in the weights construction process is to make all input data equally significant in the objective function. Several approaches have been applied to solving these problem and related tests have been performed. Finally, these weights were constructed in order to normalize errors from input data. In this case, the effect was achieved by using a square of weights w^I_i in the objective function (Eq. (4)) for each territorial unit, where the weights are the inverse of the average. The weights for all territorial units then look as follows:

$$\forall i \in I: \quad w^I_i = \begin{cases} \dfrac{\sum_{d \in D} p_{id}}{\sum_{d \in D} M_{id}} & \text{for nonzero } \sum_{d \in D} M_{id} \\ 0, & \text{for } \sum_{d \in D} M_{id} = 0 \end{cases} \tag{10}$$

When utilizing weights according to Eq. (10), the importance of errors in the objective function gets normalized.

The weights w^D_d are generally set according to the quality of the extrapolation model.

3.3. Computational tests of proposed model

To illustrate and discuss benefit of the model, we present a special test case at the end of this section. For our explanatory example, we consider two input data sets specifying waste production. The hierarchical regional structure (see Fig. 1) is taken into the account as defined for the Czech Republic. This means 1 × L0, 14 × L1 and 206 × L2 (see supplementary materials). The first data set, M1, represents the original input data from 2015, as received from the authorities (presented in Section 4 and in supplementary materials). For each of L0 and L1 nodes, the areal constraint is satisfied in this dataset. The second data set, M2, is generated by incorporating a random error into M1. The multiplier from normal probability distribution, N(1, 0.01) was repeatedly generated and applied. As a result, areal constraints were violated since it is not possible to guarantee that the values in the L1 node are the sum of values for emulate random errors in all its L0 nodes. In fact, we are describing a multiplicative model. Areal constraints are violated for M2 but not for M1. Both M1 and one instance of M2 entered the core calculation. There were two initial estimates for every node and the algorithm was tested to see how it addresses these initial estimates to produce the final result, R.

Before analysing the result, let us briefly comment on the anticipated results and their interpretation. Considering each node separately, the average value presented by the dashed line between M1 and M2 would become the expected result without areal constraints. Both models are handled with the same weight and there is no other information in such reduced computations. On the other hand, different new relationships between data are involved (see Fig. 5) and some other results can be obtained that are more challenging for interpretation. There are four possible expected results, labelled R1 to R4 as visualised in Fig. 6.

The cases R1 and R2, those near to the original M1 data, are favoured. Such a result is better than a simple average. In addition, it ignores M2, which is loaded by error and prefers the original M1 value. On the other hand, R3 and R4 are not welcome as they are worse than the average of M1 and M2 (see K = 0.5 in Fig. 6). These cases are unwanted when large errors and, hence, distances between M1 and M2 appear. Let us emphasise that for small errors (i.e. small distances between M1 and M2 inputs), even R3 and R4 are not far away from M1, and hence, they are usually acceptable. The following expert-based empirical criterion was introduced to analyse the discussed problem:

$$K = \frac{(|R - M1|)}{\max(|R - M1|, |M2 - M1|, |R - M2|)}. \tag{11}$$

In the case of the result between M1 and M2, K will be around 0.5 and will indicate the model's choice difficulty.

The test results are displayed in Fig. 7 a), where M2 was generated repeatedly for 100 scenarios, followed by computations of optimal solution for model Eqs. (4)–(8) for each of scenarios. Fig. 7 a) and b) separately displays the results for regions L0 and L1 and L2 nodes.

The asymmetry of results in Fig. 7 a) vindicates the benefit of proposed model by detecting errors on L0 and L1 levels. Additional information from areal constraints is positively utilised L0 and L1 nodes, where it was available. Most results are located close to M1 in the region of R1 or R2, i.e. K is close to 0. When we have L2 nodes,

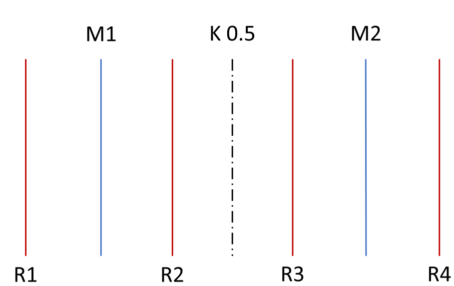

Fig. 6. A qualitative presentation of possible results.

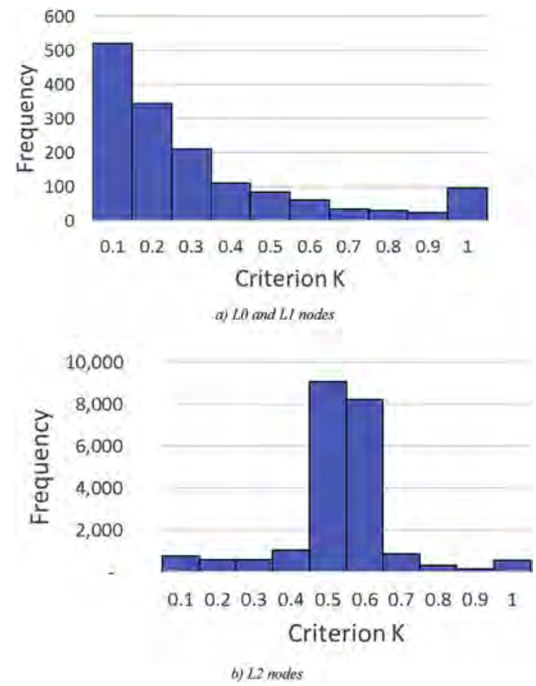

Fig. 7. An evaluation of the input data's set preference. a) L0 and L1 nodes. b) L2 nodes.

we can see the piece-wise uniform preference of the input data. The symmetry in the data is inherent and a typical 0.5 value was expected. There is no additional information provided by areal constraints for any L2 node since these nodes have no descendants. Therefore, both the M1 and M2 model are considered with similar importance. Only some L2 nodes were shifted from K = 0.5 if this helped to satisfy the areal constraint at L1 or L0 level (see the shift in R to the left in Fig. 5).

Without going into detail, we can also mention some other observations which resulted from the comprehensive testing:

- The increased standard deviations of the errors do not change the results qualitatively.
- If a systematic error is not included, then the M1 impact on the total error is about 23%.
- The largest impact on errors came from L0 and L1 levels, while L2 deals with smaller numbers and, hence, its influence is not so significant.
- The results of the test examples show that the introduced model Eqs. (4)–(8) is also suitable for cases containing systematic errors in data sets. A systematic error shifts the result while all areal constraints are still satisfied and the objective function is minimised.
- Based on our investigation, the key factor for the quality of a resulted forecast is the relationship between a random and systematic error. The empirical conclusion says that with the increase of systematic errors (compared to random errors), the tendency is more to the neutral position between the input data (K = 0.5).

There are three final comments to be made about our tests. First, in the examples where the data shift influenced by a systematic error was greater than the standard deviation of a random error, the results do not show better values than the average for M1 and M2's input data, without areal constraints. Secondly, some iteration results look better for the average of the input data (K > 0.5) is specific for particular generated data. Finally, when repeatedly generating from the same probability distributions, the average results (for K) would converge to 0.5, i.e., the qualitatively same R result for the resulting model and with an increasing importance of the random error (compared to a systematic error), the total results obtained from calculations are much better than the averaging of input data used overall.

4. Case study

Following on from the previous discussion about the proposed model and solution algorithm's behaviour for explanatory input data, we shall further focus on its use for a real-world case. The software implementation of the extrapolation approach and model introduced in Section 3 and related solution algorithm is called JUSTINE.

We may distinguish many types of hazardous waste according to its physical state, composition, heating value and hazardous traits (toxicity, etc.). In our specific case, we dealt with 380 categories, denoted by specific codes according to the European waste code system (European Parliament and the Council, 2000). Each of these fulfilled one of the hazardous properties defined by European Parliament and the Council (2008). Data were available for production in the last 7 y (time row 2009 to 2015) for each of the codes. The territory under investigation was the Czech Republic (L0), composed of 206 nodes, representing micro-regions (L2.X, where X denotes a specific micro-region). Each micro-region belongs to one of the 14 regions (L1.Y, where Y denotes a specific region). A time series for production of each code was available at the lowest considered level L2, i.e. for each of the micro-regions. To make the situation simpler and to avoid handling such a large amount of data, codes of similar properties were grouped into the following streams of hazardous waste (HW).

- HW for incineration (INC)
- HW for stabilization
- HW for biodegradation
- HW for a demulgation/neutralization line
- HW for incineration or stabilization
- HW for demulgation/neutralization or stabilization.

This grouping is represented in Fig. 3 by the upward move from the origin of the coordinate system and was done based on possible methods of treatment process for the individual code. There is no overlapping between the groups, i.e. each of the codes belongs to only one group. Since there is no space to provide expanded details on every group, one of the six groups, titled “INC HW for incineration” is used as an example in this case study and the subject of the following text. Other groups are mentioned too if it was a necessity to comment on results in a broader perspective.

4.1. Input data and pre-processing

For illustration, Table 1 shows input data for the INC stream. A full dataset for this stream is included in the supplementary materials. Total production is mentioned for the whole country, a selected region identified as L1.5 (Liberec region) and in all 10 descendants of this region in the year 2009–2015. Whereas production at country level decreased by 23% in this period, one can observe a completely different trend in the L1.5 region. Here production rose by 59%, especially due to a surge in the L2.86 micro-region (Liberec), which represents the most populated and industrialised city in the whole region. In contrary to municipal solid waste, the production of HW is dominantly bound to the industrial sector. There is no correlation between population and INC production. Nevertheless, we provide some basic information for comparison:

- The Czech Republic: 10.55 million citizens, gross domestic product GDP in 2015 was 169,000 EUR.
- L1.5 Region: population in 2015 was 439,640 citizens.

At first, the data related to Table 1 were verified and extreme values were identified. They were considered to be incorrect and were excluded from further computations. To avoid the subjective role of an expert's opinion in excluding these outliers, Dixon's statistical test was utilised and a significance level 0.05 was set. Original values are shown in parentheses (see Table 1). The values identified as extreme outliers were substituted by the average of neighbouring values. For example, the value for L2.63 (Jilemnice) in 2011 was replaced by the average values from 2010 to 2012, i.e., $(334+174)/2=254$. For the extreme values at the beginning or the end of the considered time period, the neighbouring value was used, e.g., the value for Turnov L2.177 from 2015 was replaced with the value from 2014.

Although Dixon's test was suitable for most of the case study's data, several limitations of its use appeared. The test fails for two significant outliers in the short-time series (see Table 2) and the same may happen in for the symmetry for minimum and maximum data outliers. The following Table 2 repeats the INC waste production data of Tanvald micro-region (L2.168), where Dixon's test did not help to identify the steep growth in the waste production. According to the results of the commonly used Q-Test, the experienced value was 0.181, which is well below the threshold value of 0.507 (for details see Dean and Dixon, 1951). Consequently, it influences the whole region L1.5. This impact on the waste production trend in the Liberec region puts the focus on the necessity to continue the discussion on data verification. In this case, the use of an outlier detection technique that is suitable for a TSA test is recommended.

4.2. Extrapolation

Extrapolation models for all territorial units, i.e. L0, L1 and L2 nodes, were generated, applying the non-linear regression model and iterative processes mentioned in Section 2.2.

In addition, the quality of extrapolation models Q_i according to Eq. (2) was evaluated for all time-series involved in our case study. The results confirmed the assumption of a better model fit for higher territorial units (L0, L1) compared to base nodes (L2) as was mentioned in section 2. Table 3 summarises Q_i to the average Q achieved at different territorial levels. Not only INC, but also all other streams mentioned at the beginning of this section were included in the assessment.

The value of Q_i may be further utilised as weights w_d^D associated with every initial estimate (M1) entering the calculation (see Section 3, Eq. (4)). Weighting was not applied in our case study as it is a subject for future computational development and testing. As mentioned in Section 2.2, the higher the Q_i, the better extrapolation model achieved and further used for constructing the weights w_d^D. A future research challenge is to establish a minimum threshold value of w_d^D. If this is not done, weights close to zero cause massive corrections by the reconciliation and, in fact, lead to unrealistic solutions.

4.3. Balanced results

The results of the extrapolation are summarised for our region in Table 4. Further details can be found in supplementary materials. First, initial guesses for 2020 were calculated by the extrapolation models. In addition to this, alternative initial estimates were

Table 1
Hazardous waste for incineration (INC); production data in the investigated region [t/y].

Node name	Node ID	Superior node	Year						
			2009	2010	2011	2012	2013	2014	2015
Czech Republic	L0	N/A	437,748	334,739	385,367	271,165	292,015	322,050	338,407
Liberec region	L1.5	L0 (CZE)	8,645	9,958	12,098	10,560	11,377	10,501	13,718
Česká Lípa	L2.21	L1.5	2,806	2,213	2,090	3,441	2,387	2,423	2,701
Frýdlant	L2.35	L1.5	717	1,049	2,419	979	1,749	1,610	1,121
Jablonec/Nisou	L2.57	L1.5	1,181	1,193	935	1,138	1,051	1,592	1,103
Jilemnice	L2.63	L1.5	235	334	254 (662)	174	225	174	261
Liberec	L2.86	L1.5	2,738	4,022	4,917	3,896	4,868	3,440	6,359
Nový Bor	L2.114	L1.5	235	263	170	162	252	213	268
Semily	L2.152	L1.5	154	372	269	238	301	227	518
Tanvald	L2.168	L1.5	95	72	128	127	118	318	373
Turnov	L2.177	L1.5	454	393	482	368	388	465	465 (951)
Železný Brod	L2.205	L1.5	29	47	26	37	38	40	62

Table 2
Dixon's test applied to INC HW production in the Tanvald micro-region L2.168.

Production [t/y]							Q-Test result	Q-Test threshold
2009	2010	2011	2012	2013	2014	2015		
95	72	128	127	118	318	373	0.181	0.507

Table 3
The average values of Q achieved for various territorial units.

Level	L0	L1	L2
Q value [-]	26.5	9.3	2.2

determined for territories at a higher level (L1, L0) in accordance with Section 2. In fact, M2 represents the sum of M1 forecasts for all descendant locations. Referring back to Fig. 3, the following sequence of the symbol may be used for M1 ($\sum$; $\rightarrow$) and M2 ($\rightarrow$; $\sum$). The difference between M1 and M2 was also evaluated for comparison.

In this case, there are nearly negligible differences of 0.2% and 0.7% between M1 and M2 for L0 and L1.5. However, there is no guarantee that similar positive results would be obtained in all L1 regions. This is documented in the next Fig. 8 and Fig. 9. Whereas for most of L1, the difference is very low (up to 2%), there are a few where the gap is significantly higher. The highest was identified in L1.11, where the difference is more than 50% (for details, see supplementary materials). At the same time, the quality of the M1 model expressed by Q is significantly lower compared to other L1 regions. (See Fig. 8 and supplementary materials).

The results confirm that it is not possible to secure, from a mathematical point of view that all models will equal due to the uncertainty-related reasons discussed above. This real-life data case justifies the application of the proposed computational tool, which can handle different models at different territorial units. Such a model was proposed in Section 3 and used on our data.

For our tree-like structure, there were 206 M1 models for 206 L2 locations. Their confidence level expressed by Q_i was different. In addition, forecasted values for 14 L1 and one L0 region entered the core-calculation. On the other hand, M2 models were not used as initial estimates since they were substituted by areal constraints (see Eq. (5)), which represents a mass conservation equation for a region and all of its sub-regions. It is of the same meaning as M2.

The calculation was made on a computer with Intel(R) Core(TM) i7- CPU @ 3.40 GHz.

Table 4
Forecasted production of INC stream for the year 2020.

Node name	Node ID	Superior node	Trend 2020 [t/y] M1 ($\sum$; $\rightarrow$)	Criterion quality M1 [-], Q	Trend 2020 [t/y] M2 ($\rightarrow$; $\sum$)	Difference M1 and M2	Prediction 2020 [t], R	Difference R and M1
ČR	L0	N/A	312,483	3.4	313,722	−0.2%	320,221	2.4%
Liberecký kraj	L1.5	L0	12,786	6.1	12,614	0.7%	12,542	−1.9%
Česká Lípa	L2.21	L1.5	2,694	1.1	N/A	N/A	2,679	−0.6%
Frýdlant	L2.35	L1.5	1,524	0.3	N/A	N/A	1,515	−0.6%
Jablonec/ Nisou	L2.57	L1.5	1,236	1.3	N/A	N/A	1,229	−0.6%
Jilemnice	L2.63	L1.5	199	0.7	N/A	N/A	198	−0.6%
Liberec	L2.86	L1.5	5,378	0.9	N/A	N/A	5,347	−0.6%
Nový Bor	L2.114	L1.5	220	0.9	N/A	N/A	219	−0.6%
Semily	L2.152	L1.5	534	0.3	N/A	N/A	531	−0.6%
Tanvald	L2.168	L1.5	335	0.1	N/A	N/A	333	−0.6%
Turnov	L2.177	L1.5	427	2.7	N/A	N/A	425	−0.6%
Železný Brod	L2.205	L1.5	67	0.6	N/A	N/A	67	−0.6%

Note: The difference between models M1 and M2 was determined as $|M1 - M2|$ divided by the average from M1 and M2. This was also done for R and M1.

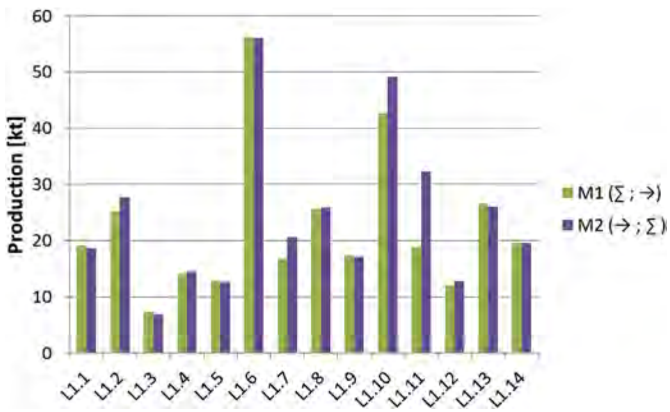

Fig. 8. The difference between the values of the models' prediction for L1.

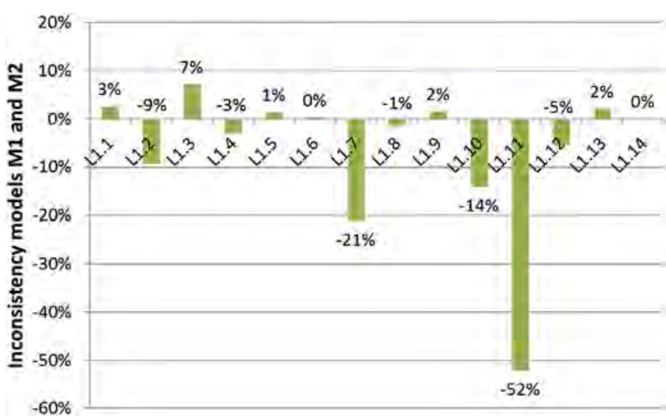

Fig. 9. Inconsistency in models M1 and M2 for L1 level.

The computational times for the areas (L0, L1 and L2 – together 221 nodes) and 6 categories (total 380 waste codes) were as follows:

- Forecasting future waste production (see Section 2) –386 $(380 + 6) \times 221$ $(206 + 14 + 1)$ computations performed in total with 10 different starting values with an average time of 0.543 s results in a total calculation time of 5.4 d.
- Reconciliation of forecasted values (see Section 3) – only one calculation with input data loading time 240 s and solving time 150 s.

