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A graph based Monte Carlo simulation supporting a digital twin for the curatorial management of excavation and demolition material flows

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ABSTRACT

The construction industry implies significant resource demands in two contexts: The supply of primary materials, as well as the conditioning and/or disposing of the materials resulting from excavation and demolition processes. Primary materials are limited and resource intensive in procurement, as well as in distribution. Landfill on the other hand requires brownfield sites and implies the risk of inert contamination of the soil. Manufacturing, re-use and recycling of these materials are thus an important step towards a circular economy and government agencies are interested in steering these material flows. From an economic point of view, these systems can be very volatile: Prices, availabilities and process capacities are fluctuating, while the locations of the construction sites change on a monthly basis. This paper presents a new approach using a digital twin of such a system to identify effective steering inputs and assist government agencies to understand the system and predict the influence of any potential measures. Based on a reduced graph representing the transportation network of the region, statistical information about the price structure of materials and services in the region as well as the decisions of different players within the systems are modelled. Using the Monte Carlo method, different material flows are quantified based on a set of statistical location parameters. The application of this model in the identification of steering inputs, as well as in the evaluation of potential scenarios is successfully demonstrated on two practical examples.

1. Introduction

The construction, modification and dismantling of civil infrastructures require significant material flows. According to the UN Environment Programme, the world wide annual demand for concrete is about 30 billion tonnes (Peduzzi, 2014) or visualized by the author as "*[…] enough concrete to build a wall 27 m high by 27 m wide around the equator*". While gravel and sand are the major ingredients of concrete, both are also required in loose form (unbound) for building projects around the globe. As summarized by Sverdrup et al. (2017), these primary materials have become rare in availability and serious considerations regarding the sustainability of the existing mining and extraction procedures have been raised. Additionally, significant transportation efforts arise, if these primary materials cannot be extracted near a construction site.

Building projects in densely populated regions are accompanied by the demolition of existing structures: The limited availability of construction terrain requires the conversion and agglomeration of already covered areas and thus, the deconstruction of already existing buildings. This can result in additional significant material flows to be handled. E.g., in 2015, 68 million tonnes of construction materials were required in Switzerland, while 18 million tonnes of excavation and construction waste were generated (Gauch et al., 2016; Wüest & Partner AG, 2015). It is already state of the art to use – at least fractions of – these materials to replace primary materials in simultaneous construction projects. Hence, besides a thoughtful use of the primary materials, the regional recycling of construction waste is a major determining factor to reduce the usage of primary materials and transportation efforts.

Whether or not (a) materials from excavation and demolition are recycled and (b) recycling materials are used in new building projects depends on different factors:

- Regulatory framework: local and federal agencies, as well as technical standards may enforce or limit certain material flows. For example, the recycling of certain percentages may be required or the

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use of recycling materials can be limited for certain purposes (Swiss Federation, 2020).

- Pricing: recycling cannot be done free of charge; the additional efforts to transform the demolition materials into construction products must be worthwhile compared to the price of primary materials and the price for landfill. This factor is significantly influenced by the fluctuating market prices as well as by the location of the construction sites (Kuster et al., 2017).
- Material quality: recycling often requires certain qualities, such as purity and geometric properties. If these are not met, recycling cannot take place or only be performed at a significant reduction in quality and uses (Moser, 2016).
- Processing facilities and capacities: the plants required to treat and recycle materials are limited in capacity. Hence, recycling at a specific time and place is only possible, if the technology and capacity are available in the region (Brunner et al., 2019, p43ff).
- Buffer sizes and availabilities: a direct transfer from a source to a destination – i.e. continuous flow of the demolition materials via a recycling facility to a new building under construction – are rare events. In all the other cases, buffers with available capacity are required to recycle materials and non-empty buffers are mandatory to procure recycling materials (Brunner et al., 2019, p45).
- Personal preferences and knowledge: material and service procurement can be affected by preferences of the players – e.g. owe someone a favour or avoid a service provider due to negative experiences made in the past – or by their knowledge – e.g. awareness about a certain service or procurement option. These are typical soft factors influencing the decision making within the system.

Managing the material flows within a region towards higher recycling quotas, limiting the use of primary materials for construction and relieving the landfill sites are the goals of various agencies. A government agency can implement new regulations (force/prohibit material flows) and/or provide new incentives (encourage/discourage material flows). It is a challenging task to select the right measures providing balance between effectiveness, acceptance and promotion of technological innovation. In order to do so systematically, one has to understand the system with respect to the influencing factors above: The resulting material flows are the outcome of a superposition of the material flows caused by individual players. Each player represents a construction site with a specific situation leading to an individual decision where to acquire materials from and what to do with excavation and demolition materials. Fluctuations in the pricing, as well as in the geographic distribution of the building sites have to be considered. It is thus a complex system to be managed by the agencies.

This paper suggests the application of a digital twin covering the relevant system dynamics as a model. With this twin, the principal behaviours can be studied, effective steering inputs can be identified and different approaches can be evaluated. This is done based on the region *Beider Basel* (RBB) in Switzerland. RBB covers 555 km^2 including approximately 480,000 inhabitants (BFS, 2018).

2. State of the art

2.1. Recycling of construction waste and excavation

Construction of buildings requires the handling of different materials. According to the good practice described by BAFU (2006), construction and demolition waste can be separated into materials resulting from excavation, mineral waste, combustible waste and others. Excavation waste is divided into two categories: Contaminated and uncontaminated waste (Tschan et al., 2018), while the origin of contamination can be of inert or geogenic nature. Mineral waste can be further subdivided into recovered asphalt, road construction waste, concrete demolition waste and mixed demolition waste. Recovered asphalt and road construction waste result from road surface work and are subject to contamination by polycyclic aromatic hydrocarbon (PAH), to which legislative rules apply while being recycled. Concrete demolition waste results from crushed construction elements made of reinforced concrete. Mixed construction waste is a conglomerate of concrete, bricks, limestone and rock. Some waste can be recycled as asphalt granulate, concrete granulate, mixed demolition granulate or recycled gravel sand.

2.2. Modelling of construction waste and excavation material flows

Different approaches exist to model these material flows: Rubli (2005), as well as Rubli et al. (2020) use a static model of these materials flows in combination with monitoring data from federal agencies. Using a mass balance as optimization criterion, the authors computed the missing material flows. Another approach is presented by Schneider (2005). Focusing on mixed demolition waste, the author suggests an inventory model of the existing buildings within a system, as well as a rule set for the use of mixed demolition granulate. Since this model considers both the material sources and transitions, the author is able to reproduce the dynamic behaviour of the system.

