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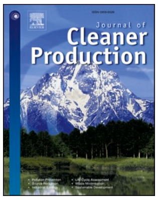

Optimal design of a post-demolition autoclaved aerated concrete (AAC) recycling network using a capacitated, multi-period, and multi-stage warehouse location problem

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ABSTRACT

Autoclaved aerated concrete is a popular building material in constructing one- and two-family houses because of its low thermal conductivity and fire resistance. Since autoclaved aerated concrete production rose significantly in the 1960s and 1970s, increasing post-demolition volumes can be expected in the following decades. However, these are currently landfilled as high-quality recycling options are still to be established.

This study develops a new capacitated, multi-period, and multi-stage network model for optimising a Germany autoclaved aerated concrete recycling network. The multi-period character of the model enables the precise consideration of increasing post-demolition volumes by constantly allowing the move of recycling plants or opening new ones throughout the planning horizon. Additionally, the multi-stage formulation facilitates incorporating an optional second recycling step, which involves additional effort and higher revenues. The model aims to find a cost-minimised recycling network and identify optimal network transformations until 2050. Results show that recycling is preferred over landfilling. The optimised recycling network uses large recycling plants for economies of scale and opens new plants in the future to handle the expected increase in post-demolition autoclaved aerated concrete. Transport costs account for the largest share of total costs (50%), while fixed costs reach around 40%, and revenues offset approximately 20% of all costs. The total costs of the network reach about 2200 M€ until 2050, which is 4600 M€ (68%) less than without establishing recycling. The results offer new insights into cost-minimal network structures and their future development to encourage decision-makers to promote autoclaved aerated concrete recycling.

1. Introduction

Recycling of construction and demolition wastes (C&DW) enjoys increasing popularity as vast amounts of primary resources can be saved (Akhtar and Sarmah, 2018). Comprehensive recycling can support reaching the UN sustainable development goals of “sustainable cities”, “responsible consumption and production”, and “climate action” (UN, 2023). Moreover, legal requirements for C&DW are tightening, and landfill capacities are decreasing. Thus, there are recycling or downcycling options for most building materials today. In Germany, 79% (95% if all recovery options are included) of C&DW waste is recycled (Kreislaufwirtschaft Bau, 2023). This rate satisfies the 70% recycling rate requirement by the European waste and recycling regulation (European Parliament and Council, 2008). However, among other waste fractions, autoclaved aerated concrete (AAC) is still disposed of nowadays.

AAC is a popular building material produced from quartz sand, cement, quicklime, anhydrite/gypsum, aluminium powder/paste, and water (Kreft, 2017; DIN 20000-404:2018-04). It has a porous structure and very low density. Therefore, AAC shows excellent thermal insulation properties. The current AAC production in Europe amounts to more than 6 million t/a (EAACA, 2023), of which around 1.5 million t/a are produced in Germany (GENESIS, 2023b). Post-demolition AAC (pd-AAC) volumes are estimated to be approximately 0.7 million t in Germany in 2022, while they are expected to reach more than 2 million t/a by 2050 (Steins et al., 2021). Thus, the OECD (2020) statement “the potential of the circular economy to support sustainable cities, regions, and countries still needs to be unlocked” is especially true for AAC. Today, the main reasons hindering AAC recycling are the low compressive strength compared to other mineral building materials and

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the small sulphate contents in AAC from the anhydrite/gypsum. Thus, the most widespread recycling options for mineral building materials (road construction, earthworks, and aggregate in concrete production (Knappe et al., 2012)) are not practicable for pd-AAC. Furthermore, reusing AAC masonry blocks is impractical as older AAC does not comply with current standards, and the deconstruction process would have to be overly careful and, thus, expensive (Gyurkó et al., 2019).

However, new recycling options for pd-AAC are investigated: Open-loop recycling options that are examined include the production of lightweight aggregate concrete (Aycil et al., 2016; Gyurkó et al., 2019), light mortar (Aycil et al., 2016), floor screed (Bergmans et al., 2016), and shuttering blocks from no-fines concrete (Gyurkó et al., 2019) made with pd-AAC input. These open-loop recycling options have in common that other products than AAC are produced. In contrast, in closed-loop recycling, pd-AAC is used to produce new AAC. This approach is also studied in the literature. On the one hand, fine pd-AAC powder can be used in AAC production to substitute sand, cement, quicklime, and anhydrite proportional to their input amount (Kreft, 2017; Lam, 2021; Rafiza et al., 2019, 2022). On the other hand, the closed-loop can be reached through a second recycling step where recycled belite cement clinker (RC-BCC) is produced (Ullrich et al., 2021; Stemmermann et al., 2024).

RC-BCC is produced in a rotary kiln from finely ground pd-AAC and additional limestone to reach the required C/S ratio of 2. The production of RC-BCC from pd-AAC is more promising than Portland cement production because CO_2-intensive limestone input can be reduced. Moreover, the process temperature is lower, enabling electric heating with further ecological savings potential compared to fossil fuels. RC-BCC can partly substitute Portland cement in the AAC production to reach a closed-loop. Recycling pd-AAC in the RC-BCC production can reach savings of up to 0.77 t CO_2-equivalents per t pd-AAC if renewable electricity provides the process energy (Stemmermann et al., 2024).

Additionally, it has been shown that AAC recycling can be superior to landfilling regarding environmental (Volk et al., 2022, 2023) and economic aspects (Steins et al., 2023a) for many recycling options: The environmental savings of pd-AAC recycling compared to landfilling reach 0.5 t CO_2-equivalents per t pd-AAC in the closed-loop recycling of pd-AAC powder in AAC production and around 0.4 t CO_2-equivalents per t pd-AAC in the open-loop recycling via production of lightweight aggregate concrete, light mortar, and shuttering blocks. Moreover, these open-loop recycling options show high savings in further environmental impacts like acidification, eutrophication, and ecotoxicity. Other options show significantly lower savings. Besides closed-loop recycling (RC-BCC production and direct recycling of pd-AAC powder), this study, therefore, only considers the open-loop recycling options of lightweight aggregate concrete, light mortar, and shuttering blocks as reasonable alternatives.