The result (i.e. the final corrected forecast) for the studied region is depicted in Table 4 in column R. Initial estimates for L0 (country) were increased. Even though there was a very small difference between M1 and M2, this was necessary. In other words, much more serious deviations at L1 and L2 level were prevented. The results also revealed a significant correction minus of 1.9% for L1.5 (Liberecký kraj). As a result, corrections in all micro-regions belonging to L1.5 were kept at a minimum. The same correction of minus 0.6% results from applied normalisation by utilization of weights (see Eq. (10)).

Significant changes were made, as can be further examined in the supplementary materials. The corrections ranged from between 0% and 10% for 86% of nodes with average of 3%. The adjustments for the rest of nodes ranged from between 10% and 31.2% and were caused due to the especially low quality of extrapolation models.

Taking into account all types of waste, the corrections ranged from between 0% and 12% for 90% of nodes. There were 17 nodes where massive adjustments up to 30% were inevitable.

5. Conclusion and future work

A complex approach to handling the problem of spatially distributed, incomplete and uncertain data forecasting was proposed. It combines several steps which provide data quality assessment, trend series analysis (to provide extrapolated future values) and initial estimate corrections via a data reconciliation model.

The investigated problem was considered at different territorial levels (regions, micro-regions and their parts), where an organisational structure is described by a tree diagram. Areal data aggregation was performed in accordance with this tree diagram for both historical data and forecasted values. Considering the different levels of detail, additional constraints called "areal constraints" were introduced and used as a main element in the reconciliation model. These constraints, which are linear, represent mass conservation equations in the tree structure and they cause corrections of the forecasts in nodes where historical data and regression models are uncertain. The objective function to be minimised is based on the least square principle traditionally implemented in industrial data reconciliation.

The principles and benefits of the proposed model and related computational algorithm were implemented into software called JUSTINE and its benefits were explained through a case study in waste management, where future amounts of hazardous waste suitable for thermal treatment was forecasted for 206 micro-regions, 14 regions and the whole country of the Czech Republic. The case study revealed that extrapolations carried out at different levels of the hierarchical organisational structure lead to inconsistent forecasts. The differences were subject to the qualities of extrapolation models, which were measured by a newly developed criteria Q.

The proposed approach is suitable for many applications of supply-chain and network flow models where future amounts of commodities (the flow of which is optimised) are to be forecasted for a lot of nodes.

Our case study dealt with several waste streams. They were without interactions. The proposed algorithm also handles issues comprising several interconnected streams, where components overlap between streams. Municipal solid waste represents a good example as it consists of several fractions, such as paper, plastics, biowaste, mineral, and so on.

Future work will focus on extending the model to handle such a multi-commodity problem.

Acknowledgement

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2017.06.107.

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ORIGINAL PAPER

Municipal Solid Waste Fractions and Their Source Separation: Forecasting for Large Geographical Area and Its Subregions

M. Pavlas[1] · R. Šomplák[1] · V. Smejkalová[2] · P. Stehlík[2]

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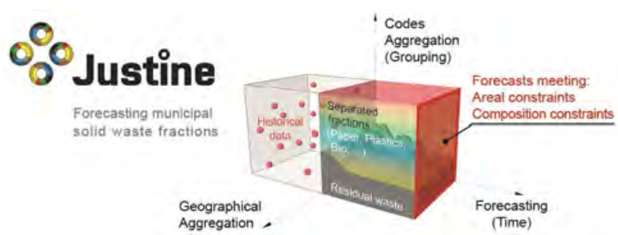
Abstract

This paper introduces an approach toward forecasting municipal solid waste and its fractions in a large geographical area divided into subregions. A multi-commodity system, where components overlap between streams of residual waste and separately collected recyclables, is developed to predict composition, future amounts and separation efficiencies. The approach combines a reconciliation-based balancing model with regression analysis and time series analysis. Regression analysis provides models which are later used to get complete information for all nodes of tree-like structure describing the geographical area of interest. Time series analysis proposes initial models on future amounts for all fractions. The balancing model with newly formulated composition constraints corrects initial estimates, which is a key issue especially for short-time series where precise extrapolation models can hardly be secured. The developed approach contributes to analysing rational recovery targets by reflecting the current situation in individual (micro) regions and, at the same time, it exploits examples of good practice from regions with high recovery rates. Here the analogy with rigorous regression models (historical data from one region can serve as one scenario for another region) is utilised. The algorithm is demonstrated through a case study inspired by an extensive project for the Ministry of the Environment of the Czech Republic.

Graphic Abstract



Keywords Municipal solid waste · Circular economy · Separation efficiency · Separation rate · Network flow model · Paper separation · Plastic separation · Forecasting

✉ M. Pavlas
martin.pavlas@vutbr.cz

1 Sustainable Process Integration Laboratory – SPIL, NETME Centre, Faculty of Mechanical Engineering, Brno University of Technology – VUT Brno, Brno, Czech Republic

2 Institute of Process Engineering, Faculty of Mechanical Engineering, Brno University of Technology – VUT Brno, Brno, Czech Republic

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Abbreviations

ARIMA	Auto-regressive integrated moving average
ARMA	Auto-regressive moving average
BAU	Business-as-usual scenario
BIO	Bio-waste
CA	Correlation analysis
CE	Circular economy
CEP	Circular economy package
CZE	Czech Republic
GLA	Glass
GLM	Generalised linear model
MSW	Municipal solid waste
NN	Neural networks
PAP	Paper
PLA	Plastics
RA	Regression analysis
RES	Residual solid waste
RES_{PAP}	Paper in residual waste
RES_{PLA}	Plastics in residual waste
RES_{GLA}	Glass in residual waste
RES_{OTH}	Other fractions in residual waste
SE	Separation efficiency
SEP	Waste collected as separated
SEP_{BIO}	Bio-waste collected as separated
SEP_{PAP}	Paper collected as separated
SEP_{PLA}	Plastics collected as separated
SEP_{GLA}	Glass collected as separated
$TOTAL_{SEP}$	Total amount of waste collected as separated
TSA	Time series analysis
$k \in K$	Set of micro-regions
$j \in J$	Set of regions
$t \in T$	Set of time periods
x_k	Waste production in micro-region k
f_k	Prediction model for micro-region k
F_j	Prediction model for region j
m_k^*	Prediction model for micro-region k in specific time period
M_j^*	Prediction model for region j in specific time period
t_r	Specific time period
m_k	Corrected value of prediction model for micro-region k
ε_k^m	Correction for micro-region k
M_j	Corrected value of prediction model for region j
ε_j^M	Correction for region j
$\delta_{i,opt}$	Defines the sum of least square errors
Q	Quality of extrapolation model criterion
a, b, c	Regression parameters
N	Number of years
T_1, T_2	First and last point of time series
$d_{i,t}$	Historical data of time series i in the year t
e	Euler's number

Statement of Novelty

This paper introduces an approach toward forecasting municipal solid waste and its fractions in a large geographical area divided into subregions. Recyclables as paper, plastics, glass and their contents in residual waste is modelled in a new way. In addition, current and future residual waste composition and separation efficiencies are predicted. The approach combines several techniques of statistics and optimization. Additional constraints are newly proposed for a tree-like structure, which secures that amount of waste produced in all subregions is equal to amounts produced in a region consisting of these subregions. The developed approach contributes to analysing rational recovery targets and, at the same time, it exploits examples of good practice from regions with high recovery rates. The case study is solved.

Introduction

Whereas developing countries face increasing production of waste and are in the process of establishing organised waste treatment systems, in the EU and in other developed countries the so-called circular economy (CE) is widely discussed as a concept with minimised waste production and maximum secondary sources utilisation. The initiative is implemented into legislative by so-called circular economy package (CEP). Within the framework of CEP, the amended Directive [1] introduces ambitious goals in municipal solid waste (MSW) recycling. Whereas meeting the goals will be monitored on the country level, measures have to be implemented at the micro-regional and municipal level. Similarly, current separation efficiency and its future progress have to be monitored on this level of detail, too. It is believed that CE will change needs on infrastructure that processes gathered waste streams and produces desired semi and final recycling products.

Regardless of the geographical area in question, be it a developing country or an EU Member State, the basic assumption for qualified and efficient decisions and consequently also policy settings in waste management is the availability of quality forecasts. Estimates of the amount of MSW serve as a basis for infrastructure plans (landfill, waste-to-energy, advanced sorting lines and recycling systems and their combinations) and provide inputs for advanced modelling tools. Inaccurate forecasts can lead to an increase in construction costs or operating costs (waste collection and processing).

The paper is focused on simultaneous forecasting on MSW amounts in fragments of a large geographical area. The outcomes of the methodology proposed can be beneficial for (i) analysis on future waste management concepts of a particular region; (ii) complex modelling of waste flows between producers and processing plants within one or more regions. Therefore, a brief review on state-of-the-art in reverse models is provided first highlighting poor pre-processing of quantitative data on production. Since the problem relates to forecasting in waste management in general, recent works published in this field are provided first. Limitations of frequent approaches are highlighted. Finally, based on a research gap identified, the contribution of this paper is introduced at the end of this section.

Reverse Models—Tools for Waste Management Improvements

Reverse models, which are a special case of supply chain models, focus on the pathway of used products back from customers, as described by Ghiani et al. [2]. Reverse models are promising and often used tools for optimisation of networks in waste management as highlighted by [3]. There have been several works published on this issue. Since they involve analysis of a network comprising 10^2 to 10^3 nodes, we focus on how waste quantities are addressed here. Rudi et al. [4] presented a case study application of a biomass value chain design for the tri-national Upper Rhine Region. The task was based on mixed integer linear programming. It took into account household waste (incl. a fossil fraction). Even though, future scenario 2030 is modelled, the allocated quantities related to 36 locations are not provided. Zis et al. [5] focused on municipal solid waste generated in remote areas and examined alternative options for its treatment. The research focused on 13 small Greek islands. It is claimed, that a regression estimate model was constructed (as it provided the best fit) to predict waste generation until the year 2040. No details on waste quantities are provided. Saif et al. [6] focused on optimisation of system with transfer stations handling organic MSW operated in 5 locations of the central west part of Mexico. The available waste amounts are mentioned for each of the locations without providing any details. Galan et al. [7] oriented on construction and demolition waste. The aim of the paper was to identify the locations and capacity of the transfer stations and processing plants and the corresponding distribution network. Fifty-one municipalities of the Cantabria region in Spain were included. The waste quantities were simply considered proportional to the population, based on an average annual amount produced in the whole region.

Gathering waste production data and its reprocessing into a suitable form are crucial steps leading to the practical application of any optimisation tool for modelling future improvements in waste management. Regarding network flows modelling generally, the situation is complicated due to:

- Forecasting is inevitable since the calculation focuses on future state modelling.
- Waste quantities have to be known for all nodes of the investigated region.
- There are interactions between streams. MSW consists of several sub-streams and fractions, such as paper, plastics, bio-waste, mineral, etc. Some of them are recyclables, and these are collected separately within various collection systems (containers, bring-in systems, kerb-side or a combination thereof). Efficiencies in the systems may differ; however, they are supposed to increase over time, resulting in higher rates of recyclables and a lower amount remaining in residual solid waste (RES).

Approaches Towards Forecasting MSW

There have been several works published on the topic of MSW quantities modelling and forecasting. They come from different countries and regions and employ different statistical techniques. Regression analysis (RA) or time series analysis (TSA) are often employed, and sometimes both are combined. A comprehensive review on this topic was published by Beigl et al. [8] in 2008.

The RA implemented in a large number of models explain variations in production among producers. A wide range of independent (explaining) parameters is tested to find those with the most significant impact. These often include gross domestic product, income, share of different types of housing, type of heating, tourism rate, container distance, etc. The correlation analysis (CA) is often performed for the choice of regressors.

CA and RA have been frequently practised. Both were applied recently in the study undertaken to evaluate the quantity and composition of household solid waste to identify opportunities for waste recycling in Can Tho city, the capital of the Mekong Delta region in southern Vietnam [9]. Similarly, Lebersorger and Beigl [10] identified and quantified differences in MSW production and collection on the municipal level in Province Styria, Austria. Socio-economic indicators were involved. A large set of 116 indicators from 542 municipalities in Austria was investigated. Li et al. [11] introduced a model, based on the interrelationships of expenditures on consumer goods, time distribution, daily activities, residents' groups and waste generation, to estimate MSW generation by different activities and resident groups in Beijing. Geographically weighted regression was applied to predict MSW production in Turkey [12].

Regarding forecasting, knowledge of explanatory parameters opens new opportunities for an indirect change of future course of the production. Initiatives for encouraging desired trends of explanatory parameters may be discussed. Alternatively, the explanatory parameters may be forecasted and results may be introduced into the regression models to forecast waste production.

RA, if employed correctly from a mathematical point of view, requires that strict conditions are met before RA may be applied. Among others, the residues were supposed to be of the normal distribution, see Ruckstuhl [13] for nonlinear regression. These conditions may be relaxed by more generalised ones resulting in the generalised linear model (GLM) [14]. GLM can solve problems other than just the normal distribution of residues, for example, the problem of residues heteroscedasticity, multicollinearity and distribution of residues. Guisan et al. [15] collected information about GLM and discussed utilisation of several new approaches, such as GLM in a regression tree. GLM can also be successfully applied in nonlinear models, as Lane [16] showed. Zhang et al. [17] summarised the possibilities of neural networks (NN) as an alternative forecasting approach, Abbasi and Hanandeh [18] dealt with other artificial intelligence algorithms. Azadi and Karimi-Jahni [19] verified NN and multiple linear regression (MLR) predictive models by four performance measures. NN model showed higher accuracy in the sense of mentioned measures for the chosen case study. The classical methods are sometimes combined, grey model together with TSA was successfully implemented for estimation of waste production in Xiamen City, China [20]. The consideration of variables such as demographics and socio-economic factors is not needed.

The above-discussed methods (RA, GLM, NN) require independent variables. In addition, independent variables should be available from all the regions. Since the socio-economic data are very often available only on the state level or for large regions, this situation discards RA involving this kind of variables from any investigations with micro-regions and small territorial units. TSA employs time as the sole explanatory parameter. Waste amounts in previous years are investigated to develop a model which describes the variation over time. Forecasts are then derived by extrapolating historical data.

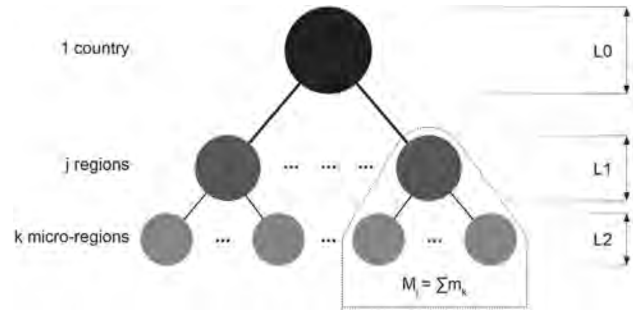

Fig. 1 Investigated geographical area represented by hierarchical tree-like structure (simplified after [29])

Some articles dealt with waste production forecasts for detailed time steps ([21] in time steps of 1 week). A shorter time interval is inevitable when waste collection systems are optimised. Extensive data processing to predict waste production in Finland was described by Korhonen and Kaila [22]. Socio-economic factors can significantly affect the amount of generated waste. For example, the influence of tourism on the production of waste was discussed by Arbulú et al. [23]. Mwenda et al. [24] analysed, compared and selected the best time series model for forecasting the amount of solid waste generated in the city, Arusha (Tanzania) by using ARMA (auto-regressive moving average)/ARIMA (auto-regressive integrated moving average) and exponential smoothing models. Here only tens of samples were available for forecasting. Monthly production between 2008 and 2013 was analysed.

The work presented by Ghinea et al. [25] used a small dataset prognostic tool [26] combining RA and TSA for forecasting MSW generation in Iasi (Romania) in 2023 with the use of data from the period 2001 to 2013. This study also focused on predicting the number of solid waste fractions (paper, plastic, metal, glass, biodegradable and other waste). A different methodology was chosen by Intharathirat et al. [27] who presented an analysis of possibilities for determining the prediction interval for MSW production. This analysis was conducted over a long-term period, and it used optimised multivariate grey models. However, only 13 samples were available here.

From a mathematical point of view, accuracy is secured only for series with a large number of values. Concerning strategic decision-making, which this paper focuses on, the time series method for waste production (which are reported on an annual basis) are often too short because older data are not available. Any attempt at a rigorous TSA of such data results in a heavily skewed estimate of the real underlying trend, and hence, is of limited use. There is also the practical impossibility of stage-wise identically independent probability distributions of random errors or homoscedastic random errors as it is required by ARMA models [28].

As a consequence, a precise data analysis is nearly impossible, and the only component which can be observed is the trend one. Therefore, this technique is preferred to model large data, that is data gathered within a shorter period (daily, hourly, etc.) to support tactical and operational decisions.

Contribution of this Paper

In this contribution, an approach towards forecasting of MSW streams and their parameters is introduced.

From the previously mentioned points, we may assume that strict assumptions limit RA applications. Regarding TSA, one has to cope with short time series. From a statistical point of view, the accuracy of extrapolation models is rarely guaranteed with a high level of confidence if the series consists only of few points. Despite this setback, these models do provide important information about the trend. Therefore, they are acceptable from an engineering point of view as no other models are available, and they offer an improvement to existing approaches.

In comparison to previously published works, this is done for a large geographical area consisting of up to hundreds of points, where waste is generated (see L2 for micro-regions in Fig. 1). The division of the region has been inspired by the official European NUTS (Nomenclature of Units for Territorial Statistics) and LAU (Local Administrative Units) system. The level L0 corresponds to NUTS 1 which represents the national level. Next level, L1 signifies the NUTS 3. But the most detailed structure relevant for this paper is L2, which is the organisational structure of the Czech Republic. It does not have the equivalent in the European NUTS and LAU system. The problem is not decomposed. Instead, it is solved simultaneously for all nodes and desired parameters. Simultaneous forecasting of MSW and its components seems to be inevitable for the following reasons:

- It is a multi-component system where components interact.
- Regression models are limited by unavailable socio-economic data from micro-regions.
- Short time-series hinder formulation of reliable extrapolation models.
- Simultaneous forecasting, if done in the tree-like structure, can be used effectively to overcome poor extrapolation quality, for details see Pavlas et al. [29].

To our best knowledge, such an approach has not been published before, and therefore it may be considered novel. The approach extends the idea of application of reconciliation technique based tool presented by Pavlas et al. [29], see Section "Reconciliation Technique Based Tool". Whereas uncertainty related to poor extrapolation models was introduced and discussed by Pavlas et al. [29], the extension of the algorithm presented in this contribution is done in terms of handling:

- The multicommodity problem (see Section "Waste Composition and Composition Constraint") and proposal of composition constraints.
- Incomplete data by two-level methodology (see Section "Regression Models to Get Complete Information").
- National targets are cascaded down to regions and micro-regions. Specific local aspects of these subparts are considered. On the other hand, the realistic performance of individual regions is used to define rational national targets.

The proposed approach can be applied for investigations of a particular area. However, it can also support reverse logistics model. Simultaneous forecasting of the waste amounts for the large geographical area, and its subregion can serve as inputs for reverse logistics models.

Materials and Methods

A balancing tool based on a reconciliation technique is introduced first in this section. Then its extension towards a system enabled handling of several fractions within the interconnected system is discussed next. Finally, the most crucial steps of the algorithm are pointed out in more detail.

Reconciliation Technique Based Tool

Pavlas et al. [29] discussed the varying quality of extrapolation models, especially the varying quality caused by the short time series. The paper focused on hazardous waste. However, similar issues are concerned with other waste streams, including MSW and its fractions. The original problem was denoted "uncertainty of forecasted values" since it meant a challenge to make any projection by using TSA [29]. The problem was linked to the extreme variability of historical data and the effects of random components. Also, outliers must be identified and handled.