Different players in the system can select different services to handle waste (such as recycling or landfill). To study the influence of these individual approaches on the overall system dynamics, Masui et al. (2000) suggest the use of an economic model. The authors show that this kind of model is able to identify the major input variables to steer the system towards a sustainable point of operation. Hao et al. (2019) demonstrate the use of an economic model to identify potential control strategies to eliminate undesired material flows within a construction waste disposal system of a region.

Transportation costs can have a significant impact on the overall material and service costs of construction sites. To model these costs, Shi et al. (2019) suggest a graph based approach. In combination with genetic algorithms, the authors identify optimal locations for different recycling plants and assist the authorities in planning new recycling strategies and systems. Alternatively, the problem of optimal site selection can be solved by linear programming, as shown by Pan et al. (2020), as well as by Rahimi and Ghezavati (2018). The latter further introduce stochastic programming to cope with uncertainties in the model and its parametrization.

Dependent on the research questions and project aims, different modelling and analysis techniques are used in literature. In order to study a systems dynamic and predict the effects of curatorial measures, causal models are preferable. To address the six factors presented above, both economic and dynamic effects need to be considered. Further more, quasi-random fluctuations must be considered. Hence, causal dynamic statistical models implementing economic sub-models are considered the superior approach to address the challenges described above.

2.3. Digital twins for decision making

Digital twins are digital representation of physical systems. The digital twin includes the data and system models required to describe the relevant dynamics of its physical counterpart (Jones et al., 2020). An important characteristic of digital twins – compared to common simulation – is a direct coupling of physical and digital entities (Stark and Damerau, 2019). Digital twins can provide a significant benefit during the development of new products and system: By paralleling the development of the physical system and its digital twin, optimization and verification of development steps can be assisted and significantly improved (Tao et al., 2018). As presented by Agostino et al. (2020), digital twins can be used to assist decision making in complex systems. In this particular configuration, the digital twin enables the evaluation of different actions based. This is done by feeding the digital twin with real-time – or nearly real-time – data (Stark and Damerau, 2019). The digital twin will then evaluate each action using the implemented simulation models and providing the data base for a well informed decision making in the real system.

3. Background and outline of the system

In the context of this contribution, the supply of construction material to the construction sites and the provision of post-treatment services for excavation and demolition material from the construction sites are investigated. Asphalt based materials are at this point excluded from the scope, since special rules apply here regarding the procurement as well as the post-treatment (Swiss Federation, 2020, Art. 20).

A construction site has an input and an output side (see also Fig. 1). On the input side, two kinds of materials can be distinguished:

- *bounded materials*: these are products with a distinct aggregate in combination with a – generally cement based – binder. The application is mainly within constructive elements, as well as for cladding and filling (e.g. supporting pillars, and walls, as well as non-supporting walls and floors or separation layers).
- *unbounded materials*: gravel and/or sand with a distinct aggregate used for fillings, foundations and other applications in a loose form. Typical examples are draining layers.

On the output side, four generalized material categories can be identified within the scope of this investigation:

- *excavation, uncontaminated*: uncontaminated soil, gravel, sand and rocks resulting from excavation work.
- *excavation, contaminated*: same as the first category, but with a inert or geogenic contamination exceeding the legislative levels. These material categories are subject to a post-treatment procedure (e.g. washing and/or land filling).
- *construction demolition, concrete*: partially broken concrete elements stripped from their steel reinforcements and free of contamination such as glass, gypsum, bricks and other materials.
- *construction demolition, mixed*: this category contains mainly bricks, concrete, limestone and rock.

The antipodes to the construction sites in Fig. 1 are the providers of recycling and disposing services. Fig. 2 schematically shows the potential transformation of the output materials of the construction sites to input materials and disposed waste.

Several kinds of post-treatment are possible:

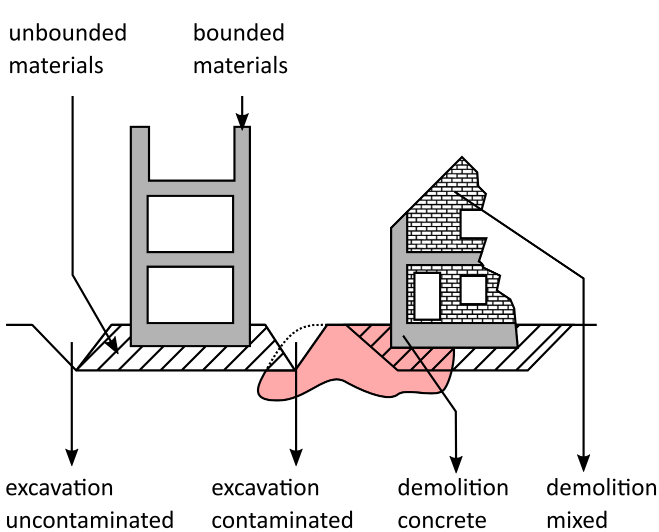


Fig. 1. Simplified outline of the system from the construction site's point of view. The example includes a new building (left), as well as the dismantling of an existing one (right).

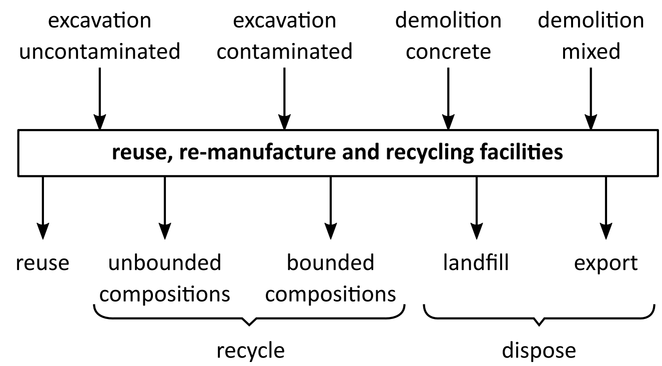


Fig. 2. Simplified outline of the system from the recycling facilities' point of view.

1. *Reuse*: the material can be used without additional treatment. In most cases this is only possible for uncontaminated soil used for terrain adjustment.
2. *Re-manufacture*: uncontaminated excavation material can contain significant amounts of gravel separable by a washing process. This leads to (primary) gravel, which can be used as a bound or unbound construction material. In the scope of this work, this is treated as a recycling process, since it implies an up-cycling process.
3. *Recycle*: using single or multi-stage processes, some output materials of the construction sites can be transformed into input materials. This is applied for all material categories. Typical procedures are washing, crushing and sieving. In practice, buffers are required to enable the operation of the different processes.
4. *Dispose*: this is a final decision; the material will not be used within the local construction material circulation and thus has to be replaced by primary material. Options to do so are export and landfill. The latter can be done by use for terrain adjustment or filling of old gravel pits (uncontaminated materials) or in specially designated landfill sites for inertially contaminated materials.