However, the design and optimisation of a pd-AAC recycling network for the following decades is missing in the literature[1] and will be the focus of this study. Such a recycling network includes transporting the material to be recycled from its point of generation to a recycling plant. The locations and capacities of these recycling plants as well as transports shall be optimised, while the costs and efficiencies of processing are considered. In the specific application of pd-AAC recycling, an optional second recycling step is also part of the recycling network. The recycled products, i.e. purified pd-AAC and RC-BCC, are finally transported to demand locations (granting a revenue) to produce AAC, lightweight aggregate concrete, light mortar, and shuttering blocks. These transports to demand locations are the final sink of the recycling network modelling, the production efforts for the new products are not included. Moreover, the model does not include building dismantling processes, route planning for transport, and operational aspects of the recycling process.

There are numerous studies on (recycling) network models available. Reverse logistic networks with multi-period consideration and possible capacity adjustments are studied by Alumur et al. (2012), Jahangiri et al. (2022), Pan et al. (2020), Rahimi and Ghezavati (2018), and Rosenberg et al. (2023). Multi-stage networks are also investigated by Figueiredo and Mayerle (2008), Jahangiri et al. (2022), Mansour and Zarei (2008), and Tuzkaya et al. (2011), while multi-product formulations are given by Ene and Öztürk (2015), Gomes et al. (2011), Listeş and Dekker (2005), and Pati et al. (2008). Reverse logistic networks that encompass stochastic factors are investigated by Lieckens and Vandaele (2007), Listeş and Dekker (2005), Roghanian and Pazhoheshfar (2014), Ene and Öztürk (2015), and Trochu et al. (2020). Moreover, some studies focus on modelling the recycling of (mineral) construction waste (Barros et al., 1998; Listeş and Dekker, 2005; Rahimi and Ghezavati, 2018; Trochu et al., 2020).

However, none of these studies includes a capacitated, multi-stage, multi-period approach considering different products and investigating scenarios for uncertainties, which is required for pd-AAC recycling network modelling. Thus, this paper aims to develop a new recycling network model that extensively extends the warehouse location problem (WLP) to consider the specific characteristics of pd-AAC recycling. These are (1) the dynamics of significantly increasing supplies, (2) different recycling plant capacities with economies of scale, and (3) two recycling stages, with the second one being optional.

The model's multi-period approach allows it to react precisely to increasing volumes. It is possible to open, close, expand or relocate plants at anytime. Moreover, the model considers the capacity limitations of recycling plants and economies of scale in larger plants. As the trade-off between economies of scale and transport costs will be a central element of the optimisation, exact modelling of realistic transport distances and product-dependent transport costs is ensured. The optional second recycling step produces a new, higher-quality product from the pd-AAC. This production needs additional effort but can also achieve a higher revenue. Deciding whether or not to use this optional second recycling step is another critical element of the optimisation. Therefore, the model includes this characteristic using a multi-stage formulation with independent locations at the second recycling stage and precisely calculated recycling costs.

An optimal solution is to be calculated for this model to answer the following research questions: How does a cost-optimal recycling network for pd-AAC look like, and how does it need to be adapted in the future when waste volumes increase significantly?

This study is structured as follows. First, section 2 describes the methods, including the mathematical formulation of a capacitated, multi-period, and multi-stage pd-AAC network model, as well as the input data. Section 3 presents the results of the model optimisation and their interpretation. Section 4 includes the discussion and states limitations. Finally, a conclusion is drawn in section 5.

2. Methods

2.1. Mathematical formulation

The newly developed capacitated, multi-stage, and multi-period model (section 1) is used for pd-AAC recycling network modelling and optimisation. Future expected pd-AAC amounts, given by parameter S, are assumed to emerge at different supply locations specified in the set $\mathscr{S}$. These amounts can be transported to recycling plants or landfilled. Variable x determines the recycling network product flows, while variable y indicates opened recycling plants, and variable z specifies the time when a recycling plant is opened. Pd-AAC amounts can be landfilled (variable l), but landfilling is limited to a maximum share (L) of the supply to reach a specified recycling rate.

The pd-AAC recycling process consists of a mandatory first step (pd-

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[1] So far, the authors have only examined a rough estimate of an optimal European network design with substantial simplifications compared to this study (Steins et al. 2023b).

Table 1

Sets, decision variables, and parameters used for the pd-AAC recycling network modelling.