The uncertainty was reported quantitatively, and it was demonstrated that the quality of forecast increases with the level of data aggregation. Data on hazardous waste production available for the Czech Republic (CZE) and its organisational units (see L0, L1, L2 in Fig. 1) was analysed.

Extensive investigation of this dataset also revealed a violation of mass-balances in a tree-like hierarchical structure which describes the organisational arrangement of the investigated region. In other words, the following basic

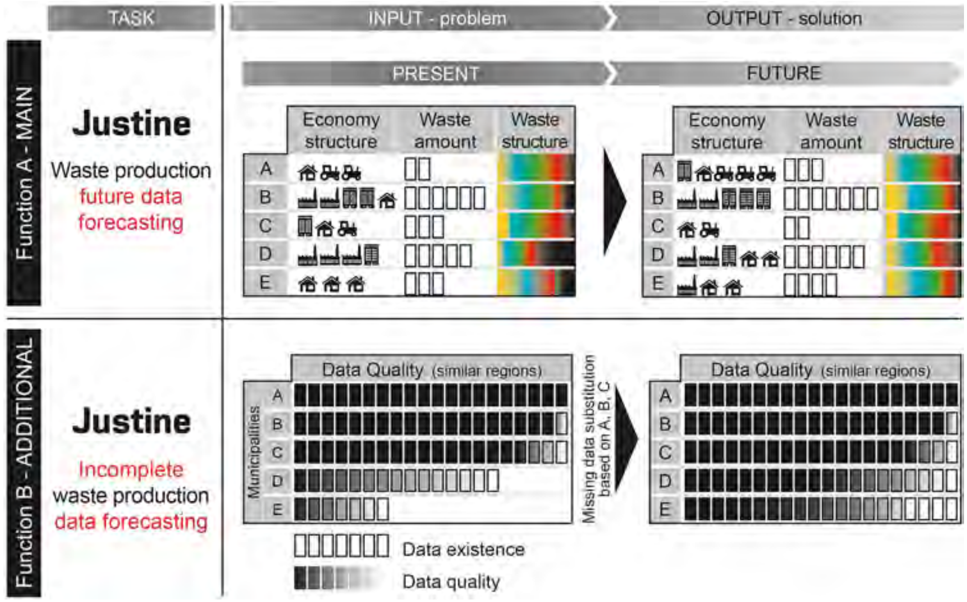

Fig. 2 Basic idea and two functions of system for forecasting waste amounts of MSW

assumption was violated if extrapolated values were treated: The sum of forecasted values for all lower organisational units in the region must be equal to the result of the forecast performed on the aggregated data of the region. Further investigation revealed that the achievement of a full consistency is not guaranteed even from a mathematical point of view. Nonlinear extrapolation models do not generally meet the rule Eq. (1), that is m_k^* is not equal to M_j^* (Eq. (2)):

$$\sum_{k\in K} f_k(t, x_k) = F_j\left(t, \sum_{k\in K} x_k\right), \forall t \in T, \quad (1)$$

$$m_k^* = f_k(t_r, x_k), \forall k \in K; M_j^* = F_j\left(t_r, \sum_{k\in K} x_k\right), \forall j \in J, \quad (2)$$

$$m_k = m_k^* + \varepsilon_k^m, \forall k \in K; M_j = M_j^* + \varepsilon_j^M, \forall j \in J. \quad (3)$$

The parameters x_k indicate productions; the functions f_k and F_j determine prediction models for micro-regions (L2) k and for superior territory j (L1 and L0), respectively; parameter t specifies the time. Based on Eq. (2), m_k^* and M_j^* denote the prediction model in a specific time period t_r for micro-region k and region j, respectively. To ensure the validity of Eq. (1), the values m_k^* and M_j^* are corrected by ε_k^m and ε_j^M in Eq. (3). This adjustment maintains the validity of relationships in the hierarchical structure, as Fig. 1 shows.

Reported uncertainty at a lower level (quality of extrapolation models was often low) was reduced by newly proposed areal constraints. It guarantees mass conservation in a tree-like structure. Additional information from areal constraints is positively utilised to produce more reliable forecasts. Deviations are realised by a data reconciliation-based tool.

Extension Towards Modelling A Multi-Component System

In this paper, the original algorithm, also called Justine, is adjusted to handle so-called multi-commodity system, where components overlap between observed streams. MSW represents a good example as it consists of several fractions (see section "Waste Composition and Composition Constraint"). For simplicity, let us considered only the following fractions: paper (PAP), plastics (PLA), glass (GLA) and bio-waste (BIO). Generally, these fractions may be either gathered as separately collected recyclables (SEP, for example by kerbside collection systems) or they may contribute to residual waste quantities – RES. RES comprises paper (RES_{PAP}), plastics (RES_{PLA}), glass (RES_{GLA}) and others (RES_{OTH}). Whereas SEP streams are candidates to subsequent refining through sorting processes to prepare recyclables, the latter residual stream is subject to limited material recovery possibilities. RES stream is preferred to energy recovery. Each of the fractions can be further composed of other elements. For example, PLA consists of foils, 3D-hollows, PET of different colours, etc. This fractioning was not considered for demonstration reasons in this paper.

In this respect, the algorithm was extended by the following:

- RA is providing models, which are later on used to get complete information for all nodes, including nodes

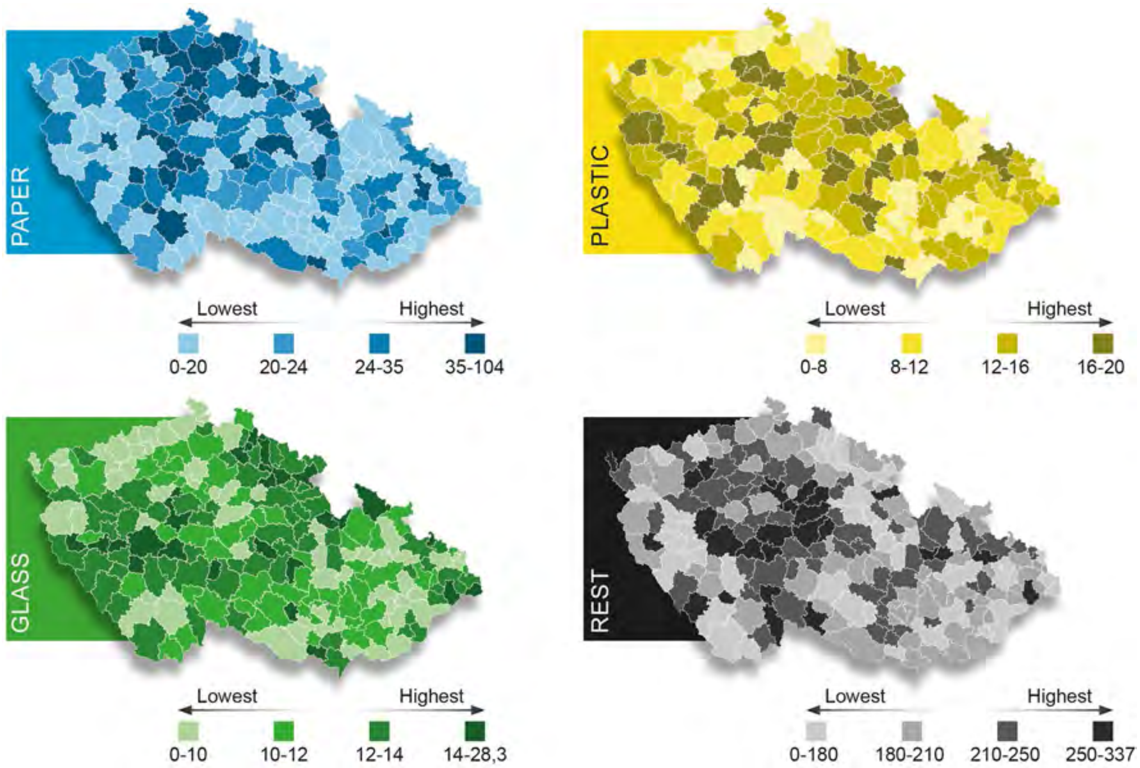

Fig. 3 MSW fractions rates distributed in investigated region of CZE [kg/(cap·y)], L2 detail, data 2014

where input data is missing (see Function B in Fig. 2 and section "Regression Models to Get Complete Information").

- Extrapolation techniques for data on various levels of detail (see Function B in Fig. 2 and section "Trend Series Analysis—Initial Models Generation").
- Specification of newly formulated composition constraints (see Eq. (4) through Eq. (11) and section "Waste Composition and Composition Constraint").
- Modification of reconciliation-based balancing model (see section "Balancing and Corrections of Initial Estimates").

At this point, the main aim of Justine concerning practical application on MSW is mentioned. It is illustrated in Fig. 2 as the main function A in the upper part of the figure. The aim is to forecast future waste amounts and composition (SEP, RES and its fractions) in various locations (see A, B, C, D, E) while taking into account current specific features of the localities (housing, economic and population changes, etc.) and their expected future development. The analysis is covered by prediction models (TSA or RA).

However, the forecasting can only be performed if all current input data is known. In this case, we talk about the complete dataset. Oppositely, the incomplete dataset means that some information is missing and not all information from all locations is available. Particular information is available only from a few geographical units. And here, the auxiliary function of the approach (see the lower part of the Fig. 2) is appreciated. The incomplete dataset is transformed into complete information by assessing missing data. The assessment is done by RA, and this step is described in more detail in section "Regression Models to Get Complete Information". This function is considered as an initial phase which precedes the forecasting. However, in some applications, it acts as a standalone analysis. For instance, see [30], where it was applied to predict current metal, and glass content in RES collected from several micro-regions. The result was then compared with bottom ash investigations from waste-to-energy facilities.

Input Data

Yield and Production Data

First, let us review the input data. Essential inputs for a particular case addressing household waste are as follows:

- separated paper yield (all points, all levels (L0 to L2), several years),
- separated plastic yield (all points, all levels (L0 to L2), several years),

- separated glass yield (all points, all levels (L0 to L2, several years),
- separated bio-waste yield (all points, all levels (L0 to L2), several years) and
- residual waste amount (all points, all levels (L0 to L2), several years).

The L2 level is considered as a base level in this paper. Following the tree diagram (see Fig. 1), the historical base data may be aggregated to generate productions on higher levels. The aggregation is highlighted by the sum in Fig. 1. This summation was labelled as "areal aggregation" in [29]. This areal aggregation corresponds to the administrative division where data for higher organisational levels (regions, country, see L1 and L0 level in Fig. 1, respectively) is reported as sums of production in all subordinate nodes. It also secures that mass is conserved in the system around the particular node and its descendants, as required by Eq. (1).

An example of spatially-distributed data for the CZE, the year 2014 and level of detail L2 (micro-regions) is illustrated in Fig. 3. The production is expressed as specific per capita and year [kg/(cap·y)].

The current collection rates can be summarized as follows: PAP 17.5–30.0 kg/(cap·y); PLA 10.1–14.5 kg/(cap·y); GLA 10.2–13.3 kg/(cap·y); BIO 19.9–58.9 kg/(cap·y). The lower and upper values are represented by 25 percentile and 75 percentile, respectively.

The time series exists for each territorial unit (L0, L1, L2) and also for each waste type RES, PAP, PLA, GLA, BIO. Each of the L2 regions commonly makes provision of such data. Therefore this data is denoted as "complete". In our case, the task encompasses 206 time series at L2. Considering an organisational structure, additional aggregated time series were generated: 14 on L1 and one on L0 level.

Data fluctuation varies from region to region, which is essential for the forecasting step. This topic is covered in section "Trend Series Analysis—Initial Models Generation" in more detail. Therefore, the quantity of data is "complete" and "uncertain".

Additional and very valuable input information is on residual waste composition.

Waste Composition and Composition Constraint

Often, this type of data is available only from a few points, since the complex waste composition analysis is labour and time-consuming. Also, the result is only relevant to the specific period and a particular location. Therefore, this data is denoted as INCOMPLETE and also UNCERTAIN. Uniform methodology on composition analysis is often missing. For instance, it is standardised by ÖNORM Serie S 2123 in Austria. The analyses often have different objectives, and results are not easily comparable. However, every composition analysis provides useful information, which can positively contribute to more precise models if integrated into the complex system as presented in this paper.

There is a strong difference in the composition of waste produced in cities and villages. The cases were studied in many papers, such as [31]. Key aspects are the overall MSW production and current level of primary sorting by producers. Whereas developing regions report high bio-waste shares, developed regions and related consumerism increase the production of packaging materials like paper and plastics. The production (sum of RES plus SEP) is proportional to the economic power of the specific territory, Bandara et al. [32] shows. The economic power can be measured with the gross domestic product on the country level or similar parameters for smaller geographical areas, for example, average income, living standards etc. The correlation of waste amounts with economic power may be shortly disturbed by the rise of public awareness of waste reduction and similar educative actions. On the other hand, the distribution between SEP and RES is highly locally dependent, and it is subject to the adopted collection scheme, taxation and other economic incentives (for example, Pay-as-you-throw mechanism). Public awareness and environmental thinking play an important role, too.

Information about RES composition forms another set of equations. There are approximately eight extra equations originating from mass balances of fractions:

$$PAP = SEP_{PAP} + RES_{PAP} \tag{4}$$

$$PLA = SEP_{PLA} + RES_{PLA} \tag{5}$$

$$GLA = SEP_{GLA} + RES_{GLA} \tag{6}$$

$$MSW^{*} = SEP_{PAP} + SEP_{PLA} + SEP_{GLA} + RES \tag{7}$$

$$TOTAL_{SEP} = PAP + PLA + GLA \tag{8}$$

$$SEP = SEP_{PAP} + SEP_{PLA} + SEP_{GLA} \tag{9}$$

$$RES_{SEP} = RES_{PAP} + RES_{PLA} + RES_{GLA} \tag{10}$$

$$RES = RES_{PAP} + RES_{PLA} + RES_{GLA} + RES_{OTH} \tag{11}$$

All of them were applied for all locations and all levels (L0–L2). They are called "composition constraints".

Separation Efficiency

Separation efficiency is highly monitored characteristics which evaluate the performance of any collection system in place. Many studies focus on measures to enhance separation efficiency of individual fractions and the system as a whole [33]. Separation efficiency (SE) is defined as:

$$SE_{*} = \frac{SEP_{*}}{TOTAL_{*}}. \tag{12}$$

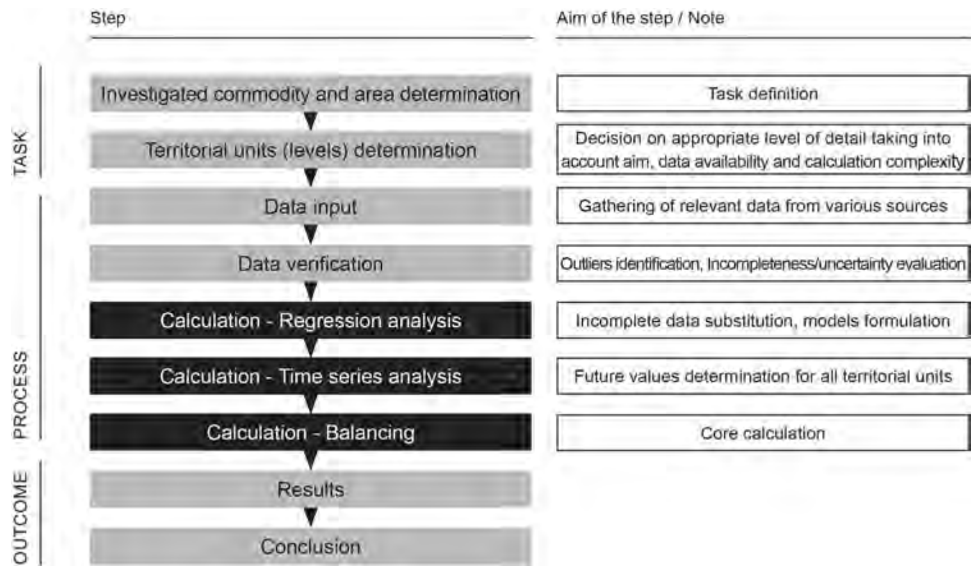

Fig. 4 Schematic representation of overall methodology with highlighted steps relevant to this paper

The symbol * indicates the fraction of MSW (e.g. PAP, PLA, GLA). SE will be further evaluated in section "Future Amounts Modelling". SE can also form constraints, which is demonstrated in scenario 4.

Steps in the Algorithm

The overall methodology consists of several steps which are listed in Fig. 4. In this paper, we focus on three crucial steps which are labelled as "Calculation" in Fig. 4.

Regression Models to Get Complete Information

After introducing steps processing all inputs, data is gathered and verified. As mentioned above, some historical data is "incomplete". Typically, this incompleteness concerns composition. Therefore, the calculation starts with a detailed analysis to get complete information in all nodes. Where input data is missing, it is substituted by models. Also, the models are used to identify outliers.

Detailed RA is performed. The goal is to develop models which help explain variation in parameters within the investigated area. In the case of household waste, it was:

- Model on PAP, PLA, GLA yields as separated (SEP) and its residual values (RES) as a function of the housing structure.
- Model on the composition of residual waste as a function of the housing structure.

A correlation between RES and other MSW fractions (e.g. metals, BIO) has not been revealed by CA and RA and

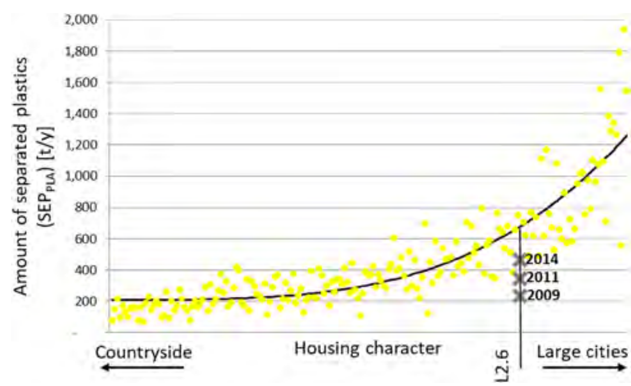

Fig. 5 Regression model of SEP_{PLA} as function of housing character in 2009

L2 data. It is assumed that the increase in the amount of these fractions is not compensated by RES reduction. Minor fractions such as textile are excluded as well.

The housing structure represents an important socio-economic aspect with significant influence on the results. The influence was confirmed by several studies [31]. Three categories of buildings were considered in our case of the CZE. They differ with inhabitants' density, which is a count of inhabitants living in one building. They were single houses (up to 8 inhabitants) and small apartments houses or multi-dwelling units (up to 30 inhabitants) and blocks of flats or apartments houses (more than 30 inhabitants). Considering that there are 10.5 million Czech citizens living in the CZE, half of these lives in individual houses. The other half lives in blocks of flats.

These three types of housing entered RA. Other socio-economic variables, such as age, income, education etc., were identified as insignificant.

Table 1 Average values of Q achieved for various territorial units (–)

MSW fraction	L0	L1	L2
RES	2183.5	2528.7	593.1
SEP_{PAP}	1483.4	247.9	100.0
SEP_{PLA}	4452.2	652.3	176.4
SEP_{GLA}	1127.7	697.6	149.7
SEP_{BIO}	59.5	33.6	19.7

The meaning of Q can be found in [29]

In general, RA represents the behaviour of an average producer. The disadvantage is that such an average model can hardly be applied equally to describe the future trend in all particular micro-regions. There are often local specifics which influence previous and future performance. On the other hand, RA provides information about distribution around this average. So, producers performing below, around and above the average may be identified. In this respect, results may be used as benchmarks, and future targets can be specified.