Whichever path is finally chosen for a specific situation depends on the regulations, the technical feasibilities (process and buffer availability) and economic considerations (in this particular order). Hence, the central questions for the individual players in the system – i.e. the construction sites – are: *What is the optimal procurement process for the required materials in the given situation?* and *What is the optimal post-treatment service for the excavation and demolition materials in the given situation?* The superposition of the players' decisions determines the system's mass flow dynamics. In the following section, we will derive a model to answer these questions dynamically for a set of players in order to predict the system dynamics.

4. Digital twin development

In this study, we introduce a digital twin model of the excavation and demolition material flows in a region. This digital twin supports the local authorities to understand the system dynamics and to test new curatorial management strategies towards a sustainable material flow. The requirements for this model based on the presented outline of the system are:

- distinguish between two different input material categories (unbound/bound compositions)
- distinguish between four different output material categories (excavation uncontaminated/contaminated and demolition concrete/mixed)
- consider the technical and legal regulations regarding the reuse, recycling and disposal of the different material categories

- consider the available (stationary) recycling processes, as well as their availability and buffer capacity of the different material categories
- considering the fluctuating locations of the construction sites
- implement a routine to model the decisions made by different agents in the system based on the expected economic performance of different options
- evaluate the effects of the fluctuating market pricing on the expected material flows

We will combine the methodologies currently used as state of the art – namely rule-sets, economic decision models, graph based approaches and stochastic programming – and extend them with a multi-agent simulation. In the following, the conceptual design and mathematical description of the digital twin used is presented.

The concept of the developed model is depicted in Fig. 3.

Central elements are two nested loops: These loops are required to handle the fluctuations in the locations of the construction sites, as well as to quantify the effects of pricing uncertainties. The inner loop – the *location-loop* – represents the different demands of different construction sites. Given are the annual expected construction materials as $m_{comp,ubnd}$ (unbound materials) and $m_{comp,bnd}$ (bound materials) and the expected materials resulting from excavation and demolition waste as $m_{ex,ucon}$ (excavation uncontaminated), $m_{ex,con}$ (excavation, contaminated), $m_{dem,con}$ (demolition, concrete) and $m_{dem,mix}$ (demolition, mixed). Each of these annual mass flows is divided into N_L individual flows at a random location. These mass flows are then compiled together with the information about the region (geology and contamination of the ground as well as the road system) and the pricing for different materials and services to form a scenario. Each scenario represents a material/service demand at a specific location with specific prices for potential material sources and destinations. This information is fed into a decision making model representing the player's behaviour. Using the information about the current availability and capability of the facilities, this model returns a decision where to acquire materials from and which channels to use for the excavation and demolition materials. The decision is fed back to the facilities sub-model. This sub-model includes a memory of the prior transactions. The overall mass flows within the system are now computed as a simple superposition of all the individual (stochastic) mass flows predicted in the location-loop.

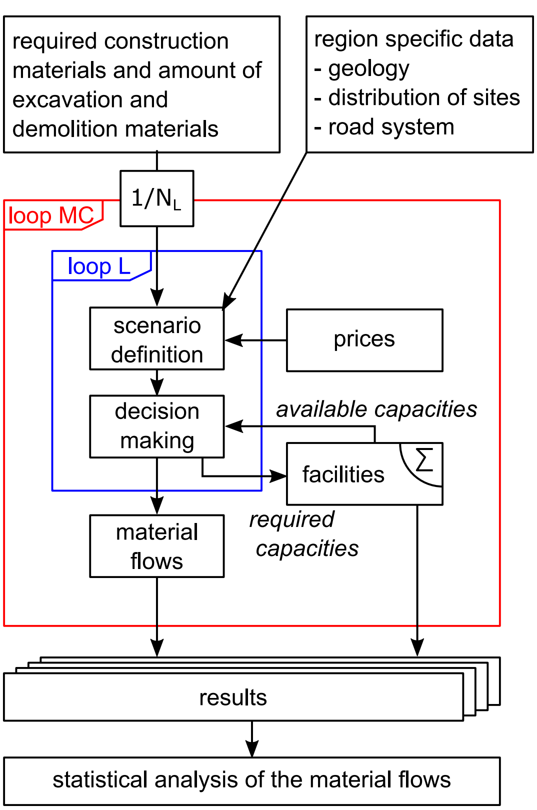


Fig. 3. Conceptual structure consisting of the inner location loop (L) and outer Monte-Carlo loop (MC).

The second loop implements a Monte-Carlo-simulation (MC-simulation). Within each cycle of the loop, a set of new prices is drawn, according to their probability density function (PDF). By doing so N_{MC}-times, different results for the mass flows within the system are generated. Each of these sets represents a specific situation regarding the location and order of service demands within the region, as well as pricing for different services. Hence, one can now perform a statistical analysis of these data sets and characterize the different mass flows – e.g. the amount of materials heading for landfill – by at least two statistical location parameters.

For the systematic identification and quantification of the influencing factors, the model according to Fig. 3 is used in combination with a sensitivity analysis. This is realized by a systematic variation of selected factors of influence. The three nested loops – location-loop, MC-loop and sensitivity analysis – result in a high number of iterations. If, for example $N_L = 100$, $N_{MC} = 1,000$ and a design of experiment (DoE) with 10 factor level combinations, one will end up with $1,000,000$ runs of the decision making model. This is an important fact to be considered during the model building and implementation. In the following sections, we will discuss the required sub-routines – *scenario definition*, *facilities* and *decision making* – for the implementation of the discussed digital twin.

4.1. Scenario definition

Within each cycle of the MC-loop, N_L different scenarios are generated and evaluated. A scenario is defined by a location $\underline{x}_i$ within the region, geological property g_i, input materials $\underline{m}_{in,i}$, output materials $\underline{m}_{out,i}$ and current pricing $\underline{p}_k$:

$$s_i = \left\{ \underline{x}_i, g_i, \underline{m}_{in,i}, \underline{m}_{out,i}, \underline{p}_k \right\} \tag{1}$$

$\underline{x}_i$ is a 2D-vector $[x_i, y_i]^T$, representing the coordinates.[1] $\underline{x}_i$ is drawn out of the set $\mathscr{X}_L$ of potential construction sites according to their PDF F_L:

$$\underline{x}_i \sim F_L^{-1}(\mathscr{U}) \tag{2}$$

$\mathscr{X}_L$ and F_L can be estimated using statistical data from a geographic information system (GIS). The geological properties $g_i \in \{0, 1\}$ indicate whether or not significant amounts of gravel are expected during the excavation at the site. This is an important piece of information for the decision making later on. The value g_i is determined, given the set of gravelly regions $\mathscr{X}_g$:

$$g_i = \begin{cases} 1 & \text{if } \underline{x}_i \in \mathscr{X}_g \\ 0 & \text{else} \end{cases} \tag{3}$$