Sets	
$\mathscr{D}$	set of demand locations
$\mathscr{K}_1$	set of possible recycling plant capacity levels (first recycling step)
$\mathscr{K}_2$	set of possible recycling plant capacity levels (second recycling step)
$\mathscr{M}$	set of commodities
$\mathscr{R}_1$	set of possible recycling plant locations (first recycling step)
$\mathscr{R}_2$	set of possible recycling plant locations (second recycling step)
$\mathscr{S}$	set of supply locations
$\mathscr{T} = \{0,...,T\}$	set of time periods
Decision variables	
l_{smt}	quantity of commodity $m \epsilon \mathscr{M}$ landfilled at supply location $s \epsilon \mathscr{S}$ in time period $t \epsilon \mathscr{T}$
x_{sr_1mt}	quantity of commodity $m \epsilon \mathscr{M}$ transported from supply location $s \epsilon \mathscr{S}$ to recycling plant location $r_1 \epsilon \mathscr{R}_1$ in time period $t \epsilon \mathscr{T}$
$x_{r_1r_2mt}$	quantity of commodity $m \epsilon \mathscr{M}$ transported from recycling plant location $r_1 \epsilon \mathscr{R}_1$ to recycling plant location $r_2 \epsilon \mathscr{R}_2$ in time period $t \epsilon \mathscr{T}$
x_{r_1dmt}	quantity of commodity $m \epsilon \mathscr{M}$ transported from recycling plant location $r_1 \epsilon \mathscr{R}_1$ to demand location $d \epsilon \mathscr{D}$ in time period $t \epsilon \mathscr{T}$
x_{r_2dmt}	quantity of commodity $m \epsilon \mathscr{M}$ transported from recycling plant location $r_2 \epsilon \mathscr{R}_2$ to demand location $d \epsilon \mathscr{D}$ in time period $t \epsilon \mathscr{T}$
$y_{k_1r_1t}$	indicator variable for the status of a recycling plant of capacity level $k_1 \epsilon \mathscr{K}_1$ at recycling plant location $r_1 \epsilon \mathscr{R}_1$ in time period $t \epsilon \mathscr{T}$
$y_{k_2r_2t}$	indicator variable for the status of a recycling plant of capacity level $k_2 \epsilon \mathscr{K}_2$ at recycling plant location $r_2 \epsilon \mathscr{R}_2$ in time period $t \epsilon \mathscr{T}$
$z_{k_1r_1t}$	indicator variable for the opening of a recycling plant of capacity level $k_1 \epsilon \mathscr{K}_1$ at recycling plant location $r_1 \epsilon \mathscr{R}_1$ in time period $t \epsilon \mathscr{T}$
$z_{k_2r_2t}$	indicator variable for the opening of a recycling plant of capacity level $k_2 \epsilon \mathscr{K}_2$ at recycling plant location $r_2 \epsilon \mathscr{R}_2$ in time period $t \epsilon \mathscr{T}$
Parameters	
$C^{transport}_{sr_1mt}$	transport costs of commodity $m \epsilon \mathscr{M}$ from supply location $s \epsilon \mathscr{S}$ to recycling plant location $r_1 \epsilon \mathscr{R}_1$ in time period $t \epsilon \mathscr{T}$
$C^{transport}_{r_1r_2mt}$	transport costs of commodity $m \epsilon \mathscr{M}$ from recycling plant location $r_1 \epsilon \mathscr{R}_1$ to recycling plant location $r_2 \epsilon \mathscr{R}_2$ in time period $t \epsilon \mathscr{T}$
$C^{transport}_{r_1dmt}$	transport costs of commodity $m \epsilon \mathscr{M}$ from recycling plant location $r_1 \epsilon \mathscr{R}_1$ to demand location $d \epsilon \mathscr{D}$ in time period $t \epsilon \mathscr{T}$
$C^{transport}_{r_2dmt}$	transport costs of commodity $m \epsilon \mathscr{M}$ from recycling plant location $r_2 \epsilon \mathscr{R}_2$ to demand location $d \epsilon \mathscr{D}$ in time period $t \epsilon \mathscr{T}$
$C^{var,first\ step}_{mt}$	variable recycling costs of commodity $m \epsilon \mathscr{M}$ in time period $t \epsilon \mathscr{T}$ in the first recycling step
$C^{fixed,first\ step}_{k_1t}$	fixed costs for operating a recycling plant of capacity level $k_1 \epsilon \mathscr{K}_1$ in time period $t \epsilon \mathscr{T}$ in the first recycling step
$C^{open,first\ step}_{k_1r_1t}$	opening costs for a recycling plant of capacity level $k_1 \epsilon \mathscr{K}_1$ at recycling plant location $r_1 \epsilon \mathscr{R}_1$ in time period $t \epsilon \mathscr{T}$ in the first recycling step
$C^{var,second\ step}_{mt}$	variable recycling costs of commodity $m \epsilon \mathscr{M}$ in time period $t \epsilon \mathscr{T}$ in the second recycling step
$C^{fixed,second\ step}_{k_2t}$	fixed costs for operating a recycling plant of capacity level $k_2 \epsilon \mathscr{K}_2$ in time period $t \epsilon \mathscr{T}$ in the second recycling step
$C^{open,second\ step}_{k_2r_2t}$	opening costs for a recycling plant of capacity level $k_2 \epsilon \mathscr{K}_2$ at recycling plant location $r_2 \epsilon \mathscr{R}_2$ in time period $t \epsilon \mathscr{T}$ in the second recycling step
$C^{landfilling}_{smt}$	landfilling costs of commodity $m \epsilon \mathscr{M}$ at supply location $s \epsilon \mathscr{S}$ in time period $t \epsilon \mathscr{T}$
$C^{revenue}_{dmt}$	revenue for selling the commodity $m \epsilon \mathscr{M}$ at demand location $d \epsilon \mathscr{D}$ in time period $t \epsilon \mathscr{T}$
D_{dmt}	demand of commodity $m \epsilon \mathscr{M}$ at demand location $d \epsilon \mathscr{D}$ in time period $t \epsilon \mathscr{T}$
$Dist_{sr_1}$	distance between supply location $s \epsilon \mathscr{S}$ and recycling plant location $r_1 \epsilon \mathscr{R}_1$
$Dist_{r_{1r_2}}$	distance between recycling plant location $r_1 \epsilon \mathscr{R}_1$ and recycling plant location $r_2 \epsilon \mathscr{R}_2$
$Dist_{r_1d}$	distance between recycling plant location $r_1 \epsilon \mathscr{R}_1$ and demand location $d \epsilon \mathscr{D}$
$Dist_{r_2d}$	distance between recycling plant location $r_2 \epsilon \mathscr{R}_2$ and demand location $d \epsilon \mathscr{D}$
E_{nmt}	efficiency of the production of commodity $m \epsilon \mathscr{M}$ from commodity $n \epsilon \mathscr{M}$ in time period $t \epsilon \mathscr{T}$
K_{k_1mt}	recycling plant input capacity for commodity $m \epsilon \mathscr{M}$ at capacity level $k_1 \epsilon \mathscr{K}_1$ in time period $t \epsilon \mathscr{T}$
K_{k_2mt}	recycling plant input capacity for commodity $m \epsilon \mathscr{M}$ at capacity level $k_2 \epsilon \mathscr{K}_2$ in time period $t \epsilon \mathscr{T}$
L_{mt}	maximum share of the supply allowed to be landfilled for commodity $m \epsilon \mathscr{M}$ in time period $t \epsilon \mathscr{T}$
S_{smt}	supply of commodity $m \epsilon \mathscr{M}$ at supply location $s \epsilon \mathscr{S}$ in time period $t \epsilon \mathscr{T}$