This is demonstrated in Fig. 5, where the benefit of RA models, if applied on a long-term basis, is shown. A model on SEP_{PLA} as a function of housing structure compares separation yields in similar micro-regions. Whereas it seems that highlighted node L2.6 is an outlier, according to 2009 data, it improves significantly with time, and in 2014 it is much closer to an average model. Another discovery is that the average increases with time, which is not visible directly from Fig. 5 since only 2009 data is displayed.

These findings have been exploited to forecast RES fractions. Continuing with L2.6 as an example and considering similar plastics generation in similar regions (other parameters are not important as revealed by CA), the Fig. 5 indirectly says that the waste that has not been separated must remain part of the RES. If separation is increased in the coming years, the amount of RES is adequately reduced.

By using RA in a similar way for all the fractions of SEP (SEP_{PAP}, SEP_{PLA}, SEP_{GLA}) and RES (RES_{PAP}, RES_{PLA}, RES_{GLA}), it is possible to estimate the total production of individual fractions.

Trend Series Analysis—Initial Models Generation

As far as all information in the nodes is complete, the second part of the methodology starts. It establishes the future values of desired parameters. TSA is performed for data on all hierarchical levels (that is L0, L1, L2) and models on future production in all micro-regions, all regions and the whole country are formulated. Not only the input time series SEP_{PAP}, SEP_{PLA}, SEP_{GLA} and RES_{OTH} are extrapolated, but also series newly derived by function B in Fig. 2 are treated in the same way (RES_{PAP}, RES_{PLA}, RES_{GLA} and RES_{OTH}). In other words, the composition of RES is extrapolated, too.

Regarding the involved models, the model used (function f or F depending on the level, see Eq. (1)) is generally defined as [29]:

$$m^* = a + bt^c \tag{13}$$

where t is an independent variable whose values are the year(s) of waste production, m^* is the dependent variable giving the amount of produced waste in year t and a, b, c are regression parameters to be estimated. Additionally, $m^* \geq 0$ is valid. The correlation between independent variable t and waste production m^* differs for individual time series. The Pearson correlation for MMW on L0 level is

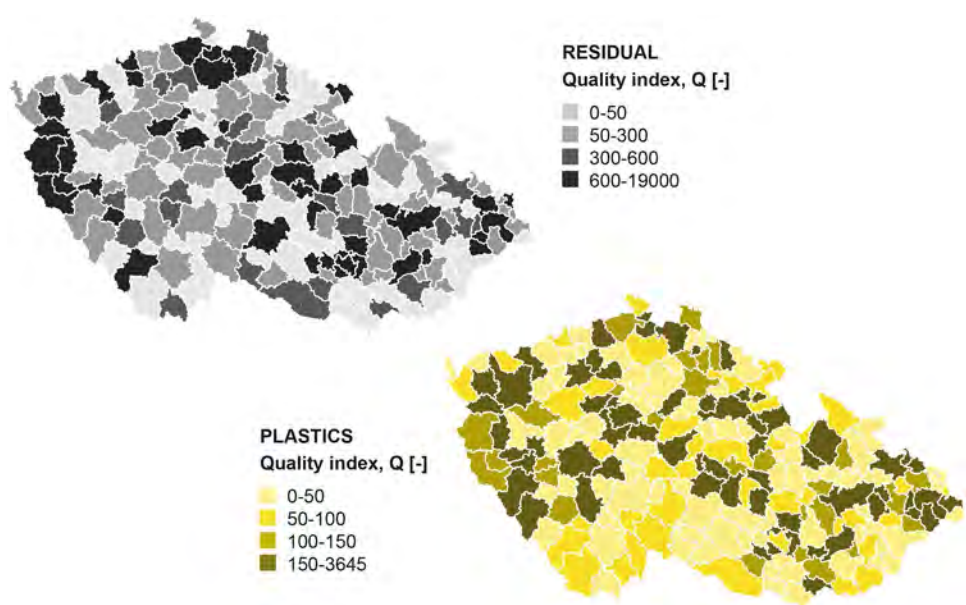

Fig. 6 Quality of extrapolation model expressed as Q and its spatial variation among micro-regions (L2) for RES and SEP_{PLA}

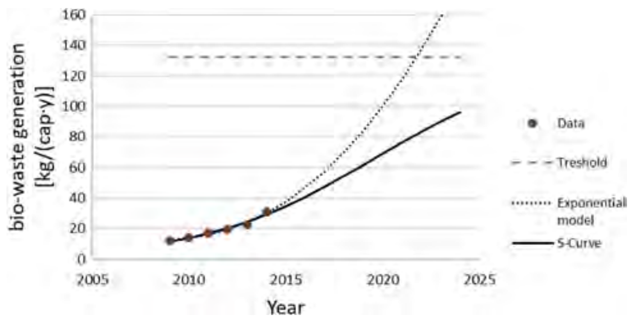

Fig. 7 Increased SEP_{BIO} as reported for CZE (L0 level) and its extrapolation models

$r_{MMW,L0} = -0.904$. The separated fractions are described by $r_{PLA,L0} = 0.995$, both $r_{PAP,L0}$ and $r_{GLA,L0}$ are almost equal to 0.9. For the next territorial units L1, L2 the correlation is lower due to higher data variability.

To measure the quality of the extrapolation model in case of short-time series, where traditional metrics fail, a parameter Q was proposed by Pavlas et al. [29]. This Q was evaluated for all time series as a part of a study presented in section "Results". The analysis confirmed the statement presented by Pavlas et al. [29] that with deeper aggregation, the quality of extrapolation models is increased. Whereas the original work of [29] was focused on hazardous waste, here we present the results for MSW and its fractions. The details on how parameter Q is calculated can be found in [29].

The Table 1 summarizes average values of criterion Q_i for various territorial units. Q variation for RES and SEP_{PLA} among micro-regions is visualised in Fig. 6.

The higher value of the criterion Q_i leads to better quality of the extrapolation model. As Table 1 shows, the better model fit is achieved for higher territorial units. With the only exception when in case of RES, L1 exceeds L0. The small difference proves that this data of RES has comparable quality on levels L0 and L1. It is caused by significantly larger amounts of this type of waste than others.

Low-quality indexes open a discussion on suitable models [Eq. (13)]. There are a variety of potential models. Their testing on the L2 level for the same dataset was performed in [34]. To keep the processing time reasonable (1442 time series, seven fractions, 3665 models), a special approach based on cluster analysis was proposed. The outcomes pointed out that the quality of the forecast is subjected to MSW fractions. RES was forecasted with high preciseness. The situation is much complicated for SEP fractions, where the Q is much lower, especially on micro-regional level L2.

Because of this principle, outcomes from TSA describe so-called "Baseline scenario" or "business-as-usual scenario (BAU)", where no significant changes in the course are expected. In some cases, extrapolation provides unrealistic models, which leads to overestimation or underestimation. As an example, the model on future amounts of SEP_{BIO} for CZE L0 is presented in Fig. 7.

There is no expectation that the production will follow the exponential model on a long-term basis. The sharp increase reported by latest data, as a response on new legislation introduced in 2014, will be exhausted within a couple of years as soon as a waste management system in the majority of municipalities will be adjusted. Therefore, an additional corrective model specifying realistic future target respecting the character of the area is needed.

A logistic function (Sigmoid) could be a good candidate for these cases Eq. (14):

$$m^* = \frac{1}{1 + e^{-(a+bt)}}, \tag{14}$$

where m^* is the amount, e is Euler's number, a and b are constants and t represents time. Logistic function (Sigmoid) reaches values within the range 0 and 1. Therefore data on production have to undergo a transformation. For this reason, a threshold has to be determined. In the case of SEP_{BIO}, it is the maximum fraction rate which can be potentially achieved in the studied area. This value, in case of SEP_{BIO}, is subject of the housing structure, as confirmed by several previous works (e.g. [35].). Karkanias et al. [36] focused on the home composting scheme in Northern Greece and the effect of this programme on the citizens' behaviour. The following threshold per capita is assumed for two types of urban areas:

- Blocks of flats: 60 kg/(cap·y).
- Single-family houses: 200 kg/(cap·y).

Whereas the production of 60 kg/(cap·y) of kitchen waste is assumed in both residential types, an additional 140 kg/(cap·y) of yard waste is expected in case of individual buildings. The building structure of the CZE mentioned in section "Regression Models to Get Complete Information" expects an average SEP_{BIO} of approximately 132 kg/(cap·y) (see a threshold in Fig. 7) and absolute amount of 1400 kt/y.

Balancing and Corrections of Initial Estimates

The computational system processes a variety of spatially distributed forecasts (initial models) on production and composition at every point obtained by the RA or TSA above. In the next step, these initial models are treated by reconciliation-technique based algorithm [29]. Applying areal and composition constraints, the initial forecasts are corrected to get a solution with the overall lowest distances between initial models and the result. Such a solution is denoted "final forecasts".

Table 2 Average composition of RES in 2014 (L0–country level)

Fraction	Amount (%)
PAP	8.11
PLA	9.25
GLA	4.37
BIO	28.21
Other	47.41

From a mathematical point of view, the procedure follows the principle of least squares method as a proposed in [29]. Least square method, in its traditional applications, results in a description where square distances between each of the input data and the description (model) are minimised. Following the visualisation in [29] input data from TA and RA is horizontally fragmented forming vertical groups of points. Each of the groups is associated with one unknown parameter, which in our case is the amount of RES and all SEP fractions. Input point estimates may differ and even frequently provide contradictory information. Balancing performs corrections where distances between resulting values (an unknown parameter) and all available forecasts are minimised, taking into account each of the locations, all territorial units and all fractions. The task cannot be decomposed due to the additional constraints and reasons mentioned above (section "Waste Composition and Composition Constraint").

Results

Several examples of a comprehensive analysis done for the area of the CZE are presented in this section. The simultaneous calculations for 206 micro-regions, 14 regions and the country were performed. Data on residual waste amounts and the yield of separately collected fractions for the years 2009 to 2014 were available. Residual waste analysis coming from a few micro-regions represented additional input.

The investigated system involved several fractions. RES and amount of SEP for three fractions, namely PAP, PLA, GLA were considered as one interacting system. Regression models on the composition of RES and amount of SEP for these fractions were generated. RA also revealed that there is no correlation between amounts of BIO and amount of RES. Considering increased BIO generation (see Fig. 7), lower amounts of RES were expected. Unfortunately, this was not confirmed by the analysis of L2. Amount of BIO dominantly consists of garden waste and the only little amount is kitchen waste diverted from RES. Therefore, BIO was forecasted as an independent stream with no interaction with RES. The same applies to metals which were also considered as an individual stream. RES_{OTH} fractions were forecasted in the second step, and

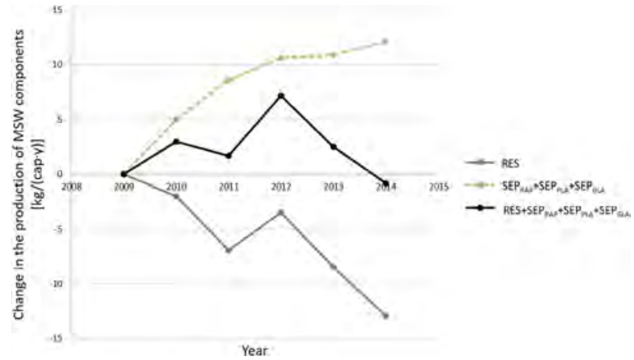

Fig. 8 Trend in MSW fractions generation

this stream contains fractions with no link to RES production. RES_{OTH} is composed of BIO, metal, textile, etc.

Average Composition and Overall Trends on L0

First, results for apex L0 are presented. It is worth mentioning that these results represent a bottom-up approach. They were formulated by an analysis on lower levels, that is on L2 and L1. In other words, trends on L0 are corrected taking into account trends on lower hierarchical units L1 and L2.

Current (2014) generation of MSW in the CZE is 5324 kt/y (506.3 kg/(cap·y)). 34.8% of this amount is supposed to be materially recovered [37]. Amount of waste considered in the analysis is 2661 kt (253 kg/(cap·y)), which is 50% of the overall production of MSW. Excluded was 2663 kt of RES_{OTH}, because it forms a completely new waste stream. There is no link between SEP and RES.

Composition of RES

Average composition of RES was estimated involving available inputs and models. The methodology itself is based on RA. It includes several explaining parameters including housing structure which was identified as the most significant variable. The methodology is described in more detail in [30].

The sum of PAP, PLA, GLA counts approximately 23.8% of RES. This amount represents approximately 9.5% of the total MSW. In the case of achieving absolute sorting efficiency (SE for all fractions is equal to 100%), the rate of material recovery of MSW will increase to 44.3%. For comparison, targets implemented by CEP are 60% in 2025 and 65% in 2030.

Table 3 Maximum feasible SE for fractions as proposed for CZE (%)

Fractions	Housing structure		
	Rural area (%)	Combined (%)	City (%)
PAP	93	86	70
PLA	73	64	52
GLA	90	89	73
$SEP/TOTAL_{SEP}$ Eqs. (9)–(8)	86	72	59

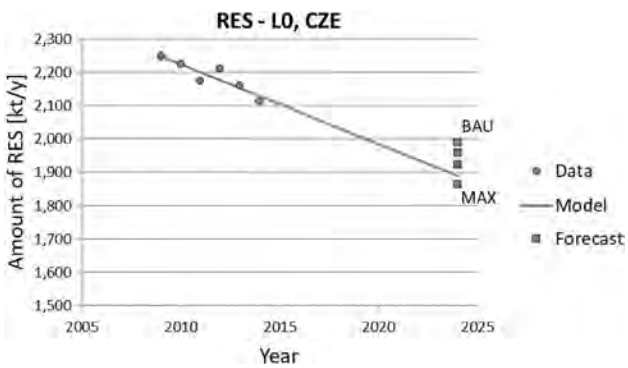

Fig. 9 Forecasted amount of RES for various scenarios, L0, CZE

As Table 2 summarises, the other fractions occupy a significant part of RES. Nevertheless, they are not part of the analysis.

Reported Trends

Overall production of RES is approx. 200 kg/(cap·y) plus 53 kg/(cap·y) was collected as separated SEP_{PAP}, SEP_{PLA} and SEP_{GLA}. This production is stable in the investigated time interval 2009 through 2014. A drop in 2015 compared to 2009 was approximately 0.5% (see Fig. 8), which is a negligible change. However, a significant reduction in RES is observed and is accompanied by an increase in SEP. In other words, considering the constant generated amount, fractions were transformed from RES to SEP, which is the desired trend.

Future Amounts Modelling

Time series from 2009 to 2014 (both input and developed by RA) were extrapolated using the methodology described in sections "Trend Series Analysis—Initial Models Generation" and "Balancing and Corrections of Initial Estimates". The year of interest was 2024, which is an important future milestone in the waste management of the CZE. As given by [38], landfilling of untreated residual MSW, recyclable fractions and fractions suitable for further recovery is to be

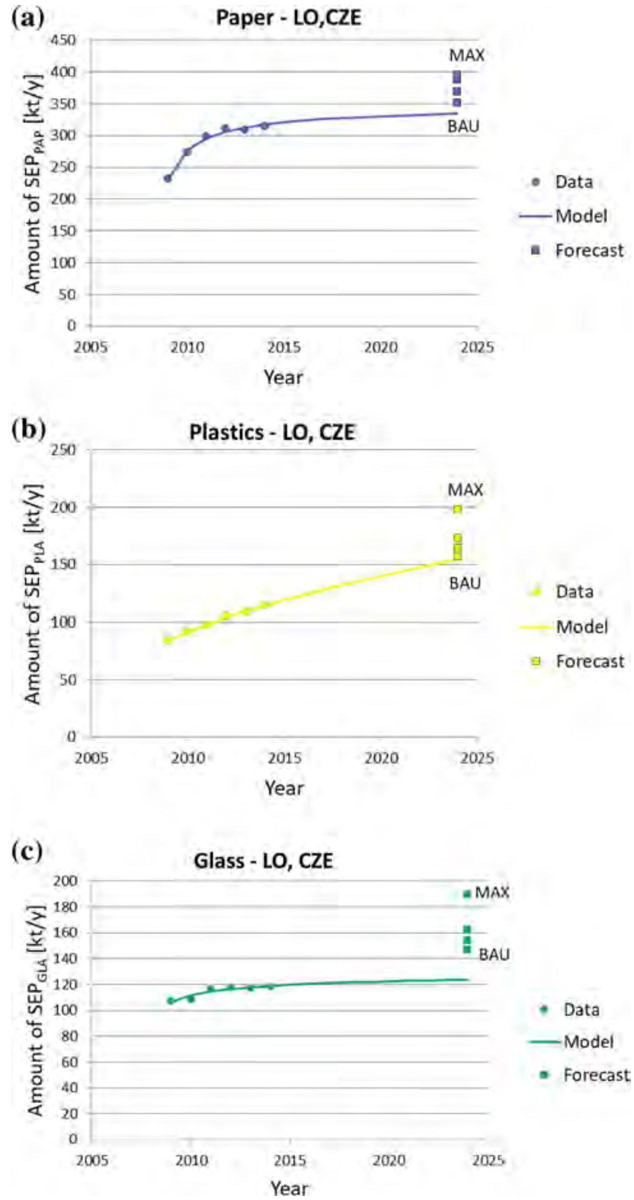

Fig. 10 Forecasted amount of SEP fractions for various scenarios, L0, CZE. **a** Paper, **b** Plastics, **c** Glass

banned since 2024. This change requires the improvement of existing infrastructure.

Following the mass conservation equations Eqs. (4) to (6), it is assumed that higher SE decreases fraction content in RES. The following four scenarios were modelled:

- Scenario 1–A basic scenario which reflects recent trends in the development of waste management in the CZE. Forecasts are based on TSA. No significant corrections of observed trends are expected. This scenario can also be denoted as a business-as-usual scenario (BAU).