Again, statistical data from a GIS is used to determine $\mathscr{X}_g$. $\underline{m}_{in}$ and $\underline{m}_{out}$ include the two inflows and four outflows for a construction site as defined in Fig. 1:

$$\underline{m}_{in,i} = \begin{bmatrix} m_{comp,ubnd,i} \\ m_{comp,bnd,i} \end{bmatrix} \text{and } \underline{m}_{out,i} = \begin{bmatrix} m_{ex,ucon,i} \\ m_{ex,con,i} \\ m_{dem,con,i} \\ m_{dem,mix,i} \end{bmatrix} \tag{4}$$

For the sake of simplicity $m_{x,i} = m_x / N_L$ is used; i.e. the total amount

[1] Within this work, the *Swiss coordinate system* is used. The approach however is not limited to this specific coordinate system.

of materials is distributed evenly on the N_L locations.

4.2. Decision making

The goal of the decision model is to reproduce the situation based on decisions for the materials flows within the systems made by the planners and operators of construction sites. One has to distinguish between the output side of the construction site – e.g. *Where to go with the excavation and demolition material?* – and the input side – e.g. *Where to obtain the required material from?* Fig. 4 shows the complete decision making model.

As depicted in Fig. 3, this model is applied on each material type on the input and output side for each scenario within the inner loop.

For output materials, the initial question is whether the material category is useable or not ①. In our model, this quality related decision is made based on the empirical value r_k:

$$q_{rec,k} = \begin{cases} \text{true} & \text{if } x \le r_k \\ \text{false} & \text{else} \end{cases} \quad \text{where } x \sim \mathscr{U}(0,1) \tag{5}$$

r_k is selected specifically for each output material based on empirical data available. This parameter represents the purity of the materials, as well as the separation behaviour on the construction sites and the legislative rule-set. If $q_{rec,k} = false$, the material category is marked for landfill or export (whatever is cheaper). Otherwise, we continue with the decision model and identify the facilities capable to provide the required services – ② and ③. In order to select the economically optimal facility $F^*(m_{out,i,k})$ for each $m_{out,i,k} \in \underline{m}_{out,i}$, we evaluate each facility regarding w.r.t costs $c(F, m_{out,i,k})$ ④:

$$F^*\left(m_{out,i,k}\right) = \underset{F \in \mathscr{F}}{\operatorname{argmin}} c\left(F,\ m_{out,i,k}\right), \tag{6}$$

where $\mathbb{F}$ is the set of facilities able to provide the demanded service at the current instant.

A very similar decision sequence is applied for input materials: Firstly, we check, if the use of recycling materials fits the legislative and technical limitations ⑥. If not, we will use primary materials from the cheapest source available; otherwise, we continue with the evaluation of potential suppliers of recycling materials. Again, we want to find the optimal facility $F^*(m_{in,i,k})$ with respect to the expected costs $c(F, m_{in,i,k})$. Only facilities capable to provide – ④ and ⑤ – are considered:

$$F^*\left(m_{in,i,k}\right) = \underset{F \in \mathbb{F}}{\operatorname{argmin}} c\left(F,\ m_{in,i,k}\right), \tag{7}$$

where $\mathbb{F}$ is the set of facilities able to satisfy the demand at the current instant.

4.3. Facilities

A facility represents a distinct location, where specific input materials can be obtained and/or output materials can be recycled or disposed. A facility can be a pure source (e.g. gravel pit), a pure destination (e.g. landfill), a recycling facility combining output and input mass flows or a combination of all of them. Multiple facilities at the same location are possible. E.g. a company delivering primary material (facility 1), providing recycling services (facility 2) and owning a landfill site (facility 3). Each facility $F_j \ \forall j \in \{1, 2, \ldots, N_F\}$ is characterized by its availability $\underline{l}_{\ in,j}$, capacity $\underline{l}_{\ out,j}$, buffer size $\underline{l}_{\ b,j}$ and location $\underline{x}_j$. Additionally, a facility has a memory about the material input and material output, as well as the current buffer quota, denoted as $\underline{m}_{\Sigma in,j}(t)$, $\underline{m}_{\Sigma out,j}(t)$ and. $\underline{m}_{\Sigma b,j}(t)\underline{l}_{\ in,j}$ and $\underline{l}_{\ out,j}$ imply the limits in material availability for each input and output material. Both may have entries due to technical or legislative limitations. Facilities where $\underline{l}_{\ out,j} = 0$ are pure material sources, whereas facilities where $\underline{l}_{\ in,j} = 0$ are pure material destinations. Recycling facilities have a non-zero buffer size $\underline{l}_{\ b,j}$ and ability $\underline{\underline{T}}_j$. $\underline{l}_{\ b,j}$ denotes the size of the buffer. A buffer is required, since the availability of excavation and demolition materials is generally decoupled from the demand for construction materials. $\underline{\underline{T}}_j$ is a transcription of the facilities' abilities for the transformation of output materials from the construction sites to new input materials according to 2. The entries of $\underline{\underline{T}}_j$ are 0 (transformation not possible) or 1 (transformation possible).

4.4. Generic cost model

Given a material type $\mathscr{M}$ and source $\mathscr{S}$ or disposal procedure $\mathscr{D}$, we want to know the mass specific cost given a construction site location $\underline{x}_i$ and facility location $\underline{x}_j$. For the acquisition of input materials, the costs depend on the material (*mat*) and transportation (*tr*) costs:

$$c_{in}\left(\mathscr{M}, \mathscr{S}, \underline{x}_i, \underline{x}_j\right) = c_{mat}(\mathscr{M}, \mathscr{S}) + c_{tr}\left(\underline{x}_i, \underline{x}_j\right) \tag{8}$$

Disposal costs are modelled as the superposition of triage (*tg*), disposal process (*dpr*) and transportation costs:

$$c_{out}\left(\mathscr{M}, \mathscr{D}, \underline{x}_i, \underline{x}_j\right) = c_{tg} + c_{dpr}(\mathscr{M}, \mathscr{D}) + c_{tr}\left(\underline{x}_i, \underline{x}_j\right) \tag{9}$$

To reflect the time dependent fluctuations in pricing, prices are drawn individually from a uniform distribution for each scenario.