AAC processing) that includes crushing and purifying to produce pd-AAC powder and pd-AAC granulate. These products can either be directly transported to demand locations for AAC, lightweight aggregate concrete, light mortar, or shuttering block production or undergo the optional RC-BCC production (= optional second recycling step). Efficiencies of the two recycling steps are reflected by the parameter E. The model's set $\mathscr{M}$ contains all the commodities. Both recycling steps do not necessarily have to be executed at the same location. Thus, possible recycling plant locations are given separately for the first (set $\mathscr{R}_1$) and the second recycling step (set $\mathscr{R}_2$).

The recycling plants can differ in input capacity, influencing recycling costs. The sets $\mathscr{K}_1$ and $\mathscr{K}_2$ contain all possible recycling plant capacity levels (for indexing: 0, 1, 2, …) for both recycling steps, while parameter K specifies concrete input capacities of the different levels. Finally, the recycling end products are delivered to demand locations (set $\mathscr{D}$). These are limited to a maximum demand D. Also, the model includes different time periods specified by set $\mathscr{T}$, as pd-AAC amounts are expected to rise in the future, and the optimal network design could, thus, significantly change over time.

The overall objective is to minimise the total costs of the pd-AAC recycling network. Costs are divided into the categories variable recycling costs (C^{var}), fixed recycling plant costs (C^{fixed}), recycling plant opening costs (C^{open}), landfilling costs ($C^{landfilling}$), and transport costs ($C^{transport}$). Including opening and fixed costs enables realistic modelling of a recycling plant's cost structure. The parameter for the transport costs only gives costs per distance. So, the actual distance of the transport ($Dist$) has to be specified. Additionally, revenues for the final products of the recycling process are included ($C^{revenue}$).

The model reflects a capacitated, multi-period, and multi-stage recycling network. Further characteristics of the model include determinism (no stochastics for supply amounts or costs are considered), multi-sourcing (different regions can supply a recycling plant), and direct delivery without interactions between plants of the same stage. The model's sets (calligraphic upper-case characters), decision variables (lower-case characters), and parameters (upper-case characters) are presented in Table 1, along with all indices to precisely determine the values for all locations, capacities, commodities, and periods. The cost-minimising model is formulated in equations (1)–(16). The model can be classified as a mixed-integer problem.

$$
\begin{aligned}
min \sum_{t\in\mathscr{T}} \Bigg[\sum_{m\in\mathscr{M}} \Bigg(& \sum_{s\in\mathscr{S}} \sum_{r_1\in\mathscr{R}_1} x_{sr_1mt}\cdot Dist_{sr_1}\cdot C^{transport}_{sr_1mt} + \sum_{r_1\in\mathscr{R}_1}\sum_{r_2\in\mathscr{R}_2} x_{r_1r_2mt}\cdot Dist_{r_1r_2}\cdot C^{transport}_{r_1r_2mt} + \sum_{r_1\in\mathscr{R}_1}\sum_{d\in\mathscr{D}} x_{r_1dmt}\cdot Dist_{r_1d}\cdot C^{transport}_{r_1dmt} \\
& + \sum_{r_2\in\mathscr{R}_2}\sum_{d\in\mathscr{D}} x_{r_2dmt}\cdot Dist_{r_2d}\cdot C^{transport}_{r_2dmt} + \sum_{s\in\mathscr{S}}\sum_{r_1\in\mathscr{R}_1} C^{var,first\ step}_{mt}\cdot x_{sr_1mt} + \sum_{r_1\in\mathscr{R}_1}\sum_{r_2\in\mathscr{R}_2} C^{var,second\ step}_{mt}\cdot x_{r_1r_2mt} \Bigg) \\
& + \sum_{r_1\in\mathscr{R}_1}\sum_{k_1\in\mathscr{K}_1} C^{fixed,first\ step}_{k_1t}\cdot y_{k_1r_1t} + \sum_{r_2\in\mathscr{R}_2}\sum_{k_2\in\mathscr{K}_2} C^{fixed,second\ step}_{k_2t}\cdot y_{k_2r_2t} + \sum_{r_1\in\mathscr{R}_1}\sum_{k_1\in\mathscr{K}_1} C^{open,first\ step}_{k_1r_1t}\cdot z_{k_1r_1t} + \sum_{r_2\in\mathscr{R}_2}\sum_{k_2\in\mathscr{K}_2} C^{open,second\ step}_{k_2r_2t}\cdot z_{k_2r_2t} \\
& + \sum_{s\in S}\sum_{m\in\mathscr{M}} l_{smt}\cdot C^{landfilling}_{smt} - \sum_{m\in\mathscr{M}}\Bigg(\sum_{r_1\in\mathscr{R}_1}\sum_{d\in\mathscr{D}} x_{r_1dmt}\cdot C^{revenue}_{dmt} + \sum_{r_2\in\mathscr{R}_2}\sum_{d\in\mathscr{D}} x_{r_2dmt}\cdot C^{revnue}_{dmt} \Bigg) \Bigg]
\end{aligned}
\tag{1}
$$