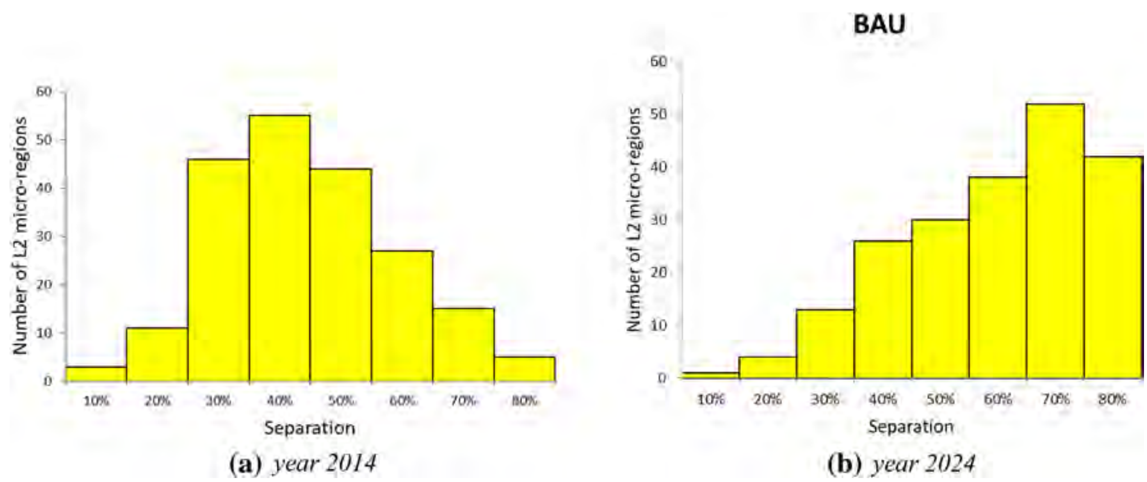

Fig. 11 Frequency diagram of plastics separation efficiency [%] for 206 CZE micro-regions in 2014 and 2024

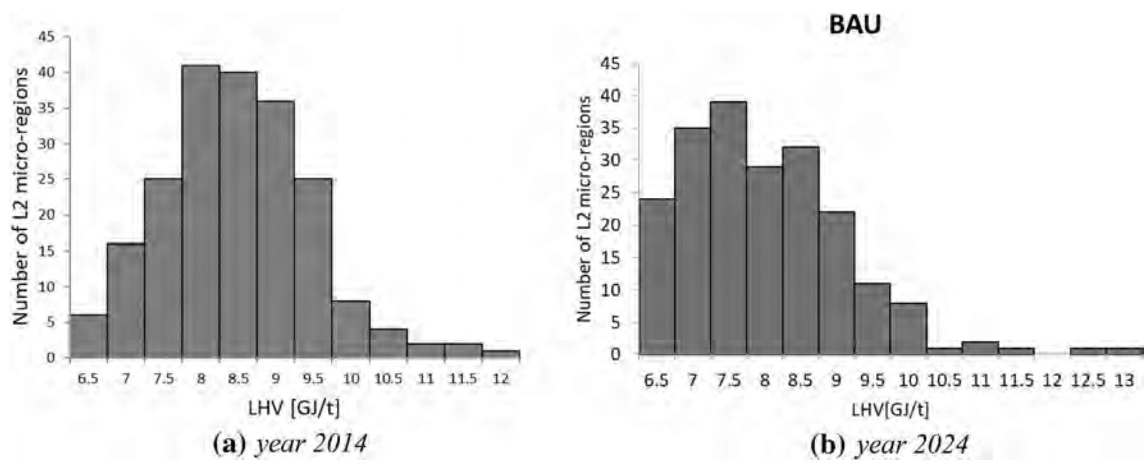

Fig. 12 Frequency diagram of lower heating value [GJ/t] of RES for 206 CZE micro-regions in 2014 and 2024

- Scenario 2–The second scenario extends the previous one. Increase in SE of 5% is assumed for all investigated fractions on an annual basis.
- Scenario 3–The second scenario extends the previous one. Increase in SE of 10% is assumed for all investigated fractions on an annual basis.
- Scenario 4 (MAX)–This scenario introduces challenging separation targets. Following the cooperation between our team with experts from Germany, the experience of waste management development in Germany was exploited and the maximum feasible SE were proposed individually for fractions. Here, the housing structure was considered an influential parameter. The limiting SE forming additional constraints for balancing the results are summarised in Table 3.

Representative outcomes from the complex analysis are displayed in the following figures.

Fig. 13 Production and separation efficiency of plastics in selected micro-region

First, the development of RES is forecasted in Fig. 9. Afore-mentioned four scenarios are distinguished. The outcome confirms the recent trend, where the production of RES is constantly reduced. Solid line denoted as “Model” describes an extrapolation model obtained by applying

Table 4 Summarization of data reconciliation results on the L0 and L1 levels in the year 2024

Fractions	L0 value—model (kt/y)	L0 value balanced scenario BAU (kt/y)	L0 correction (%)	L1 (14 nodes) average correction (%)	L1 min correction (%)	L1 max correction (%)
RES	1887.8	1989.3	5.4	4.9	0.7	13.9
PAP	334.1	351.1	5.1	6.1	0.002	13.5
PLA	154.4	156.5	1.3	14.2	3.4	37.0
GLA	123.5	146.6	18.5	14.3	1.4	48.5
Total	2500.1	2643.5	5.7	1.4	0.3	2.5

Table 5 Results of scenario modelling on L0 level in the year 2024—Separation efficiency (%)

	Scenario 1 (BAU)	Scenario 2	Scenario 3	Scenario 4 (MAX)
PAP separation rate	70.6	74.1	77.8	79.4
PLA separation rate	49.2	51.7	54.3	62.3
GLA separation rate	62.3	65.4	68.9	80.5
Separation rate of recyclables	62.3	65.4	68.7	74.5

Eq. (13). Function value for this model for argument 2024 represents an "initial" estimate. This value is corrected to get the final estimate according to section "Balancing and Corrections of Initial Estimates".

More detailed analysis of paper, plastics and glass fractions is provided in Fig. 10, where amounts of SEP_{PAP}, SEP_{PLA} and SEP_{GLA} are in an opposite relation with RES. The expected increase in three fractions leads to the elimination of these fractions in RES. The resulting amount of RES decreases, too.

The following increase in separation of fractions is expected for scenario BAU:

- Paper separation increased from 65.4% in 2014 to 70.6% in 2024. The rest of the paper is present in RES.
- Plastics separation increased from 35.2% in 2014 to 49.2% in 2024. The rest of the plastics is present in RES.
- Glass separation increased from 50.5% in 2014 to 62.3% in 2024. The rest of the glass is present in RES.

Detailed Analysis at L2

The trends on country level L0 presented in the previous section stem from the situation in regions and micro-regions, which is the basic principle of the proposed approach. In other words, contributions of micro-regions to achieving national targets in separation have been investigated, too. SE forecasts on all 206 L2 units were determined. These are displayed in Fig. 11 for plastics in 2014 and BAU scenario 2024. Comparison of both frequency diagrams clearly shows development towards more effective waste management, where the mode in 2024 reaches 70%, while it was 40% in 2014. The positive trend in increased separation of calorific fractions (not only of plastics but also of paper) results in a decrease in lower heating value (compare diagram for 2014 and 2024 in Fig. 12).

Particular Region L2

Figure 13 demonstrates one particular result for a selected L2 micro-region and fraction plastic. It shows the constant production of plastic waste between 2009 and 2014 and a slight decrease to 2024. It also stresses an ineffective plastic separation, since only 15% of its production was separated in 2014. This very low value is highlighted concerning Fig. 11a. The micro-regions belong to less-performing micro-regions of the CZE. A future increase in yield is expected, resulting in lower amounts of plastics in residual waste and significantly increased efficiency. Similar outcomes were obtained for all territorial units but are not mentioned to keep the contribution of reasonable length.

Discussion

The presented approach combines trend analysis in historical data followed by data reconciliation (see section "Steps in the Algorithm"). The plain trend in the data is corrected in a particular year to address additional constraints. The model takes into account the links in the territorial structure (as Fig. 1 shows) as well as the relations between the waste fractions [Eqs. (4)–(11)]. The effect of data reconciliation is summarised in Table 4. First, initial guesses denoted as L0 value-Model, which can be considered as a traditional way of treating the extrapolation, is provided. Then, balanced result and extent of corrections in percentage are evaluated for L0. Finally, corrections at the L1 level are elaborated. In the case of L1 level, the average value of corrections, as well as the ranges, are shown. It can be observed that to gain balanced scenario BAU, the model value has to be corrected meaningfully in some cases. Especially GLA required significant correction both at L0 and L1 level, which is caused by higher variability in historical data.

Currently, waste management is facing some changes, and legislative interventions affect waste production. EU member states are obliged to meet targets on minimum waste separation in the coming years as a result of efforts to material or energy waste recovery.

The approach presented can also be used successfully for scenario modelling. Scenarios defined in the section "Future Amounts Modelling" will be considered. Scenario 1 (BAU) denotes the same development to future as was established in the historical data (Table 5). Scenarios 2 and 3 consider 5% resp. 10% increase of SE on the L0 level. The results specify, how much the lower territorial unit would improve their separation to reach the required SE on L0 level. The last scenario MAX shows the highest possible SE on L0 level.

The Czech Republic is committed to separate 50% of MSW by 2020 with a 5% increase each five years up to 2035. There are four methods introduced to evaluate current rates of preparation for reuse and recycling in [39]. In this paper, the calculation method no. 1 has been applied. The results are presented at the bottom of Table 5. CZE meets the target for 2020 (50%) and 2030 (60%) even for Scenario 1 (BAU), which exceeds 62% of considered recyclables separation rate (PAP + PLA + GLA).

Conclusion

In this contribution, an approach towards simultaneous forecasting of waste amounts and waste parameters at different territorial units, which has been first introduced in [29], is further developed. In general, the approach can be applied to any task where forecasts are performed based on spatially distributed data from previous years. This data is supposed to be incomplete (data for locality is missing), sometimes even uncertain.

In this paper, the original algorithm is adjusted to handle a so-called multi-commodity system where components overlap between observed streams. MSW represents a good example as it consists of several fractions, such as paper, plastics, glass, metals and bio-waste. These fractions may be gathered either as separately collected recyclables (for example, by kerbside collection systems) or they may contribute to residual waste quantities with limited material recovery possibilities. The algorithm was extended by the following: (1) regression analysis providing models which are later used to get complete information for all nodes, including nodes where input data is missing; (2) extrapolation techniques for data on various levels of detail; (3) specification of newly formulated composition constraints; (4) modification of reconciliation-based balancing model. The complications related to short-time series, which are very frequent in the waste management field, was highlighted. From a mathematical point of view, preciseness is secured only for series with a large number of values. Any attempt at a rigorous time series analysis of short-time series is going to result in a heavily skewed estimate of the real underlying trend, and hence, is of limited practical use. Therefore, extrapolation models provided by such an analysis are considered as initial estimates, which are further corrected by the balancing model to meet areal and composition constraint. Such simultaneous forecasting done in the tree-like structure is an effective measure to overcome poor extrapolation quality.

The algorithm is demonstrated through a case study inspired by an extensive project for the Ministry of the Environment of the Czech Republic. Future amounts of residual waste and recyclable fractions, such as paper, plastic, glass and kitchen bio-waste produced in one country as well as in its 14 regions and 206 micro-regions, are forecasted. The source-separation efficiency in all of the 206 micro-regions is analysed for four different future scenarios. The basic scenario called "BAU—Business as usual scenario" reported the following increase in separation on the country level: Paper separation will increase from 65.4% in 2014 to 70.6% in 2024; plastics separation will increase from 35.2% in 2014 to 49.2% in 2024; glass separation will increase from 50.5% in 2014 to 62.3% in 2024. The rest of the paper, plastics and glass is present in the residual solid waste. Amount of bio-waste comes dominantly from garden waste, and an only little amount is from kitchen waste diverted from residual waste. Therefore, bio-waste was forecasted as an independent stream with no interaction with residual waste. Its amount is expected to rise from 40 kg/(cap·y) in 2014 to 130 kg/(cap·y) in future.

Similar results were derived for all of the territorial units of the investigated area. Some examples for micro-regional level were presented including investigation of the lower heating value of residual waste. While the current average value is 8.5 GJ/t, it is expected to decrease to 7.8 GJ/t by 2024 in response to increased source separation of calorific fractions.

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Demand modelling in district heating systems within the conceptual design of a waste-to-energy plant

Ondřej Putna*, František Janošťák, Radovan Šomplák, Martin Pavlas

Institute of Process Engineering, Faculty of Mechanical Engineering, Brno University of Technology (BUT), Technická 2896/2, 616 69, Brno, Czech Republic

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ABSTRACT

The paper deals with the issue of fluctuations in heat demand and how they are dealt with when planning investments in the field of energy recovery of waste. The lifetime of Waste to Energy plants (WtEP) is typically 20–30 years. Their construction is also a time and investment-intensive business and requires a robust design with low sensitivity to future changes in key parameters.

The paper analyses the effect of fluctuations in heat demand on the accuracy of techno-economic models and their outputs. The aim is to determine the sensitivity of optimisation models to the applied time step. The sensitivity of two different models is compared – a simple model of a WtEP cooperating with a gas boiler and a complex model of a WtEP integrated with a combined heat and power plant.

Optimisation models, commonly used to design these facilities, perform calculations in certain time steps, typically on an annual or monthly basis. The simplification from hour to month time step may cause inaccuracies. The paper offers alternative solutions to modelling methods of WtEP, using so-called correction coefficients. They help to increase the accuracy of the models while maintaining acceptable calculation time.

1. Introduction

Approximately 1.3 trillion tonnes of municipal solid waste (MSW) are currently produced worldwide, which represents about 180 kg per person annually. It is assumed that this value will increase to 2.2 trillion by 2025 [1]. In developed countries, including the EU, this value is significantly higher. Such growth gives new opportunities for the development of efficient waste management (WM). Especially since it is the MSW that contributes considerably to many global environmental problems such as ecosystem damage, climate change, or depletion of available resources [2].

The EU established a WM hierarchy in 2008 to deal with the problems associated with waste production. According to EU wide regulation [3], the most suitable methods are waste prevention, material recovery and recycling. Another way of processing is energy recovery. The worst way is to deposit the resulting waste into a landfill. Material recovery is often costly and cannot be used for all types of waste [4]. Energy recovery presents an appropriate alternative, mainly in developing countries. Energy recovery helps to eliminate the ever-increasing amount of waste and it can also be a complementary source of energy by substituting primary fossil fuels. Given that over 80% of global energy is produced from fossil fuels [5], waste energy recovery can play an important role in reducing dependence on fossil fuels and reducing the net amount of CO_2 produced [6]. has conducted an analysis of global warming potential in various ways of handling municipal waste and claim that energy use can save up to 500 kg of CO_2eq per tonne of processed waste.

There are many different waste-to-energy (WtE) technologies used for energy recovery as reviewed by Ref. [7], including incineration, pyrolysis, gasification, anaerobic digestion and landfilling with gas recovery. Worldwide, the incineration is one of the most commonly used WtE technologies and for this reason, the construction of new WtEP is currently a much-debated issue. European countries can be divided into three groups depending on the WM level [8]. In this respect, many developed countries use waste to recover energy and also achieve high levels of material recycling. An example is Norway. Construction of new WtEPs in this country is discussed in Ref. [9]. Another group is countries that use only a part of the municipal waste energy, and there is more construction

* Corresponding author.
E-mail address: ondrej.putna@vutbr.cz (O. Putna).

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Abbreviations

C	WtEP capacity [kt/y]
c	amount of waste entering the boiler in the WtEP [t/h]
D, D^s, D^w	total heat demand, demand for heat in form of steam, hot water [TJ]
d, d^s, d^w	average total heat demand, demand for heat in form of steam, hot water [GJ/h]
$P_{max,\ min}$	maximum, minimum heat output of the WtEP [TJ]
$q_{WtEP,\ GB,CHPP}$	heat energy supplied from the WtEP, gas boiler [GJ/h]
$Q_{WtEP,\ GB,CHPP}$	heat energy supplied from the WtEP, gas boiler [TJ]
R	ratio of average monthly heat demand and maximum heat output of the plant [−]
r	dissipated heat [GJ/h]
v	turbogenerator power [MW_e]
x	steam flows [GJ/h]
CDR	condenser
CHP(P)	combined heat and power (plant)
DHS	district heating system
FCHS, k	fluctuation coefficient of heat supply
IRR	internal rate of return
MI(N)LP	mixed-integer (non-)linear programming
NPV	net present value
PP	payback period
ROI	return on investment
WM	waste management
WtE(P)	waste-to-energy (plant)

of new WtEPs, such as the UK. The role of WtEPs in the WM of the UK is reported in Ref. [10]. In Poland, which can be included in this group, six new WtEPs have been put into operation in 2016 [11]. The last group is countries where waste is not used as energy or material at all or only to a very limited extent. Following the trend of countries with well-developed WM systems, it can be expected that countries with poor WM systems attempt to increase the energy recovery of waste. As a result, the construction of new WtEPs continues to be a very topical issue that needs to be addressed.

For a thorough understanding of the intent of this article, it is necessary to cover three basic themes:

- understanding the project economics of combined heat and power plants (CHPP),
- selecting the relevant criteria for determining the return on the project,
- modelling the current and future operation of CHP facilities.

1.1. WtE project planning

It is necessary to consider the entire WtE project life cycle, about 20–30 years [3]. There are important parameters for assessing the economics of the project and operation planning, which vary with time and which are difficult to predict accurately in the long-term and even the short-term. In such cases, stochastic models can be used to take these uncertainties into account [12]. shows this approach in the case study when planning the WtEP operation using uncertain parameters.

A WtEP uses heat from waste incineration to fulfil heating and power demands if it incorporates a turbine generator. Planning for the production of heat and power in different time steps is described in Ref. [13]. Waste disposal income is the main parameter in the WtEP economy, but the revenue from heat also plays an important role, see Fig. 1.

The pie chart was created for a WtEP with a processing capacity of 130 kt/y and a heat demand of approximately 600 TJ/y. Another example of the WtEP income structure can be found in Ref. [14]. Revenue for individual commodities (i.e. heat, power and scrap) is calculated using a two-stage optimisation model.

The figure shows that income for heat sales is around 25% of the total income. Regarding capacities lower than 40 kt/y, the heat accounts for more than one-third of the total income. The correct estimation of the quantity and price of the heat delivered affects the success of the whole project. The selection of the plant location is a very important decision due to the availability of a district heating

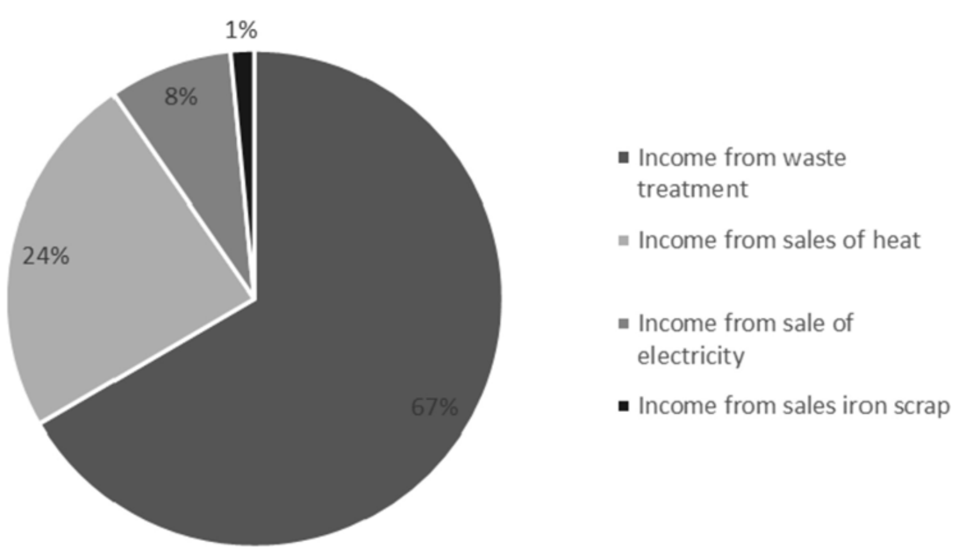

Fig. 1. An example of the income structure [%].

system (DHS) and/or industrial heat supply. This ensures the useful recovery and exploitation of heat at a known quantity and price. Throughout the lifetime of a WtEP, the demand for heat can be significantly reduced as the demand-side energy efficiency increases with time and no new consumers are added, see Ref. [15].

In this paper, district heating is considered as significant fluctuations in heat demand may occur there. In some countries, the heat price depends on the season. For example [16], considered different heat prices for each month. The research was carried out in the Nordic countries and there is a significant drop in prices in the summer months. However, a variation in demand could be defined as well for power (e.g. price variation due to the seasonal character of renewable sources etc.). The profitability of new planned projects is estimated based on all of these unknown fluctuations. The models introduced further in the paper use operational data from existing locations in the Czech Republic, where DHSs are relatively widespread. About 38% of Czech households use district heating according to the Czech Statistical Office.