Tariff models in the investigated region differ between short and long distance transportation. Long distance transportation is invoiced by distance covered d, whereas short distance transportation is invoiced by the time needed (transportation time t_{tr} plus loading time t_{lo}):

$$c_{tr}\left(\underline{x}_i, \underline{x}_j\right) = \begin{cases} d\left(\underline{x}_i, \underline{x}_j\right) \cdot c_{tr/km} & \text{if } \ d\left(\underline{x}_i, \underline{x}_j\right) \ge d_{sd} \\ \left[t_{tr}\left(\underline{x}_i, \underline{x}_j\right) + t_{lo}\right] \cdot c_{tr/h} & \text{else} \end{cases} \tag{10}$$

Both, the hourly rate $c_{tr/h}$ and the distance rate $c_{tr/km}$ are modelled as uniform distributed variables, draw specifically for each scenario. The limit d_{sd} short distance transportation can be calculated based on an assumed average transportation speed.

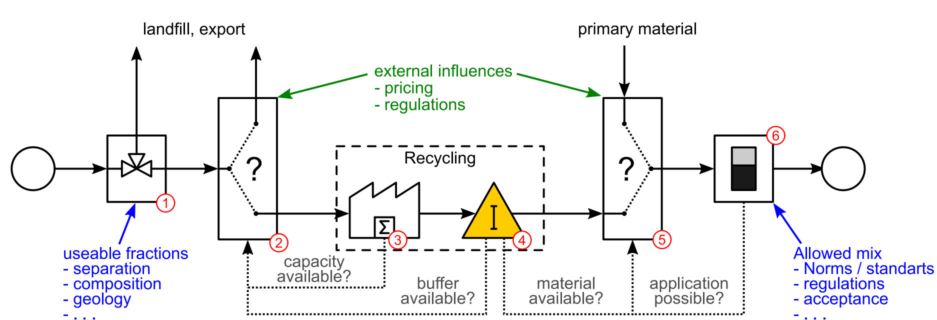


Fig. 4. Decision model for the recycling of materials: Each box represents an assessment of the materials followed by a go/no-go-decision. Solid lines indicate a material flow, whereas dashed lined show an information flow.

The cost model requires the quantification of distance and time between the construction sites and the facilities providing the required materials and/or services. Since the evaluation of the cost model takes place in the inner loop (see Fig. 3), these quantifications have to be done in a computationally efficient way. Using the *OpenStreetMap* (OSM), allows us to efficiently compute a total distance matrix (TDM) containing the distance between all relevant locations in the region. Using the speed limit information available in the OSM dataset, we are further able to estimate the journey time on the shortest path. The computation of the TDM is a pre-processing step and has to be done only once per region. During the simulation runs, the distance and time quantifications are thereby limited to a simple table look-up. Details for the TDM computation can be found in Appendix A.

During the parametrization of the model, additional data sources are used. These range from the mentioned public OSM-dataset to statistical data recorded by the local administration, data obtained by interviews with local agents, as well as data from other region used as a comparison. Appendix B shows a detailed list of the used materials.

4.5. Digital twin application

According to Jones et al. (2020), as well as Stark and Damerau (2019) the data exchange between the digital and physical entities are a key attribute of a digital twin. The scope of the presented digital twin is the evaluation of the systems dynamics and the performance quantification of potential curatorial measures. Fig. 5 shows the principal work flow. The physical system includes the local administration, as well as different stakeholders such as site operators, construction companies and the builder-owners. Using statistical data obtained by the local administration from these stakeholders the digital twin is parametrized. The digital twin can then be applied to test, evaluate and verify the performance of different scenarios. Based on the quantified scenario performance, the decision making for new new incentives, rules or permits is systematically supported.

5. Applications and results

5.1. Lightweight simulation framework

The implementation of the model, as well as of the required simulation framework, has been realized as a lightweight Java application. The framework is designed to easily modify the models parametrization, but also the cost and decision-making models. The latter is achieved by a hierarchical structure and modular set-up. Internally, the implementation follows the model-view- controller (MVC) software design pattern.

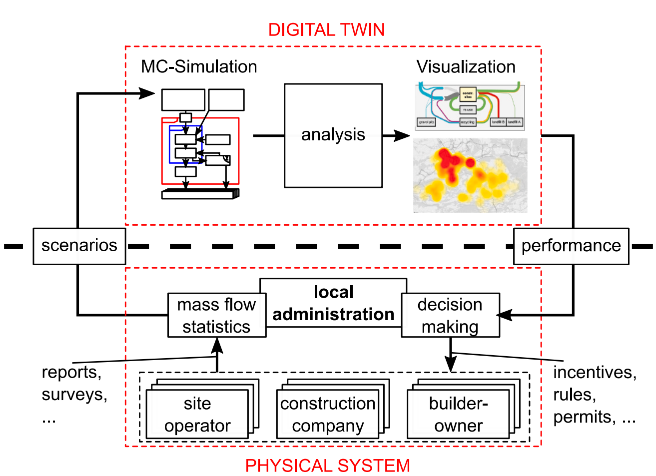


Fig. 5. Structure of the digital twin application including the presented MC-simulation of Fig. 3 in the digital entity.

MVC enables us to easily extend the framework with functionalities such as a sensitivity analysis of input parameters or additional analysis routines. The pre-processing of the road network to the TPM is performed on a dedicated simulation computer. Using 256 GB of RAM and 48 parallel CPUs, this step requires about 30 min to complete. Studies of the same region rely on the same TPM. The TPM enables a simple lookup to quantify the required travelling distances and times. Hence, region-specific studies can efficiently be performed on conventional desktop machines.

5.2. Verification

For the verification, the simulated mass flows are compared to the real mass flows within the investigated system. The quantification of the latter are a challenging process, since the local authorities do not monitor all the mass flows. Using the monitoring data of the local landfill sites, the annual performance reports of the licensed service sites as well as statistical data of the customs authority, one is able to trace different parts of the mass flows within the system. We combined this information with expert consultations – in both administration and industry – to quantify the total annual demand for building materials as well as construction and demolition waste. These consultations provided insights into material flows not included in the official monitoring process and enabled the reconstruction of the real mass flows within the investigated system as depicted in Fig. 6a. A subsequent simulation of the actual system using the implemented framework (see Fig. 6b) is in line with this reference data both in a qualitative and quantitative way. Thus, the model is successfully verified.

Since the used parametrization is obtained using available data sets from a GIS and the OSM project, the presented parametrization approach is independent of specific measurements of the investigated region. It could thus be applied to any region with a sophisticated GIS in place.