$$s.t. \sum_{r_1\in\mathscr{R}_1} x_{sr_1mt} + l_{smt} = S_{smt} \forall s\in\mathscr{S}, \forall m\in\mathscr{M}, \forall t\in\mathscr{T} \tag{2}$$

$$\sum_{s\in\mathscr{S}} l_{smt} \le L_{mt}\cdot\sum_{s\in\mathscr{S}} S_{smt}\ \forall m\in\mathscr{M}, \forall t\in\mathscr{T} \tag{3}$$

$$\sum_{r_2\in\mathscr{R}_2} x_{r_1r_2mt} + \sum_{d\in\mathscr{D}} x_{r_1dmt} = \sum_{n\in\mathscr{M}}\left(E_{nmt}\sum_{s\in\mathscr{S}} x_{sr_1nt}\right)\ \forall r_1\in\mathscr{R}_1, \forall m\in\mathscr{M}, \forall t\in\mathscr{T} \tag{4}$$

$$\sum_{d\in\mathscr{D}} x_{r_2dmt} = \sum_{n\in M}\left(E_{nmt}\sum_{r_1\in\mathscr{R}_1} x_{r_1r_2nt}\right)\ \forall r_2\in\mathscr{R}_2, \forall m\in\mathscr{M}, \forall t\in\mathscr{T} \tag{5}$$

$$\sum_{r_1\in\mathscr{R}_1} x_{r_1dmt} + \sum_{r_2\in\mathscr{R}_2} x_{r_2dmt} \le D_{dmt}\ \forall d\in\mathscr{D}, \forall m\in\mathscr{M}, \forall t\in\mathscr{T} \tag{6}$$

$$\sum_{s\in\mathscr{S}} x_{sr_1mt} \le \sum_{k_1\in\mathscr{K}_1} K_{k_1mt}\cdot y_{k_1r_1t}\ \forall r_1\in\mathscr{R}_1, \forall m\in\mathscr{M}, \forall t\in\mathscr{T} \tag{7}$$

$$\sum_{r_1\in\mathscr{R}_1} x_{r_1r_2mt} \le \sum_{k_2\in\mathscr{K}_2} K_{k_2mt}\cdot y_{k_2r_2t}\ \forall r_2\in\mathscr{R}_2, \forall m\in\mathscr{M}, \forall t\in\mathscr{T} \tag{8}$$

$$\sum_{k_1\in\mathscr{K}_1} y_{k_1r_1t} \le 1\ \forall r_1\in\mathscr{R}_1, \forall t\in\mathscr{T} \tag{9}$$

$$\sum_{k_2\in\mathscr{K}_2} y_{k_2r_2t} \le 1\ \forall r_2\in\mathscr{R}_2, \forall t\in\mathscr{T} \tag{10}$$

$$y_{k_1r_1t} - y_{k_1r_1(t-1)} \le z_{k_1r_1t}\ \forall k_1\in\mathscr{K}_1, \forall r_1\in\mathscr{R}_1, \forall t\in\mathscr{T}\backslash\{0\} \tag{11}$$

$$y_{k_2r_2t} - y_{k_2r_2(t-1)} \le z_{k_2r_2t}\ \forall k_2\in\mathscr{K}_2, \forall r_2\in\mathscr{R}_2, \forall t\in\mathscr{T}\backslash\{0\} \tag{12}$$

$$y_{k_1r_10} = z_{k_1r_10}\ \forall k_1\in\mathscr{K}_1, \forall r_1\in\mathscr{R}_1 \tag{13}$$

$$y_{k_2r_20} = z_{k_2r_20}\ \forall k_2\in\mathscr{K}_2, \forall r_2\in\mathscr{R}_2 \tag{14}$$

$$x_{sr_1mt}, x_{r_1r_2mt}, x_{r_1dmt}, x_{r_2dmt}, l_{smt} \ge 0\ \forall s\in\mathscr{S}, \forall r_1\in\mathscr{R}_1, \forall r_2\in\mathscr{R}_2, \forall d\in\mathscr{D}, \forall m\in\mathscr{M}, \forall t\in\mathscr{T} \tag{15}$$

$$y_{k_1r_1t}, y_{k_2r_2t}, z_{k_1r_1t}, z_{k_2r_2t} \in \{0,1\}\ \forall r_1\in\mathscr{R}_1, \forall r_2\in\mathscr{R}_2, \forall k_1\in\mathscr{K}_1, \forall k_2\in\mathscr{K}_2, \forall t\in\mathscr{T} \tag{16}$$