1.2. The profitability of a WtE project

The success of the project is measured by several different criteria. The most commons are the Payback Period (PP), Return on Investment (ROI), Net Present Value (NPV) and Internal Rate of Return (IRR) [17]. use these criteria to make an objective assessment of the success of a WtE project in China. The PP and ROI criteria have a very simple calculation, but these indicators do not consider cash-flow in individual years (only the project profit). PP and ROI do not often include the principle of the value of money over time. In most cases, the authors focus on using IRR or NPV. For example [18], deals with the riskiness of investments in WtE projects in Iran. A binomial tree analysis and a modified version of NPV (Decoupled NPV) are combined to determine the risk [19]. use a new term, waste availability factor and the IRR criterion to compute the risk of new projects in the Czech Republic. The difference between NPV and IRR is described in more detail by Ref. [20].

All these articles about the profitability of new WtE projects use data on an annual or monthly basis. However, there are parameters which are quite variable over time, for example, heat demand or waste supply. As Fig. 1 shows, a quarter of the income depends on heat sales. Attention should be paid to assess the amount of heat produced and sold during its future operation as accurately as possible. For this reason, the computation of WtE project income on annual or monthly bases (which is common practice in the early stage of project development) seems to be inappropriate.

1.3. The modelling of current or future WtEP operation

WtEPs are preferably operated as CHP systems. CHP operation modelling is a very complex task. Generally, it is a mixed-integer non-linear problem (MINLP), as described in Ref. [21,22]. deal with the long-term optimisation of the CHP system with extraction-condensing steam turbines, gas turbines, boilers for heat production and district-heating networks. The optimisation is based on MINLP and Lagrangian relaxation and the model, which works on an hourly basis [23]. modelled hourly CHP operation (the precise facility is not specified) as a linear-programming problem with a special structure. A specialised Power Simplex algorithm was used that utilises the structure efficiently. The main idea of the whole approach is to allow the decomposition of long-term models to smaller ones. A similar approach is used in Ref. [24]. Envelope-based optimisation algorithms are used to solve a decomposed, long-term model.

An interesting approach is presented also in Ref. [25], where the capacity and operation of a CHP is optimised by a genetic algorithm to maximise the technical, economic and environmental benefits.

In some articles, the authors use the software EnergyPLAN and often simulate the operation of energy systems on an hourly basis. The use of this software is described in detail by Ref. [26,27]. deal with the economics of two WtE projects in Denmark and Zagreb. EnergyPLAN was used for simulating the operation of the WtEP on electricity markets. The considered time step is 1 h. The supply of power to the grid from an existing WtEP is dealt with by Ref. [28]. A stochastic model, which includes Monte-Carlo simulation, was introduced for predicting electricity use. The considered time step is again 1 h.

All of these models with time steps shorter than a month implement a pre-selected CHP plant capacity or overly simplify plant models (linearised mathematical equation, neglect of energy losses). Regarding WtEP at an early stage of project development, the challenge is to propose an optimal capacity considering the plant's future effective operation. Capacity then enters the model as another variable and new non-linear relationships are created. All together with the size of the task, the model becomes very difficult to solve.

1.4. Aim and scientific contribution of the paper

There are several issues, which may occur while solving technical and economic models of WtEPs using uncertain parameters. These parameters change over time and, as a rule, they cannot be accurately predicted over the plant's lifetime (e.g. heat demand). Mathematical models must also often be simplified in terms of the length of the time level used, because for short periods of time (e.g. week, day, hour), they may become too difficult to solve. There are different approaches to improving the solvability of these models. For example [29] uses a so-called rolling horizon approach for the long-term planning of a CHP system operation. This approach was taken in the expectation that annual models on an hourly basis would be insolvable in terms of calculation time. Unfortunately, just like the above-mentioned approaches, the plant's parameters (capacity, type of turbine, boiler, etc.) must be selected initially. In this case, the design parameters of the plant have to be optimised, so the approach once again does not provide a possible solution. In these situations, two-stage optimisation models are often employed [30]. In such models, the first-stage (strategic) decisions are made before the realisation of any uncertainty (here-and-now approach), and the second-stage (operational) decisions are made after all uncertainties are revealed (wait-and-see approach). It means that for two-stage optimisation models, all combinations of design parameters have to be calculated, which might be very time-demanding.

The aim of this article is to introduce an approach of increasing the accuracy of the calculation while preserving the simplicity of the WtEP mathematical model in terms of time level at the same time. That is achieved by using so-called “error-correction coefficients”.

Due to their use, it is not necessary to consider the model on an hourly basis, but rather a monthly model that is much less time demanding and, moreover, does not significantly reduce the model's accuracy. Coefficients for correcting heat demand are described in more detail in this paper as a typical example of parameters which fluctuate over time (see section 2.2). The error caused by fluctuations in demand for heat has a major impact on the overall economy of a WtEP. Of course, as with heat demand, the coefficients can be applied to other fluctuating and poorly predictable parameters that affect the operation and economy of the plant. For example [31] shows CHPP modelling in terms of electricity prices, heat demand and ambient temperature.

2. Methodology

The analysis presented in this paper is based on heat demand data and its variation from a particular locality, see section 2.2. Whereas WtEPs with capacities of >100 kt/y are common [32], a WtEP with significantly lower capacities (10–40 kt/y) can be more preferable in some cases. The main reason to implement a low-capacity WtEP project is the fall in specific investment costs, which has a positive impact on the economy of the project. This is due to the possibility of using mass-produced devices and generally simpler (but fully functional) technological solutions. In the end, it is possible in some cases to set a lower gate price for these facilities than for facilities with a capacity exceeding 100 kt/y. Low-capacity WtEPs can be found especially in locations with less heat demand or where it is not possible to provide sufficient waste to operate a large WtEP. As far as operating costs are concerned, the staff costs are considerably higher for lower capacities. The necessary number of employees increases only marginally with the increased capacity. If the WtEP is built with an existing heating plant, it is often possible to share the technological elements or employees of the original source. This is especially true for smaller capacities and can bring considerable investment and operating savings. As a result, this study considers incineration plant capacities between 10 and 40 kt/y, i.e. combustion on a moving grate and combined production of power and heat in a steam cycle with a turbine. The basic WtEP scheme that is considered in the paper is shown in Fig. 2.

Municipal and residual solid waste is incinerated in a furnace. For modelling reasons, lower heating value 9.3 MJ/kg is considered, see Ref. [34]. This value is based on long-term investigations by the authors of the paper. Support fuel in the form of natural gas is only considered when starting up the plant or in exceptional operating conditions. Therefore, its use was neglected in the model.

Flue gas is used to produce steam in a boiler. The flue gas continues to the flue gas cleaning system, where harmful substances are removed, for example, dust particles, dioxins and heavy metals.

Steam generated in the boiler continues to a back-pressure turbogenerator (TG) and after that is used for district heating or flows to the condenser (CDR), depending on the current heat demand. In the model technology, steam is produced at a temperature of 220 °C and a pressure of 1.3 MPa in the steam generator. Unlike a large WtEP, small capacities typically tend to focus on heat production. This is due to the high investment costs of a high-pressure steam boiler and the condensing turbine. For small WtEPs, a back-pressure steam turbine with lower internal thermodynamic efficiency - the so-called rotating reduction – is used to produce electricity. The amount of electricity produced in this way is mainly used for the plant's own consumption. A small capacity WtEP may not be self-sufficient in terms of electricity generation and technological consumption. In such cases, additional electricity must be purchased from the grid.

2.1. Operation modes of the WtEP

This article deals with the conceptual design of a new WtEP. In order to make the WtEP project attractive to a potential investor, it is necessary to estimate the approximate profitability. Here, the criterion IRR is used as the profitability factor. For its calculation, it is necessary to determine the investment and the annual cash flow throughout the life of the project (around 25 years). It is very difficult to model the operation of a WtEP for such a time with sufficient precision.

First, data are processed on a monthly basis, which is often considered to be an acceptable level of accuracy for the model. Consequently, in the course of individual months, constant heat demand as an average value is found. This does not take into account the daily and hourly fluctuations in heat supply. In terms of heat supply, three modes are possible (see Fig. 3):

1. $d \ll P_{max}$: Monthly heat demand is significantly lower than the maximum possible delivery P_{max} from the WtEP → all demand is covered (mode 1).
2. $d \gg P_{max}$: Monthly heat demand is significantly higher than the maximum possible delivery from the WtEP → the maximum possible heat output from the WtEP is considered throughout the month (mode 2).
3. $d \cong P_{max}$: Monthly heat demand is similar to the maximum possible delivery from the WtEP → it is necessary to analyse the course of consumption and fluctuations during the month (mode 3).

If a WtEP operates in mode 2, it can apply its whole thermal power. Modelling this situation is therefore simple. Modelling in mode 1 does not cause a problem either as the WtEP is able to deliver all the heat despite its fluctuations. In mode 3, on the other hand, the amount of heat actually delivered from the WtEP may vary considerably depending on the time detail of the model. In a part of the month, the WtEP is unable to deliver enough heat energy to cover the demand, and in the other part the heat demand is

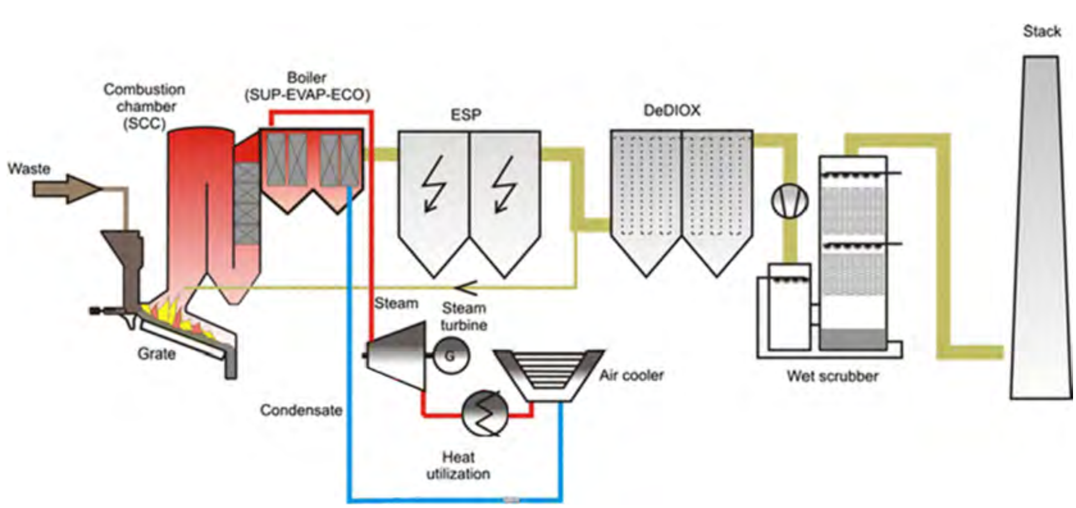

Fig. 2. Block diagram of a WtEP [33].

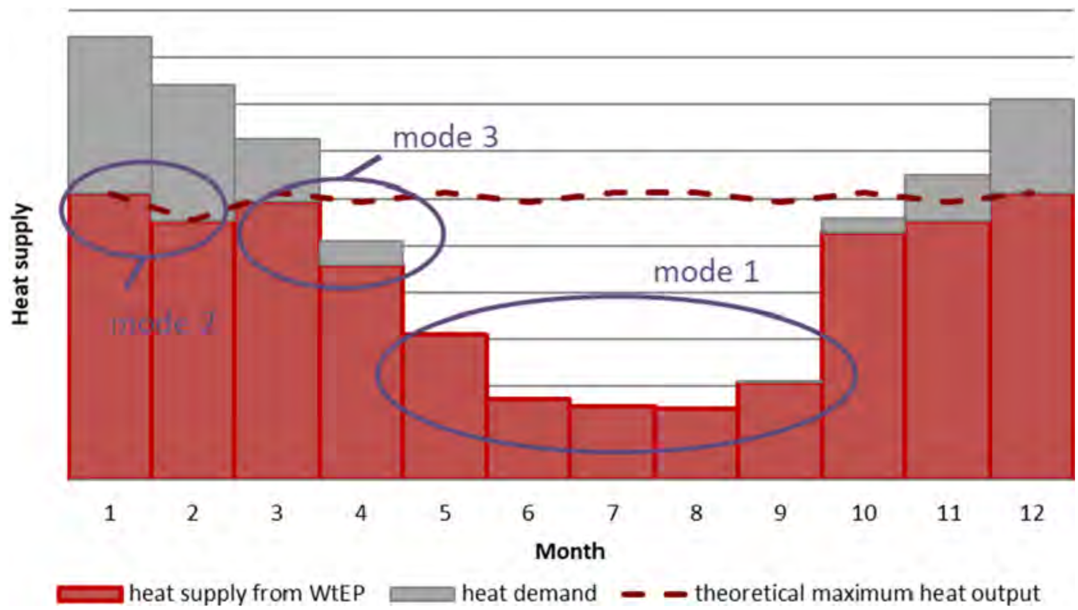

Fig. 3. The three modes with a different relationship between heat demand in the DHS and heat supply from the WtEP.

low, so the heat sales are not secured. Considering this problem, the average monthly value of demand is not adequate and it has to be reduced slightly. This is evident in months 3, 4, 10 and 11, when the whole heat demand is not covered, although the thermal output is sufficient from the point of view of monthly modelling. The rate of the reduction is the main theme of this article.

2.2. Heat demand in the DHS – a modelled case

Heat demand for steam and hot water was assumed in the modelled locality. Real data from an existing district heating plant were used and the real demand profile during the year was analysed, as well as all short-term fluctuations in demand. The heat demand data are summarised in Table 1. There is a shutdown of the entire heating plant for a period of 58 days in the summer. The total annual heat supply is 190 TJ.

The table shows only the monthly averages of the heat demand. An analysis of the available data at certain times confirmed that there are substantial deviations from the average value. The deviations are strongly dependent on the parameters of the DHS. The main parameter is its size and type of final consumers (households, companies). For illustration, Fig. 4 details the heat demand in April. The value labelled “month average” corresponds to the average demand for April as mentioned in Table 1.

On average, the hourly demand differs from the monthly average (5.75 MW_t) by approximately 25% in this month. The scale of fluctuations in the other months is shown in Fig. 5.

The magnitude of the heat demand fluctuations is related to the annual cycle and also to the heating season. In the conditions of Central Europe, the season typically lasts from September to May. Its beginning and end are logically associated with the greatest fluctuations in heat demand. The end of the heating season is characterised by a drop in demand for heat. If the heat is also used to heat hot water, the demand outside the heating season is more or less constant.

As you can see from the monthly deviations, they vary a lot in all months and, for modelling the operation of the WtEP, cannot be ignored or neglected. The effect of neglecting these variations will be shown on the following model of an integrated WtEP introduced in the next section.

3. Optimisation models

3.1. A basic technological and economic model

First, a simple technological and economic model was created for the WtEP depicted in Fig. 6. The main result of the model is the annual profit. A WtEP was considered with a small capacity *C* of 40 kt/y, a single TG and a connection to the DHS. The technological solution described in section 2 was used. The gas boiler is considered as an existing part to which the WtEP is integrated. If the WtEP is integrated, the gas boiler will no longer cover the overall demand, but it will only be used for covering peaks. The newly considered device is highlighted in blue in Fig. 6. Heat demand was modelled using data from the previous section.

In our particular simulation case, the following costs were considered:

- cost of natural gas (7.9 EUR/GJ),
- revenues for waste treatment (65 EUR/t),

Table 1
Heat demand data.

Month	1	2	3	4	5	6	7	8	9	10	11	12
Total heat demand, $D = D^s + D^v$ [TJ]	31.8	26.7	21.9	14.9	11.8	6.1	0.1	0.6	9.3	15.6	22.0	28.9
Average heat demand, $d = d^s + d^v$ [GJ/h]	42.7	39.7	29.4	20.7	15.9	8.4	0.2	0.7	12.9	21.0	30.5	38.9
Average thermal output [MW_t]	11.9	11.0	8.2	5.8	4.4	2.3	0.1	0.2	3.6	5.8	8.5	10.8
Standard deviation of hourly averages [GJ/h]	10.3	10.8	10.8	7.3	6.1	2.1	1.0	2.3	4.0	9.9	8.9	10.7

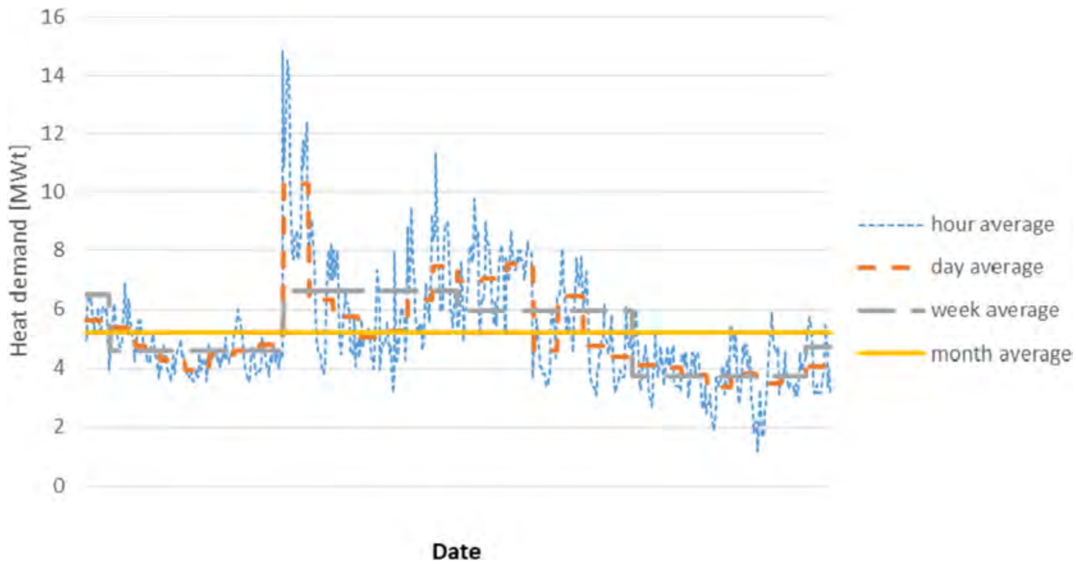

Fig. 4. Heat demand in April reported at different time intervals.

Fig. 5. Stability of heat demand by months.

- revenues for power (45.5 EUR/MWh),
- revenues for heat (7.5 EUR/GJ).

The first step is to transform this problem into mathematical form. All relations can be described by similar equations as in the paper by Ref. [35]. The main inputs needed for the calculation are:

- WtEP capacity C,
- heat demand D, covered by heat from the WtEP and Gas boiler $= Q_{WtEP} + Q_{GB}$,
- purchasing and sales prices for individual commodities (power, heat, supply water, …),
- characteristics of the TG (turbine flow, minimal and maximal power output, …),
- cost of maintenance and reinvest,
- investment needed to build the facility,
- wages of employees,
- projected wage growth and inflation.

Variables of the model to be accounted for are:

- the amount of waste entering the boiler c ($c < C$),
- all steam flows $x_1, x_2, \ldots$ in the piping system,
- power v,
- the amount of heat dissipated r,
- the amount of purchased natural gas,
- penalties (in the event of unsatisfied demand).