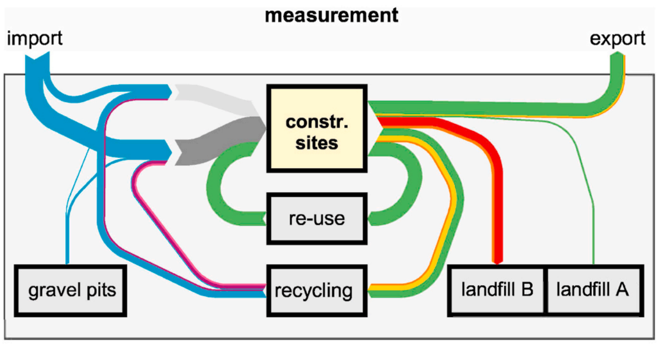
5.3. Identification of the relevant system dynamics

Fig. 7 shows a selection of the base line of the simulation, i.e. the current situation.

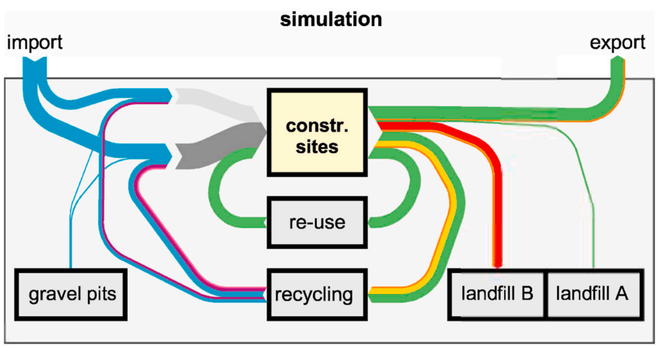
The effects of the external input variables – i.e. the input variables which cannot actively be controlled and act as disturbances – are displayed as box-plots. One can identify the main source for bound and unbound construction materials are imported gravel, followed by gravel resulting from local excavations and recycling materials from concrete. Recycling materials from mixed demolition waste are only used for bound construction materials. Uncontaminated excavation is mostly exported (complementary to the material import, which is in the same order of magnitude) or used as gravel. A small percentage is used as back-fill or put into landfill. Contaminated excavation material is put almost exclusively into landfill type B. Demolition waste concrete is almost fully recycled where mixed demolition waste is split between export, recycling and landfill type B. These findings are in-line with the known material flows within the region (see also Fig. 6).

In addition to the average, Fig. 7 also shows statistical location parameters (quartiles and 95%-quantiles). These can be used as indicators for the robustness of the system behaviour with respect to external input variables. Hence, changes in pricing and/or construction site distribution can change the system's operational point significantly. Such changes are always characterized by shifts between two or more facilities (one facility's gain is another one's loss). One can identify several potential shifts:

- excavation uncontaminated: export ⇆ landfill A
- concrete demolition waste: recycle ⇆ landfill B
- mixed demolition waste: export ⇆ recycle
- mixed demolition waste: export ⇆ landfill B
- mixed demolition waste: recycle ⇆ landfill B



(a) measurement



(b) simulation

Fig. 6. Measured and simulated material flows within the investigated system. The system's boundary is shown as underlying light grey rectangle.

These shifts result from the systems volatility and/or the parametrization uncertainty. They show the changes in the system's operational point to be expected. In other words: The are indicators for unstable operating points of the system. The happening of these shifts can thus be favourable or unfavourable. In the first case, measures to prevent the shift are needed, while the second case triggers the search for measures to foster the shift. These findings are of special importance for agencies managing the material flows.

5.4. Evaluation of curatorial measures

Land fill sites have a significant environmental and social impact: Invasions into the landscape, implied volume of traffic, raised risk of contaminated soil, an more. Moreover, the deposited material needs to be replaced by primary material, which is often subject to scarcity. One of the fundamental research question in the domain of excavation and demolition material treatment is thus: *How can we boost the recycling quotas of such materials in order to reduce the demand for primary materials and land fill sites?* The framework with the implemented and verified statistical model is applied to a case study within the scope of a regional project aiming for higher recycling quotas. There are two exemplary

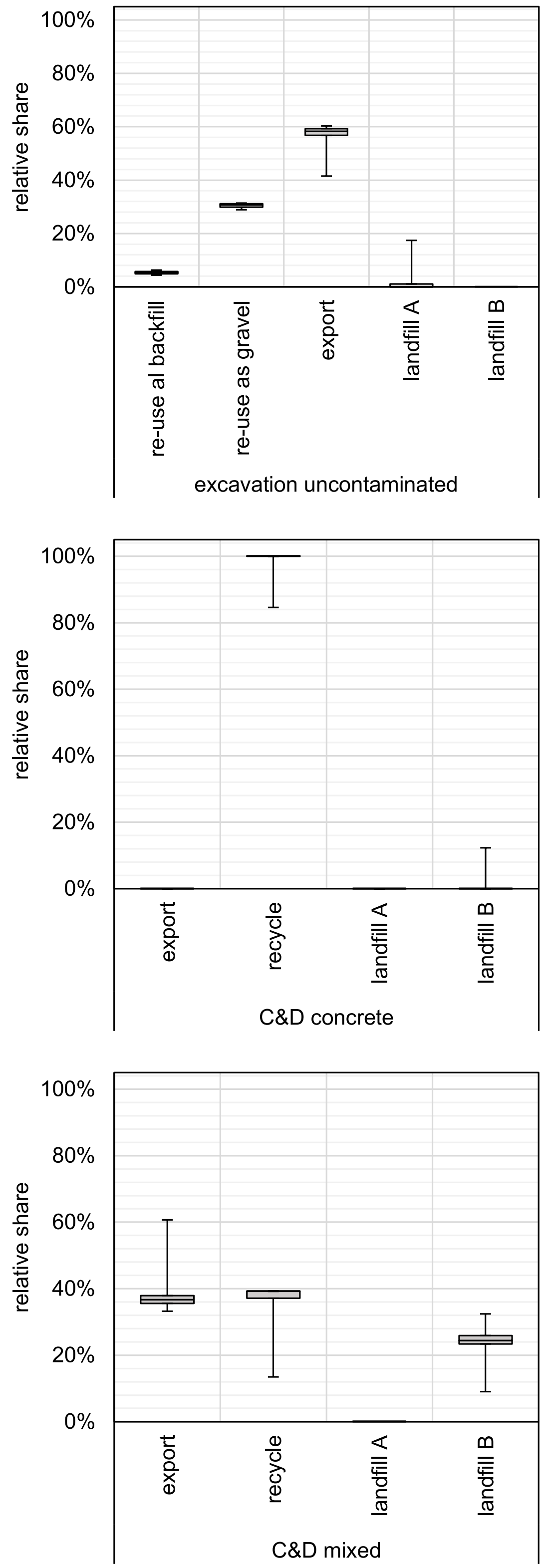


Fig. 7. Extract of the base line for the material flows as predicted by the statistical model.

questions – related to the research question above – to be investigated using the model:

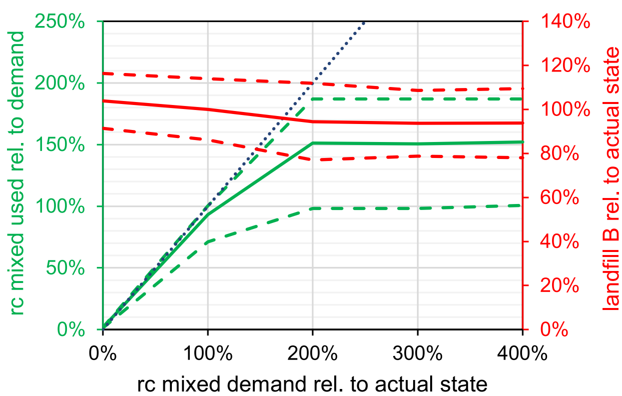
Q. 1. *What are the effects of an enhanced demand of recycling products?* I.e. can the recycling quotas be improved if only the demand is changed, but the prices stay the same? This question is of particular importance to the local agencies for strategy development.

Q. 2. *Is a washing facility for contaminated soil feasible within the region?* Washing of contaminated soil to recover its contained gravel requires significant investment into new systems with circular water systems. Before such investments are made, the model can be used to study the dependency between pricing and capacity used and thus deliver a first estimate of the planned system's payback time and return on investment.

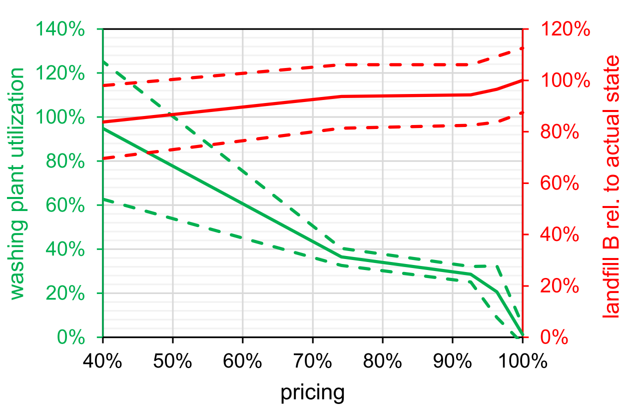
Using the implemented sensitivity analysis function of the framework, the dependencies between the studied external input variables and the target variables are obtained as presented in Fig. 8. For the demand of mixed demolition waste based recycling materials, an almost linear dependency up to about the actual demand is identified (see Fig. 8a). To reach the peak of 150%, the actual demand must however be doubled. The answer to question Q.1 therefore is: Yes, the use of mixed demolition waste based recycling materials can be boosted by solely increasing its demand. However, the demand must be increased disproportionately to the target use of mixed demolition waste based recycling materials. This gap between specific material demanded and specific material obtained results from the system's limited buffer capacity: If the intermediate buffers for mixed demolition waste are full, good material must be declined, even if the material could be used in the future (see also ④ in Fig. 4). Hence, the effect of the increased demand could be amplified, if additional buffers were provided. From Fig. 8, one can read, that the additional demand for mixed demolition waste for recycling products relieves the landfill sites type B.

The sensitivity analysis of the pricing for washing contaminated excavation material is presented in Fig. 8b.

Up to about 75% of the critical price, the washing shows a clear economic advantage compared to the alternatives (e.g. landfill). Between 75% and 90%, the slope is almost zero, indicating a very low sensitivity. Within this price margin, the influence of fluctuations of construction site locations and transportation costs on the amount of washed material are in the same order of magnitude as changes in the price of the washing. Above the critical price, landfill becomes the favourable option form an economic point of view. Hence, the sensitivity analysis delivers an upper boundary for the pricing, as well as an expected quota for a given price. To answer Q.2 one can use this relationship together with the intended capacity of the washing facility and compare the resulting upper pricing with the expected operating costs. The sensitivity analysis is further extended to the identification of spatial characteristics: Fig. 9 shows such an analysis: In the investigated case, the decision about which channel is used for uncontaminated excavation materials shows a location-specific behaviour: Locations in the south-east tend to more likely select landfill compared to locations in the north-west and vice versa for the material

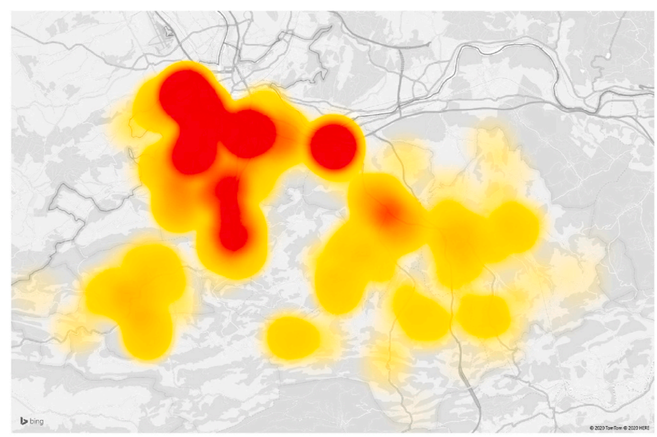


(a)



(b)

Fig. 8. Sensitivity analysis of the studied external input variables. The solid lines show the average value, where as the dashed lines show the 3σ-quantile.



(a) uncontaminated excavation material to export

(b) uncontaminated excavation material to landfill

Fig. 9. Density plots of different treatment for uncontaminated excavation material selected by different locations in the simulated region. The coloring indicates the relative count of the treatment being selected from low (yellow) to high (red). Map data: bing.com.

export. Therefore, the transportation costs, location of facilities and topology of the road system can have a significant effect on the local material flows. This is an important piece of information while planning new locations for landfill sites and other services.

6. Conclusion and outlook

Handling of construction materials, excavation and demolition waste exert a significant environmental impact, due to the high demand in material, resources and logistics. Recycling of demolition waste provides an interesting approach to close the cycle: Materials are then used multiple times and kept within the system resulting in lower primary material demands, less transportation efforts and lower demand for landfill sites. In order to create economic and legislative settings promoting a circular use of construction materials, one has to understand the system's dynamics. In this work, we present a graph based model in combination with the MC-method. Using two input material types (bound and unbound materials) and four output material types (contaminated and uncontaminated excavation, concrete and mixed demolition waste), we can replicate the system's current steady-state dynamics using a digital twin of the system. Since the approach is based on a statistical model, the robustness of the different material flows can be quantified and typical shifts between different material destinations or sources are identified. These shifts give an important insight of external control inputs to be monitored, since they have a significant effect on the system's behaviour. On the example of two problem settings (effect of an enhanced demand of recycling products and economic feasibility of a washing facility for contaminated excavation material), we demonstrated the application of the procedure using a sensitivity analysis. Since the statistical model implements a 2D-distribution of the construction and service sites, one can locally identify individual characteristics. This information could be used for future service site planning. In summary, the implemented framework provides a guidance system to analyse and understand the systems dynamics and test new technical, legislative and normative measures to steer the material flows within the system towards a sustainable material flow.