The model's objective function (equation (1)) is set to minimise total costs consisting of transport, variable recycling, fixed recycling, opening, and landfilling costs. Revenues for the final products are subtracted from these costs. The model has fifteen constraints specified by equations (2)–(16). Equation (2) ensures that all supply has to be treated in the same period as it emerges. It is either transported to a recycling plant location or landfilled. However, the total amount that can be landfilled is restricted in equation (3) to a specified share of the total quantity supplied. This restriction reflects legal regulations or self-imposed recycling goals. Equation (4) defines the flow conservation constraint for the first recycling step. The amount transported to a recycling plant location and treated there must be further transported to another recycling plant location for the second recycling step or demand locations in the same period. Storage between different periods is not allowed in the model, but intermediate storage of materials within one period (e.g. in silos of recycling plants) is considered in the costs. Moreover, the efficiency of the recycling process is considered. Similarly, the flow conservation of the second recycling step is described in equation (5). Equation (6) ensures that the amounts transported to the demand locations do not exceed the demands for the different commodities in every period. Undersupply of the demand is allowed in the model as the focus is on the waste to be recycled instead of the entire demand to be met. Equations (7) and (8) determine the capacity limitations of the recycling plants, including the fact that material can only be transported to opened recycling plant locations. Moreover, equations (9) and (10) specify for both recycling steps that at most one recycling plant can be opened in one region at the same time. Equations (11) and (12) ensure that opening costs are considered when a recycling plant is opened. The first period is handled separately in equations (13) and (14) as negative period indices are not defined ($t-1=-1$ for the first period). Finally, equation (15) defines the non-negativity of the decision variables for transport and landfilling. Moreover, equation (16) ensures that recycling plant opening and recycling plant status are binary.

2.2. *Use case and input data*

This section discloses relevant input data and assumptions for the model. A summary of these is given at the end of the section in Table 4. SI-1 in the supplementary information discloses all input data, including information that could not be described entirely in this section, for example, all elements of the considered sets and values of comprehensive parameters like the supply.

The use case investigated in this study focuses on pd-AAC in Germany since it is a crucial ACC market with all the required data available. The geographic subdivision uses the NUTS[2] 2 level, where 38 German regions are considered. Every region resembles a supply location ($\mathscr{S}$) and is a possible recycling plant location for both recycling steps ($\mathscr{R}_1$ and $\mathscr{R}_2$). The demand locations ($\mathscr{D}$) include all AAC plants in Germany where pd-AAC powder or RC-BCC can be used in a closed-loop recycling process. Overall, 31 AAC plants in Germany are identified in our own research. Other recycling options described in the literature do not necessarily depend on production plants. Instead, the pd-AAC recycling products are needed at decentralised locations, for example, directly at the construction site. The recycling plants can be constructed in five different capacity levels at both recycling stages ($\mathscr{K}_1$ and $\mathscr{K}_2$). Commodities ($\mathscr{M}$) include pd-AAC as the initial product, pd-AAC powder

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[2] Nomenclature des unités territoriales statistiques is a system for regional division of countries.

Table 2
Capacities, variable costs, fixed costs, opening costs, and required area for all capacity levels and both recycling steps (based on Steins et al., 2023a).

First recycling step					
capacity level	1	2	3	4	5
capacity [t input/a]	10,000	25,000	50,000	100,000	250,000
variable costs [€/t input]	3.38	3.38	3.38	3.38	3.38
fixed costs [€/a]	1,843,912	2,333,815	2,901,608	3,720,276	5,511,086
opening costs [€]	1,609,503	2,185,915	2,823,760	4,607,165	9,678,336
required area [m^2]	2349	5359	10,000	18,661	42,567
Second recycling step					
capacity level	1	2	3	4	5
capacity [t input/a]	7425	18,563	37,125	74,250	185,625
variable costs [€/t input]	621.51	621.51	621.51	621.51	621.51
fixed costs [€/a]	17,616,962	27,560,537	38,883,341	57,007,255	100,901,908
opening costs [€]	5,133,004	7,982,309	11,041,251	15,691,789	25,836,904
required area [m^2]	2349	5359	10,000	18,661	42,567

and pd-AAC granulate as the outputs of the first recycling step, and RC-BCC as the output of the second recycling step. Finally, all years from 2023 to 2050 are considered, but several years are merged into one period to reduce the number of decision variables and the associated complexity. The further the period is in the future, the more years are combined. Thus, the following eleven periods ($\mathscr{T}$) are considered: 2023, 2024, 2025, 2026/2027, 2028/2029, 2030/2031, 2032–2034, 2035–2037, 2038–2040, 2041–2045, 2046–2050.

The cost parameters are determined as follows. Variable costs (C^{var}) for both recycling steps are disclosed in Table 2. They include costs which directly depend on the treated amount but are independent of the capacity of the recycling plant (raw materials, electricity, waste treatment/disposal, operating supplies, catalysts, CO_2 certificates). Thus, a multiplication of decision variables in the mathematical model's objective function is avoided. All capacity-depending costs are considered in the fixed costs or opening costs.

Fixed costs (C^{fixed}) include operating labour, operating supervision, maintenance and repairs, laboratory charges, interest for working capital, taxes, insurance, overhead costs, and general expenses. Precise costs for all capacity levels and both recycling steps are given in Table 2.

Opening costs (C^{open}) for both recycling steps and all capacity levels reflect the fixed-capital investment of a recycling plant. Additionally, land costs have to be included. These depend on the recycling plant location and, therefore, are calculated separately based on regional prices per m^2 from Destatis (2021) and AK OGA (2021). Opening costs and the required land for all capacity levels and both recycling steps are given in Table 2, while regionally differing land costs are listed in SI-1.

Transport costs ($C^{transport}$) are based on Persyn et al. (2022). They identified the costs for a 40 t truck on routes between all possible combinations of NUTS 2 regions in Germany. Thus, route-specific transport costs can be used for the optimisation. These costs vary between 1.37 €/km for long distances (up to 1000 km) and more than 3 €/km for very short transports (less than 30 km). The costs are adjusted by the rise in transport prices between January 2020 and July 2023 (BGL, 2023). However, the truck's maximum payload depends on the transported commodity, leading to different costs per ton and kilometre. Pd-AAC powder and granulate, as well as belite cement clinker, can be transported in an articulated truck with an assumed maximum payload of 25 t and a maximum volume of 90 m^3. Bulk densities of pd-AAC powder (0.6 t/m^3; Gyurkó et al., 2019) and cement clinker (>0.9 t/m^3; VDZ, 2017) are high enough to use the whole 25 t payload of the truck. Pd-AAC granulate has a bulk density of 0.255 t/m^3 (Gyurkó et al., 2019) and, thus, only reaches a payload of 22.95 t when the maximum volume of 90 m^3 is used. Pd-AAC is assumed to be transported in a tipper truck with 25 t maximum payload and 60 m^3 maximum volume. The bulk density of pd-AAC is supposed to be around 0.2 t/m^3 (Gyurkó et al., 2019).[3] This low density leads to a maximum of 12 t pd-AAC payload within the given 60 m^3 truck volume and to comparably high costs.