The intermediate results of the example model are the cash flows in the individual years of an operating facility. For simplicity,

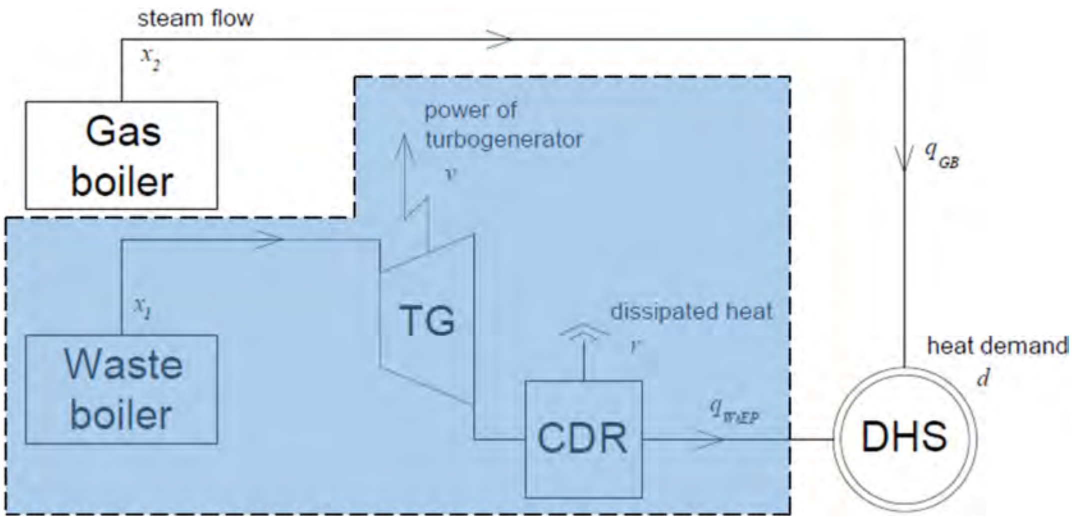

Fig. 6. Scheme of the WtEP.

the profit calculation of the WtEP was limited to one year. The results are shown in Table 2 depending on the length of time step used.

Looking at the previous table, it can be seen that the difference in the profit is almost 15% each year between the calculated results of the model on an annual and hourly basis. The difference in heat-related income is almost doubled. This income is calculated only from the heat Q_{WtEP} produced by the WtEP (without using the additional natural gas boiler). The resulting heat income for total heat $(Q_{WtEP} + Q_{GB})$ is approximately the same, because heat demand must be satisfied. The difference is caused mainly by the costs associated with the production of this heat.

The difference in the resulting IRR is shown in the following table. This is a simplified calculation of the IRR, where each year the same profit (see Table 2) is considered unaffected by inflation or projected wage growth. The IRR calculation includes the cost of building the WtEP with a waste boiler and one TG. The gas boiler enters into the model as an existing part to which the WtEP has joined, and so the gas boiler investment is not included in the IRR calculation. The input investment of a WtEP with capacity C of 40 kt/y is considered to be approximately 12.75 mil. EUR, see Ref. [36].

The difference between annual and hourly approach is clearly significant. The IRR differs by more than 2%, which is a significant drop for the investor, and so the simplified model overestimates IRR (see Table 3).

The chosen example is very easy to calculate because of its simplicity, so it is not worth comparing the computational time. For larger tasks, the influence becomes considerable, see section 3.4.

So the question is how to get the results. An hourly approach would be good to take into account, but it will likely increase the computing time, see Table 4. For this reason and due to the lack of data (only monthly averages of heat demand were available), it is not always possible to solve such a model.

This problem can be partially solved by using error-correction coefficients described in the next section. No previous literature could be found which mentions such an approach.

Table 3
IRR of project WtEP by 24 years.

Time step	Hour	Day	Week	Month	Year
IRR [%]	11.84	12.31	12.34	12.47	13.97

3.2. Error-correction coefficients

As mentioned above, the required models to capture the lifetime of the future WtEP are solvable only on a monthly basis. By neglecting the hourly fluctuations in demand for heat, it is possible to overestimate the profit. The following section deals with the introduction of correction coefficients that will ensure sufficient accuracy even when calculating on a monthly basis.

There are many parameters where hourly fluctuations should be considered the demand for electricity, heat, amount of waste in the WtEP, etc.

The following text focuses on the demand for heat parameter. Therefore, coefficients that decrease the maximum heat output of the WtEP are considered. Their use in the model is described by the following Eq (1):

Table 2
Yearly profit, heat supply and electricity supply of a WtEP and incomes from heat.

Time step	Hour	Day	Week	Month	Year
WtEP profit, Z [thous. EUR]	1619.9	1672.7	1675.8	1690.8	1862.4
Heat demand, D, $Q_{WtEP} + Q_{GB}$ [TJ]	189.6	189.3	189.6	189.6	190.5
Heat supply from WtEP, Q_{WtEP} [TJ]	**94.7**	**167.2**	**167.6**	**169.4**	**190.5**
Heat supply from GB, Q_{GB} [TJ]	94.9	22.1	22	20.2	0
Income from heat [thous. EUR]	**710.3**	**1254**	**1257**	**1270.5**	**1428.8**
Electricity generation v [GWh]	6.1	6.1	6.1	6.1	6.1
Electricity consumption [GWh]	10.1	10.1	10.1	10.1	10.1
Electricity costs [thous. EUR]	184.1	184.1	184.1	184.1	184.1

$$P'_{max} = P_{max} \cdot k, \quad (1)$$

where P'_{max} is the plant's corrected maximum heat output, P_{max} is actual maximum heat output, which is related to the processing capacity C, and k is the fluctuation coefficient of heat supply (FCHS). The idea of this coefficient was introduced in detail by Ref. [37] and an example of its application is illustrated in Fig. 7. The case shown here represents a situation, where P_{max} equals to the heat demand. This can be considered as an extreme case leading to the highest corrections. The effect of the peaks is the most significant. Both the WtEP and gas-fired boiler supply heat to cover the demand. A variation of demand within one month is displayed. The WtEP annual throughput is 10 kt/y. Considering the lower heating value of waste 9 MJ/kg and boiler efficiency 80%, it leads to P_{max} of 5.22 GJ/h. In reality, the WtEP covers the base load and supplies 3.26 TJ in this period as shown in the left part of the figure. The peaks (0.5 TJ) are covered by the gas-fired boiler. If we use the model on a monthly basis without correction, the heat supply from WtEP is inaccurately found to be 3.76 TJ.

The goal is to achieve the correct value of heat supply, i.e. 3.26 TJ and 0.5 TJ (areas above and below the P_{max} line) even in a simplified model working with a month time-step. This is secured by applying of FCHS with a value of 0.87 and results in a corrected P'_{max} (see Eq (1)) as shown in the right part of the figure.

An extensive investigation of the relationships between k, heat demand d and WtEP capacity C was performed. As a result, the dependence of k on the ratio of average monthly heat demand d and maximum heat output of the plant P_{max} was found. This ratio is denoted as R:

$$R = \frac{d}{P_{max}}. \quad (2)$$

Fig. 8 shows this dependence on one locality over three months, which represents the winter period (January), transitional period (March) and summer period (July). The processing capacity C of the WtEP and the heat output has been changed continuously, creating smooth curves.

The use of FCHS allows the calculation on a monthly basis while maintaining real heat supply potential. The calculation of the model described in section 3.1 was performed once again with the data on a monthly basis. This time FCHS were employed and the calculated annual profit was 1643.3 EUR, which corresponds to the accuracy of an hourly or daily basis calculation (see Table 2).

3.3. A generalisation of correction coefficients

The correction coefficients bring a considerable improvement to the profitability calculation. In some cases, however, no hourly data may be available to determine these coefficients. Such cases include a new DHS or cases where data is archived only at longer intervals, e.g. 1 h.

It is advisable to find a locality that is very similar to the investigated locality and has similar demand fluctuation profiles. Another solution can be to create general correction coefficients for any location. To determine whether such coefficients can be created, operational data on heat demand from a total of seven localities with DHS from the Czech Republic were collected. The values of individual FCHS obtained from this data are shown in Fig. 9.

The graph shows all the calculated coefficients, depending on the ratio R, see Eq (2). The ratio R is important but not the only parameter on which the FCHS is dependent. The reasons for these outliers are described to better understand and correctly estimate future coefficients for individual situations.

a) Low values of coefficients for the ratio of $R < 1$: Coefficients that are not close to zero with decreasing WtEP performance usually occur in the summer when the heating plant stops its operation, or there is a zero demand for heat for some time. This is, for example, the case of heat supply sites only for heating without DHW heating in the months when the heating season is over or just started. In these months, it is not possible to apply all the

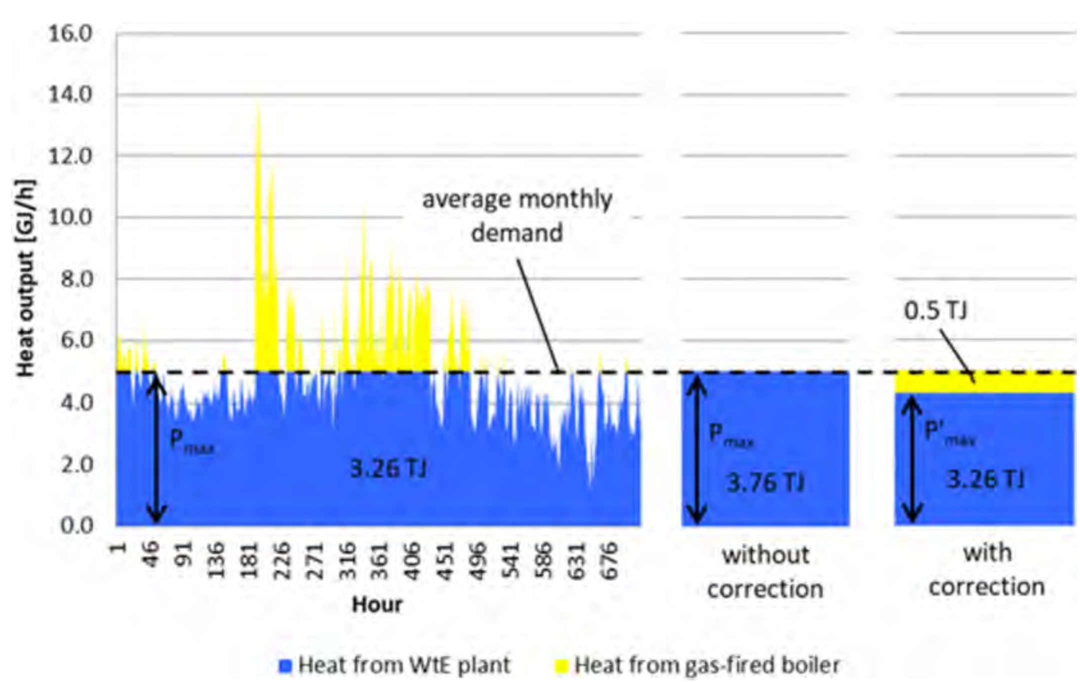

Fig. 7. The principle of use of error-correction coefficients.

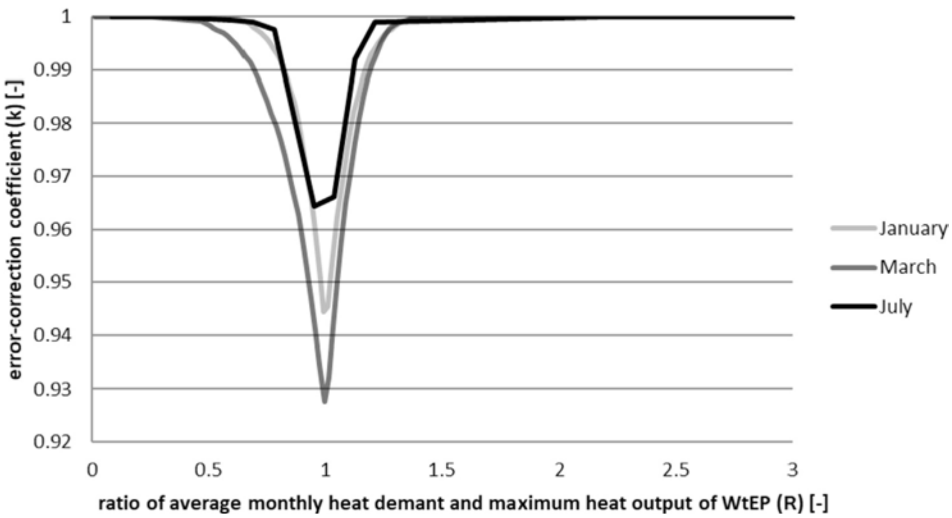

Fig. 8. Correction coefficients at one locality.

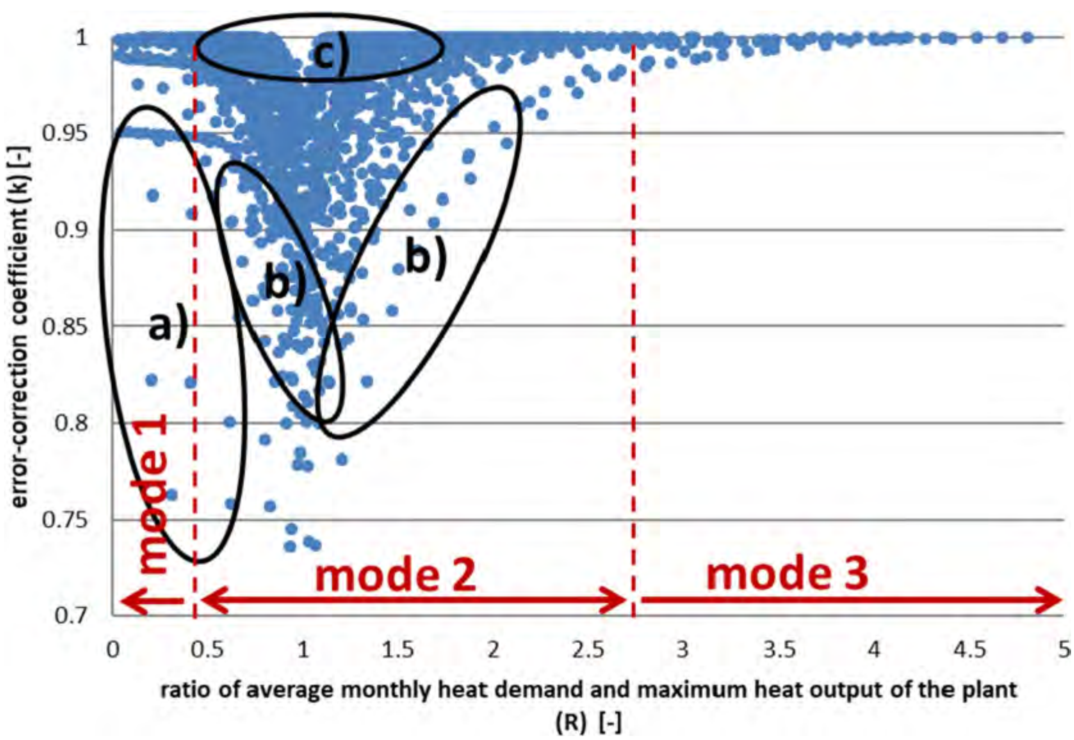

Fig. 9. Outliers of the correction coefficients.

heat produced irrespective of the power of WtEP, so the coefficient is always less than 1.

b) Generally, low values of coefficients at a ratio of R <> 1: Generally low coefficient values have two causes. Most of these values correspond to the months at the beginning or end of the heating season (May and September), i.e. with a very different demand for heat in different parts of the month. The low value of coefficients is also linked to the instability of demand in a given CZT network. Normally, the rule is that larger networks are more stable. This stability is usually only the ratio R approaching one.

c) High values of coefficients at a ratio R approaching 1: Coefficients gain higher values with a more stable demand for heat, both at the monthly level and on a daily basis. High values are observed especially in large DHSs and in winter months.

Fig. 10 plots the data after removing that outliers that are caused by non-standard operation states. The dependence of coefficients on the mentioned ratio R with a linear approximation is also shown. The FCHS for the assessed locality and a specific WtEP capacity (see Table 1) are highlighted.

For illustration, Fig. 10 shows the FCHS for the model locality and one selected maximum heat output P_{max}. It is obvious that the correction coefficients are close to 1 in the winter when the heat supply from WtEP is close to the maximum potential or in the summer when the power peaks are covered by WtEP. The effect of

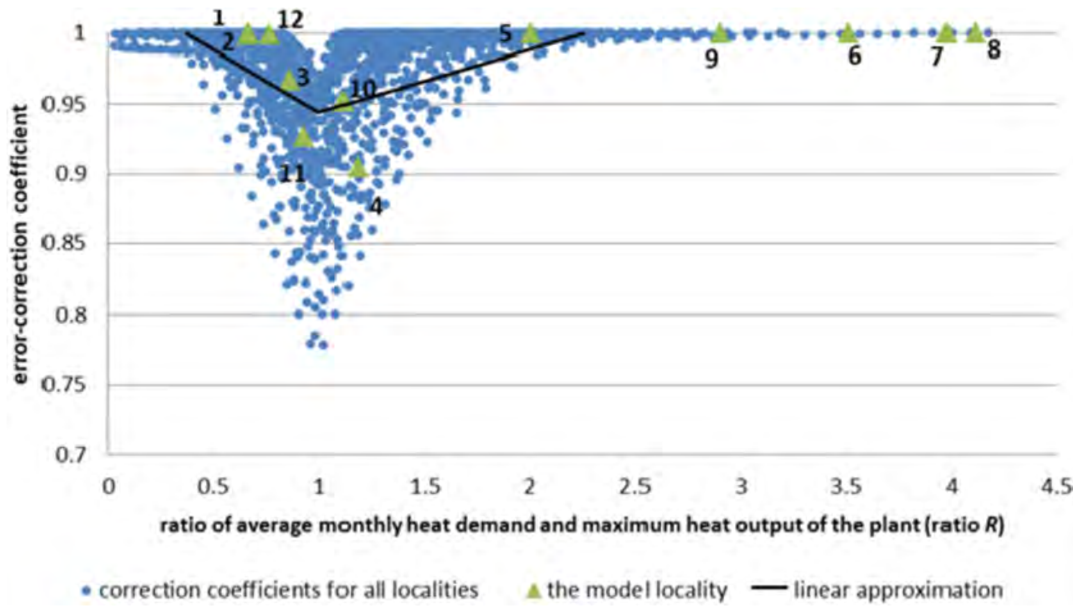

Fig. 10. Fluctuation coefficient of heat supply FCHS.

correction coefficients is most pronounced in the transition period, when the power peak is due to the greatest distortion in the simplified modelling on a monthly basis.

Only the ratio *R* was used to create a linear regression model. The values of the model are highlighted by the black line. Note the significant deviations between the approximation and real values, especially where the ratio *R* is close to 1. This means that the model is not sufficient to generate coefficients in general for any location.

Obviously, a general linear model based on data from all available locations (and only dependent on the ratio *R*) is not very accurate. If data is available on an hourly basis, it is generally preferable to create correction coefficients accurately for a given location. If data are not available, the linear replacement is at least a partial improvement and is usable.

3.4. A technological and economic model of a complex integrated system

A cooperation between WtEP and CHP plant is considered in the following example, meaning the required model is more complex compared to the investigated case study in section 3.1.

In the model example, the construction of a WtEP with a low processing capacity (40 kt/y) was considered. The same DHS was considered as in the simple example, but in this case, the heat demand was divided on demand for steam and hot water. The model used and description of the site was presented by Ref. [35]. The primary source of heat is a CHP plant composing of two coal-fired fluidised-bed boilers and two steam turbines TG1 and TG2 (existing plant). Heat supply from a WtEP directly into hot water or steam distribution system is analysed. The steam can be alternatively used to drive TG2 in so-called ‘summer mode’, see further below. A WtEP block diagram for an existing CHPP is shown in Fig. 11. In the example, an existing CHPP with TGs and a DHS connection is considered. The blue-coloured part of the diagram shows the proposed new WtEP. It also shows the boundaries for a model evaluation.

Against the above-mentioned input parameters to the example model (see section 3.1), there will be:

- the output of the CHPP's boiler,
- wages of employees at the CHPP.