The presented digital twin has been developed in the context of a specific challenge for a specific region in Switzerland. Since the digital twin implements a generic and reconfigurable model of excavation and demolition material flows, it can be adapted to the specific situations and challenges of other regions: The generic decision making model used enables an efficient transfer of the presented approach to other regions with different material and service demands, road networks, pricing models, service availability as well as legislative and normative rule-sets. The new parametrization solely requires information generally available in the GIS of local agencies. Since a flexible implementation approach is used, the existing simulation framework can be extended with additional input and output materials, and thus enable a more detailed study of different material flows. Future applications of this digital twin could thus for example consider the different material fractions of mixed construction waste.

CRediT authorship contribution statement

Simon Züst: Conceptualization, Software, Formal analysis, Validation, Investigation, Data curation, Writing, Visualization. **Rainer Züst:** Conceptualization, Investigation, Resources, Data curation, Supervision, Project administration, Funding acquisition. **Viturin Züst:** Conceptualization, Software. **Shaun West:** Writing. **Oliver Stoll:** Writing. **Clemente Minonne:** Writing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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List of symbols

c	price per tonne
d	distance
E	set of (graph) edges
F	facility
$\mathbb{F}$	set of capable facility
F^*	optimal facility
F_L	PDF of the potential sites
g	geological property
G	Graph
l	limit
$\mathscr{M}$	material type
$\underline{m}_{in}$	site input mass flows
$\underline{m}_{out}$	site output mass flows
m_Σ	memory of past mass flows
$\underline{p}$	pricing
r_k	recycling category
s	scenario
$\mathscr{S}$	material disposal type
$\mathscr{S}$	material source
$\underline{\underline{T}}$	capability matrix
t	time
V	set of (graph) nodes
$\underline{x}$	location (2D)
$\mathscr{X}_g$	Set of potential construction sites with gravel
$\mathscr{X}_L$	Set of potential construction sites

List of abbreviations

AUE Amt für Umweltschutz und Energie
DoE design of experiment
GIS geographic information system
MC Monte-Carlo
MVC model view control
PAH polycyclic aromatic hydrocarbon
PDF probability density function
OSM OpenStreetMap
RBB Region Beider Basel
TDM transport distance matrix

Appendix A. Computation of the TDM-Matrix

For the (offline) computation of the TDM the procedure depicted in figure A.10 is used: Using the *OpenStreetMap* (OSM) dataset one can extract the road system as a set of nodes V connected by a set of edge E defining a graph $G(V,E)$. G is pruned in two ways: Firstly, we only use the maximal connected sub-graph from G, secondly, we merge all path sub-graphs of degree $n > 2$ into path sub-graphs of degree two. This yields the graph $G^{'}(V^{'}, E^{'})$. $G^{'}$ is saved in a sparse matrix form using compressed row form The nodes of the sparse matrix where cache optimized to maximize the number of translation lookaside buffer hits, by improving locality. This was achieved using a $B+-$Tree (Comer, 1979) and the $CDF(G^{'})$. We then calculate all the single source shortest path options, given a source node $s \in G^{'}$ twice. There are no negative cycles is $G^{'}$, thus we can use Bellman-Ford (Ford and Lester, 1956; Bellman, 1958). Bellman-Ford operates by doing $|E^{'}|$ sweeps over the graph, to check if any edge $e^{'}(u,v,w)$ can improve the computation from $dist[v]$ given $dist[u]$ and the edge weight w. Furthermore, the low connectivity and the fact that we visit the $|E^{'}|$ edges in arbitrary order allows us to paralleling the algorithm, and thus also use the GPU Nazarifard and Bahrepour (2017). This allows us to efficiently compute a total distance matrix (TDM) containing the distance between all relevant nodes.

(a) OSM (rendering by OpenStreetMap Project) (b) Graph

to / from	A	B	C	D	E	F
A	0	1	1.1	2.2	3	2.9
B	1	0	0.6	1.7	2.5	2.4
C	1.1	0.6	0	1.1	1.9	1.8
D	2.2	1.7	1.1	0	0.8	0.7
E	3	2.5	1.9	0.8	0	1.5
F	2.9	2.4	1.8	0.7	1.5	0

(c) TDM

Fig. A10. Creation of the transport distance matrix (TDM) based on a labelled graph derived from the open street map (OSM) project for the investigated region (simplified example). Only the major roads (yellow) are considered..

Appendix B. Parametrization

Expected annual inputs and outputs: Using statistical information of the custom (for import and export out of the country) and of the regional mass flow model (Rubli et al., 2020) we estimate the yearly demand for construction materials and excavation and demolition material handling. These values have been crosschecked with the ones of other regions using the population density and economic strength of the regions as a scaling factor.

Facility properties: Using the list of operational permits provided by the local administration for the facilities in the region enables the identification of the relevant facilities, as well as their capacities. The same procedure is chosen for the landfill locations to identify their allowed annual quota.

Geological properties: The relevant information about the top soil properties are taken from the region's GIS (see figure B.11 for an example).

Construction site probability density: Using the list of construction permits provided by the local administration within the past three years, the required PDF for construction sites in the region is fitted (see also figure B.11 for an example).

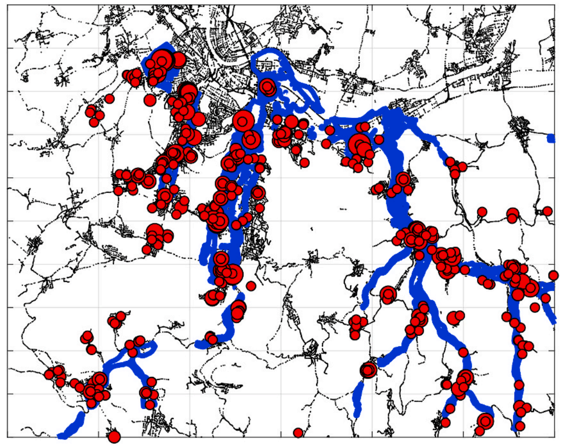

Fig. B11. Example for the region-specific input data showing the nodes of the road system (black), geological information about gravel availability (blue) and the density of construction sites (red)..

Pricing for services: Pricing for different services are highly dependent on individual contracts between the facilities and the construction site owners. Several interviews were conducted with different facility operators discussing their pricing models. The results are then merged into the PDF for the pricing.

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