Landfilling costs ($C^{landfilling}$) vary significantly between regions, ranging from 65 to 180 €/t pd-AAC (Aycil and Hlawatsch, 2020). Research in the online portals clearago.de and abfallscout.de discloses regional pd-AAC landfilling costs for nearly every postal code area in Germany. Landfilling costs per NUTS 2 region are calculated as an average of all included postal code areas within each NUTS 2 region (SI-1). It is assumed that transport costs to the landfills are already included in the landfilling fees.

The revenues ($C^{revenue}$) are based on market prices for similar products since pd-AAC recycling products are not established yet. The pd-AAC powder and pd-AAC granulate are assumed to generate 10 €/t revenues as other mineral recycling products have market prices of 5–15 €/t in Germany (initial interactive gmbh, 2023). The RC-BCC can substitute Portland cement in some applications. Thus, average German cement prices of 150 €/t (cemex, 2022; Dyckerhoff, 2022) are assumed as revenue.

Besides the costs, further parameters include distances (*Dist*), demand (*D*), efficiencies (*E*), capacities (*K*), maximum landfill share (*L*), and supply (*S*). Persyn et al. (2022) provide average road distances for transports within a NUTS 2 region and between every pair of German NUTS 2 regions. These distances are relevant for all transports from supply to recycling locations and between the recycling stages. Only transports to the demand are calculated separately as demand arises at decentralised locations (construction sites) or concrete AAC plants. A lump-sum distance of 100 km is assumed for transports of pd-AAC powder/granulate to decentralised demand locations. Moreover, distances from recycling plants to AAC plants are calculated using the geodesic distance multiplied by a factor of 1.33 to reflect the average proportion of road distance to geodesic distance in Germany (Persyn et al., 2022).

The demand of the AAC plants is calculated by multiplying the total AAC production of the respective plant with a substitution percentage of primary raw materials with pd-AAC powder or RC-BCC, respectively. All 31 German AAC plants are assumed to produce 50,000 t/a due to missing specific information. Currently, pd-AAC powder can substitute 7–10% of the overall input depending on the AAC type (Volk et al., 2023), while RC-BCC can substitute a maximum of 50% of the cement input, i.e. 8-16% of the overall input depending on the AAC type (Stemmermann et al., 2024). Thus, the pd-AAC powder demand per plant is assumed to be 4000 t/a (8%), while RC-BCC demand is 6000 t/a

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[3] Gyurkó et al. (2019) only specify bulk densities for grain sizes up to 8–16 mm which is less than usual pd-AAC from the demolition site. However, the assumption of 0.2 t/m^3 bulk density for pd-AAC is used as the density rises with grain size and shows convergence to around 0.2 t/m^3.

(12%). Furthermore, a decentralised demand at construction sites is assumed for pd-AAC powder and granulate that is used in other recycling options, especially in the ecologically promising recycling options of light mortar, lightweight aggregate concrete, and shuttering block production (Volk et al., 2023). It is assumed that the maximum possible amount of pd-AAC powder and pd-AAC granulate is used for the entire production of light mortar (61% of all input material substituted by pd-AAC powder), lightweight aggregate concrete (46%–81% of all input material substituted by pd-AAC granulate and smaller amounts of pd-AAC powder, depending on the production recipe), and shuttering blocks (36% of all input material substituted by pd-AAC granulate) (Volk et al., 2023). Thus, the decentralised demand is approximately 1,800,000 t/a pd-AAC powder, primarily for light mortar production, and 600,000 t/a pd-AAC granulate for lightweight aggregate concrete and shuttering block production. This decentralised demand would be high enough to ensure a full pd-AAC recycling even for high predicted volumes in the future.

Table 3
Annual inflation rates for relevant products/categories and the resulting inflation for all cost categories in the model.

Product/ category	Inflation p.a. [-]	Reference	Explanation
C&DW disposal	7.8%	Interzero Circular Solutions Germany GmbH (2022)	average inflation 2018–2021
electricity for industrial application	3.0%	GENESIS (2023a)	average inflation 2013–2022
building land	6.4%	Federal Statistical Office (2022)	average inflation 2012–2021
salaries	3.9%	Federal Statistical Office (2023)	average inflation 2013–2022
transport	3.8%	Noerpel-Schneider and Stölzle (2019)	average inflation based on EU sport market prices 2016–2019
machines for sorting and grading of minerals	2.8%	GENESIS (2023a)	average inflation 2013–2022
cement	3.1%	GENESIS (2023a)	average inflation 2013–2022
limestone	5.9%	GENESIS (2023a)	average inflation 2013–2022
chlorides	3.3%	GENESIS (2023a)	average inflation 2013–2022
CO_2 certificates	5.0%	assumption	past inflation rates have been subject to strong fluctuations, so an assumption is necessary
goods made from concrete or cement	3.5%	GENESIS (2023a)	average inflation 2013–2022
cost category in the model			
landfilling	7.8%		equals C&DW disposal inflation
variable costs first recycling step	4.4%	own calculation	weighted inflation of electricity, disposal, and machines
variable costs second recycling step	3.4%	own calculation	weighted inflation of electricity, disposal, limestone, chlorides, CO_2 certificates, and machines
fixed costs first recycling step	3.7%	own calculation	weighted inflation of salaries and machines
fixed costs second recycling step	3.0%	own calculation	weighted inflation of salaries and machines
opening costs first/second recycling step	2.8%		equals machine inflation
land costs first/ second recycling step	6.4%		equals building land inflation
transport costs	3.8%		equals transport inflation
revenue pd-AAC powder/ granulate	3.5%		equals goods made from concrete or cement inflation
revenue RC-BCC	3.1%		equals cement inflation
discount rate	3%	assumption	

Table 4
Assumptions and relevant data for all considered sets and parameters used for the pd-AAC recycling network modelling.