It is necessary to know the parameters of the CHPP as the WtEP profit is calculated as follows. In the first step, the operation of the existing CHPP only is simulated. Only devices not coloured blue in Fig. 11 enter the calculation. The outcome is the profit z_1 of CHPP. In the second step, the model is extended by the WtEP and the profit is calculated again. This time it is the profit z_2 of the integrated system (WtEP and CHPP). The IRR is based on the difference between $z_2 - z_1$.

Next, the demand for heat is divided into demand for steam and hot water. This will make the calculation much more complicated due to the fact that new steam flow variables will be created separately for winter and for summer operation. The piping system in winter mode is highlighted by blue dash-and-dot lines, similarly in the summer mode, it is highlighted by red dashed lines, see Fig. 11. It led to MINLP, but due to some modifications (see Ref. [38]), it was converted to MILP.

The main income affecting the economy of WtEP projects includes revenue for processing waste (65 EUR/t) and selling heat (7.5 EUR/GJ). The key outcome of the model is the WtEPs profit in the optimal mode of operation (same as the above-mentioned model).

The original model, published by Ref. [35], worked on a monthly basis, i.e. twelve-time intervals were considered to describe operation during the year. Recasting the model on an hourly basis led to task unsolvability. Put simply, it becomes a large MILP problem with over 420,000 binary variables. A few simplifying changes have to be made.

- The capacity of the WtEP is determined before calculation (fixed *C*).
- The power output is taken as a function of steam throughput on TG1 and TG2, which was described by the linear equation.
- Binary variables were removed, i.e. the model was decomposed into the subtasks (winter mode with CHPP on, winter mode with CHPP off, summer mode with CHPP on, summer mode with CHPP off).

Individual subtasks have a linear character. Each subtask was

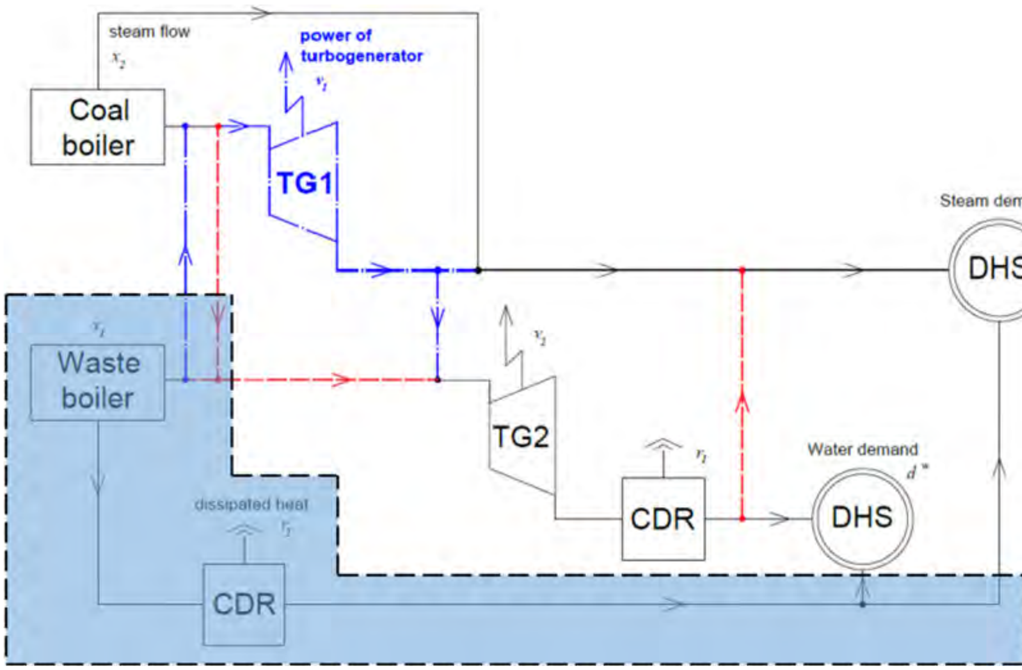

Fig. 11. Scheme of integrated system WtEP and CHPP.

Table 4
Profit of WtEP in April and calculation time.

Model time interval	Hour	Day	Week	Month	Year
Profit per month [thous. EUR]	165.6	180.4	178.1	186.7	193.2
Computational time [s]	Over 1500	51.9	9.7	5.4	5.4

counted in software GAMS by solver CPLEX. The ideal operating conditions are determined by analysing the results of individual subtasks. This means that each hour of operation is counted separately. The result of this part is the profit, the amount of fuel consumed, the amount of steam passing through individual turbines, the electricity produced, and so on. Despite this, the calculation is very challenging and requires additional adjustment after completion. The previously mentioned simplifications and only one month of data allowed the calculation to be performed on an hourly basis and the result was compared to other time steps. The results for different time intervals are shown in the following Table 4.

The results show that fluctuations in hourly demand are also very important in this case. For accurate estimates they should be included in the model, however, the computational time is enormous and it limits the model's applicability for real case studies. When considering continuous demand development during a plants lifetime (20–30 years), the calculation time would be about five days. Due to the simplifications mentioned above, the calculation should still be repeated for all selected types of TG and capacities, which would result in unacceptable overall computation times. In this regard, the month interval is a reasonable compromise when similar corrections as mentioned in section 3 are implemented.

Following the application of the above-mentioned approach, it is, therefore, possible to proceed to complex multi-stage models, which must not involve too much simplification.

3.5. Respecting the parameters of the peak-load source

As was mentioned above, a WtEP is integrated into an overall system. In a real-life situation, in addition to fluctuations over short periods of time, it is necessary to take into account the operating parameters of the parallel heat source, which are:

1. Minimum heat output – Every heat source can be operated at a certain power range. The minimum output is usually reported as a percentage of the nominal/maximum output and is mainly dependent on the type of combustion equipment and the fuel used.
2. Possibilities of shutdown – If the power supply is not needed for some time, it is possible to shut down the heat source. When the steam or hot water boiler is shut down, the boiler can be operated either in the hot or cold backup mode. The hot backup is associated with a certain fuel consumption and is used in a period when a demand for rapid power delivery may occur. In cold backup mode, the boiler is shut down in the form of wet or dry preservation.

These issues affect the heat supply from the WtEP in terms of quantity and price. Fig. 12 shows how heat supply from a WtEP is suppressed when a power range of the peak-load source is considered. The heat is supplied from a WtEP and a coal-fired boiler to a network with an annual demand of 600 TJ. In this case, the coal-fired boiler is over-sized and its minimum power P_{min} is 10 MW_t (about 25 TJ monthly). The WtEP has a thermal power of 25 MW_t (about 36 TJ monthly). It is assumed that the most economical mode of operation is maintained all the time and if there is excess heat, the supply from the coal-fired boiler is preferred. It is evident, that the full potential of the WtEP cannot be used, especially in transitional periods, when the coal-fired boiler cannot be shut down due to the need to cover peaks in heat demand.

If the minimum power of the secondary heat source is included in the input variables for calculating the correction coefficients, the correction coefficients are greatly affected. From Fig. 13 Fig. 13, the effect of this minimum power P_{min} on the value of the correction coefficients is presented on the example of one DHS. The minimum power was changed in the range of 0–20% of the maximum

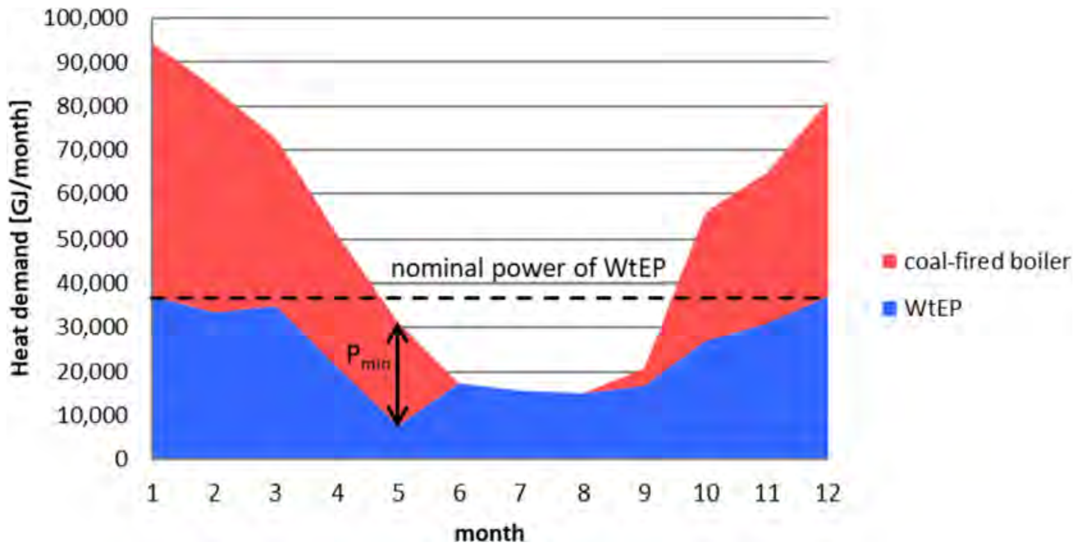

Fig. 12. Heat supply when considering the minimum output of the secondary source.

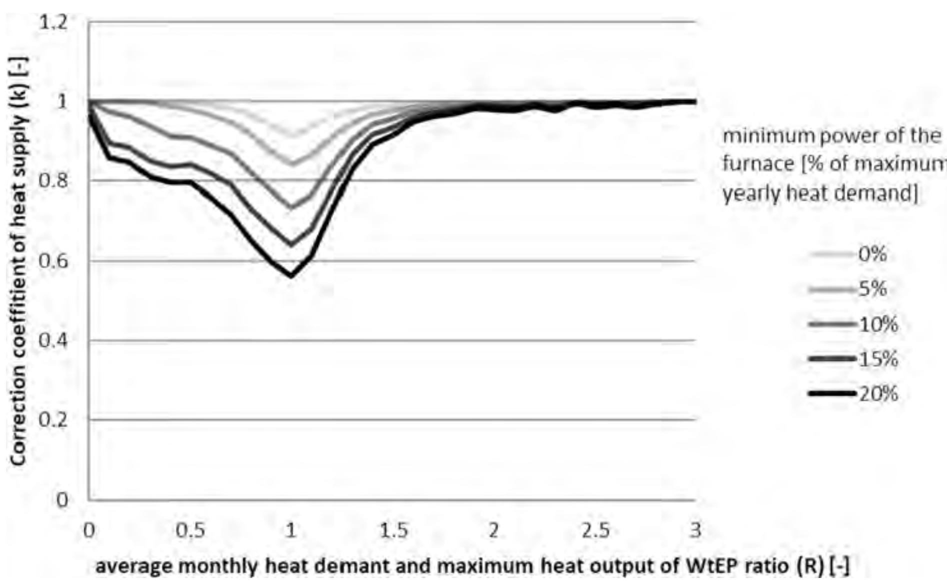

Fig. 13. The effect of the minimum power of the peak-load source.

demand in this DHS for modelling reasons. This means that the minimum power of the boiler in question also varies from 0 to 20% of its maximum power. Such low minimum power values are only common for gas boilers. In the case of solid fuel boilers, this value is considerably higher.

If this share is 0% it means that the boiler can be operated at the full range from 0 to P_{max}. If the minimum power is not considered or is zero, the correction coefficients are defined only by limited demand coverage at power peaks, so they are the coefficients described in section 5. When a minimum power of 20% of the maximum demand is considered, the correction coefficients of values down to 0.56 are achieved in months when the ratio R is approaching 1. Boiler shutdown was considered when it was not used for at least one week. Otherwise, their operation was considered at least at the minimum power level.

Fig. 13 above shows the average coefficients for all months and performances of the WtEP within one site. Further analysis of simulation results revealed that this average brings some simplifications in the area where the relationship is higher than $R > 1$, as there are step changes in the coefficient in this area, see Fig. 14. This is due to the fact that from a certain WtEP power, the peak-load source can be shut down for a part of the month. If the performance of the WtEP reaches a value corresponding to the maximum demand in a given month, the coefficient is equal to one.

Fig. 14 shows the dependence of the correction coefficients on the ratio R in March at a minimum power of 20%. It is evident that this dependence is continuous in the performance of a WtEP lower than the average monthly demand because the coefficients are affected only by the non-use of heat in the periods with a drop in demand. With the increased WtEP performance, leaps can be observed due to the possibility of shutting down the heating plant at different times. If the WtEP performance reaches the value corresponding to the maximum demand in the month, the CHPP can be shut down for a whole month, and the value of the coefficient is therefore equal to one.

Simultaneously with the correction coefficients that do not

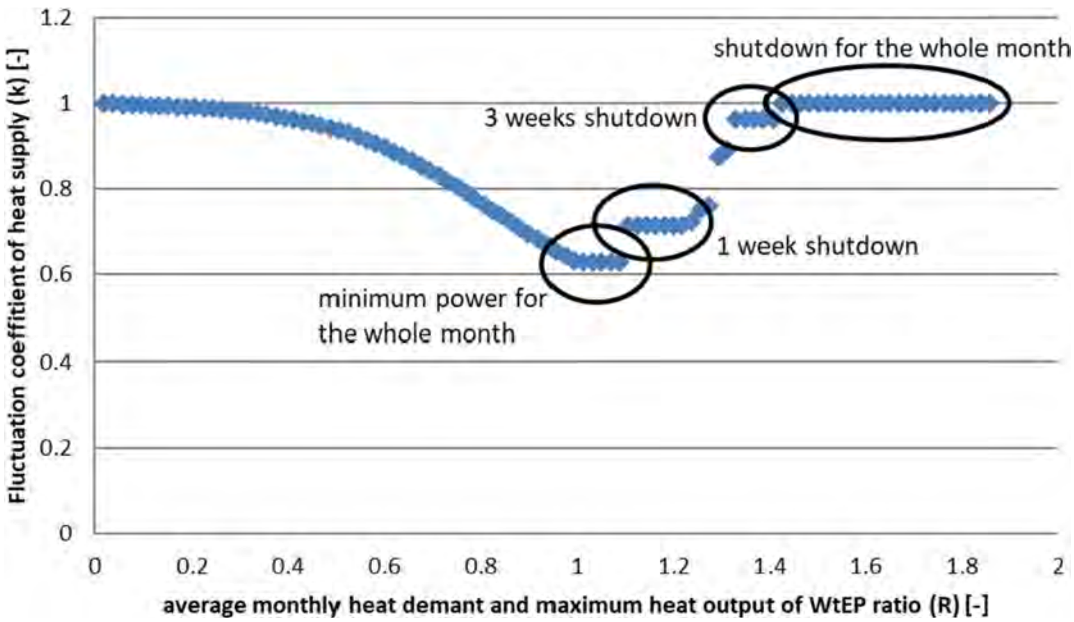

Fig. 14. Fluctuation coefficients of heat supply FCHS at the considered peak power source load.

require the minimum power of the peak-load source, a linear regression model has been created for the coefficients that are considered. Parameters that came into the model are:

- heat demand,
- ratio *R*,
- minimal power of the peak-load source,
- average monthly temperature.

The determination coefficient was based on models with a peak-load source with a minimum power below 0.5. This means that it is not possible to create correction coefficients of sufficient quality. Exact correction coefficients cannot be determined very well without knowledge of the hourly demand for heat. However, it is advisable to use them if more detailed data is not available.

4. Conclusions

A comparison of several approaches to the calculation of CHPP operation was made in the presented text. Models can be divided into several groups according to the time step used. A summary of the advantages and disadvantages in relation to the time step are shown in Table 5.

Models based on short time steps (short-term) are suitable for use with existing plants. There is no need to optimise the plant itself, but only its operation. Usually, this approach does not optimise the life of the project, but only over a short period of time. Mid-term models are already suitable for the conceptual design of WtEP. They include slight simplifications while maintaining acceptable computational demands. Long-term models are used to initially verify whether it makes sense to think about the project at all. The result is not exactly accurate since it also overlooks important factors.

This work focuses on the design concept of WtEP, but at the same time tries to eliminate the inaccuracies of models that arise during mid-term or long-term approach. For this reason, the influence of short-time (hour) fluctuations in heat demand on the accuracy of technological and economic models are described. The differences among the obtained results (estimated profit of the plant) were compared using two models. The first one was a simple model of a WtEP and peak-time gas-fired boiler. The second was a complex model of an integrated WtEP and CHPP. The most accurate input data on an hourly basis was replaced by daily, weekly, monthly or yearly averages. This measure is often necessary because computational time would be untenable.

The annual WtEP profit in the first model differed by approximately 70,000 EUR (ca 4.4%), compared to the hourly and monthly model. This difference may already have had an impact on the

Table 5
Advantages and disadvantages of the models according to the chosen time step.

	Short-term (H, D)	Mid-term (W, M)	Long-term (Y)
Usability from the perspective of a WtEP	WtEP already in operation – planning a heat and power supply diagram	Conceptual design of WtEP with given parameters, monthly heat supply	Conceptual design of WtEP, choice of WtEP capacity, estimation of investment costs
Number of time periods (lifetime of WtEP is 25 years)	H: 10^5 (8,760 × 25) D: 10^3 (356 × 25)	W: 10^3 (53 × 25) M: 10^3 (12 × 25)	Y: 10^1 (1 × 25)
Advantages	Taking into account the actual energy consumption, resource co-operation, minimum power of energy sources, load-dependent efficiency	Consider changes based on the season (heat consumption)	Easy calculation, suitable for WtEP with dominant power generation or even heat supply
Disadvantages	Large input data includes weather forecast, the operation of individual boilers, etc.	Partial simplification of the effect of daily changes	Considerable simplification, neglect of important factors

investor's decision. After applying correction coefficients, this difference was reduced to less than 25,000 EUR, which represents a variation of only about 1.4% from the hourly calculation. In the second model, the difference in the annual WtEP profit was up to 240,000 EUR. Here, the emphasis on the computational demands of the model has already been mentioned. The computing time on the hourly basis model was almost 300 times higher than the model on a monthly basis. This means that for scenario tasks where recurring calculation with other input data is required, this approach is very inappropriate. Given that many of these tasks are scenario-based, the use of correction coefficients is a suitable alternative.

The results have therefore highlighted the fact that heat demand fluctuations play a significant role in a WtEP project planning. There are several reasons why neglecting them is detrimental to the quality of the results. The first one is represented by peaks of heat demand. These peaks must be satisfied by another heat source. On the other hand, the dips mean a decrease in the applicable heat and cause a reduction in the potential of heat recovery. This problem can be partially eliminated by applying the heat supply correction coefficients, which was introduced in this paper. The accuracy of the model was significantly improved with the use of these coefficients and the time needed was kept to an acceptable level. Another reason is the possibility of shutting down the additional heat source to a certain minimum performance when heat demand is low enough. If the calculation is performed on monthly basis, the shutdown is not usually proposed for an optimum period. This applies in particular to situations where heat from large sources of solid or liquid fuels is supplied to a given DHS network.

The article, therefore, points to two basic advantages of using the proposed correction coefficients. The first is to significantly shorten the computation time by switching from short-term models to mid-term models for larger conceptual tasks. In some cases, reducing the number of variables can even ensure solvability. The second advantage is to refine models on a monthly basis without knowing the demand for heat over short periods of time (hours, days). This situation can occur, for example, when expanding the DHS network or vice versa after disconnecting some end-users. In these cases, the general correction coefficients described in section 3.3 can be used.

For instance, when a peak heat source is sized, the maximum heat demand is important. It is not possible to size the peak heat source properly if only monthly averages are used. These examples indicate that other ‘error-correction coefficients’ can be effectively used, which will be a part of future work in this area.

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