Sets	
$\mathscr{D}$	31 German AAC plants plus decentralised demand locations
$\mathscr{K}_1, \mathscr{K}_2$	five different capacity levels
$\mathscr{M}$	considered products: pd-AAC, pd-AAC powder, pd-AAC granulate, RC-BCC
$\mathscr{S}, \mathscr{R}_1, \mathscr{R}_2$	38 German regions (NUTS 2)
$\mathscr{T}$	eleven periods covering the years 2023–2050
Parameters	
$C^{transport}$	route- and commodity-specific transport costs, median values: 0.145 €/t*km (pd-AAC), 0.069 €/t*km (pd-AAC powder), 0.076 €/t*km (pd-AAC granulate), 0.069 €/t*km (RC-BCC)
$C^{var}, C^{fixed}, C^{open}$	see Table 2
$C^{landfilling}$	65 to 180 €/t
$C^{revenue}$	10 €/t (pd-AAC powder/granulate), 150 €/t (RC-BCC)
D	demand of 4000 t/a pd-AAC powder per AAC plant, 6000 t/a RC-BCC per AAC plant, total German decentralised demand of 1,800,000 t/a pd-AAC powder and 600,000 t/a pd-AAC granulate for different recycling options
$Dist$	road distances, assumed 100 km for transports of pd-AAC powder/ granulate to decentralised demand locations
E	efficiency of 99% (first recycling step) and 171% (second recycling step)
K	input capacities of first recycling step: 10,000, 25,000, 50,000, 100,000, or 250,000 t/a; and of second recycling step: 7,425, 18,563, 37,125, 74,250, or 185,625 t/a
L	30%
S	data from (Steins et al., 2021)

Additionally, efficiencies (E) are considered independently from the plants' capacities. They are defined as the output amount divided by pd-AAC input. The mechanical processing produces powder and granulate from pd-AAC with an overall efficiency of 99%. Only 1% of impurities are sorted out (Volk et al., 2023). The shares of produced pd-AAC powder and granulate can vary, depending on the crushing technology and humidity of the pd-AAC. Generally, the production of ¾ powder and ¼ granulate is a reasonable assumption (Volk et al., 2023; Gyurkó et al., 2019), reaching an overall efficiency of 74.25% (powder) and 24.75% (granulate). The RC-BCC production needs pd-AAC powder and significant additional limestone input to reach the target C/S ratio. Therefore, more than 1 t RC-BCC is produced per t pd-AAC, and the efficiency (defined as output amount per pd-AAC input amount) of the second recycling step reaches a value of 171% (Steins et al., 2023a). Costs for limestone are considered in the variable costs of the second recycling step. Efficiencies for other commodity combinations (for example, RC-BCC to pd-AAC) are zero since production is impossible.

A recycling plant of the first step is assumed to have five different input capacities (K): 10,000, 25,000, 50,000, 100,000, or 250,000 t/a. The second recycling step's plant has capacities of 7,425, 18,563, 37,125, 74,250, or 185,625 t/a (Table 2). The latter capacities correspond to the capacities of the first recycling step multiplied by the efficiency for pd-AAC powder production, allowing the entire output of a first-stage plant to be further processed in a second-stage plant of the same capacity level.

The maximum pd-AAC amount allowed to be landfilled (L) is 30% to reach a recycling rate of at least 70%, according to the European waste and recycling regulation (European Parliament and Council, 2008). The pd-AAC supply (*S*) until 2050 is based on Steins et al. (2021) and disclosed in SI-1. The model includes a time horizon of almost 30 years. Therein, costs will not remain constant. Therefore, inflation and discounting are considered to compare current and future costs (Table 3). Finally, Table 4 summarises all assumptions and relevant data

2.3. Scenario definition

The case described in section 2.2 is considered the baseline scenario (scenario 0). Besides, this study investigates scenarios to show how the optimal solution, the network structure, and the network costs change under different circumstances.

First, RC-BCC production has a substantial potential to reduce environmental impacts (Stemmermann et al., 2024) but is very costly (Table 2). Thus, scenario 1 considers support for the RC-BCC production. First, the RC-BCC demand is assumed to be 50% higher than in the baseline scenario due to, for example, political objectives for increased secondary inputs or sustainable products. Moreover, 50% higher revenues for RC-BCC are assumed in this scenario due to the product's sustainable image or potential subsidies. Finally, the variable, fixed, and opening costs (without land costs) are assumed to decrease by 3 %/a due to technological progress. However, cost inflation from the baseline scenario is still considered and offset against this cost decrease.

Given the extremely high costs for RC-BCC production, scenario 2 assumes an even higher support for the RC-BCC production. The demand is increased by 100%, the revenues are increased by 100%, and the costs are reduced by 6 %/a. Such support could only be realised with great effort. Nevertheless, possible network adaptations and saving potentials are investigated in this study.

Finally, scenario 3 assumes a significant increase in recycling costs and a reduction in landfilling costs. It is investigated whether recycling remains the preferred pd-AAC treatment option even under considerably

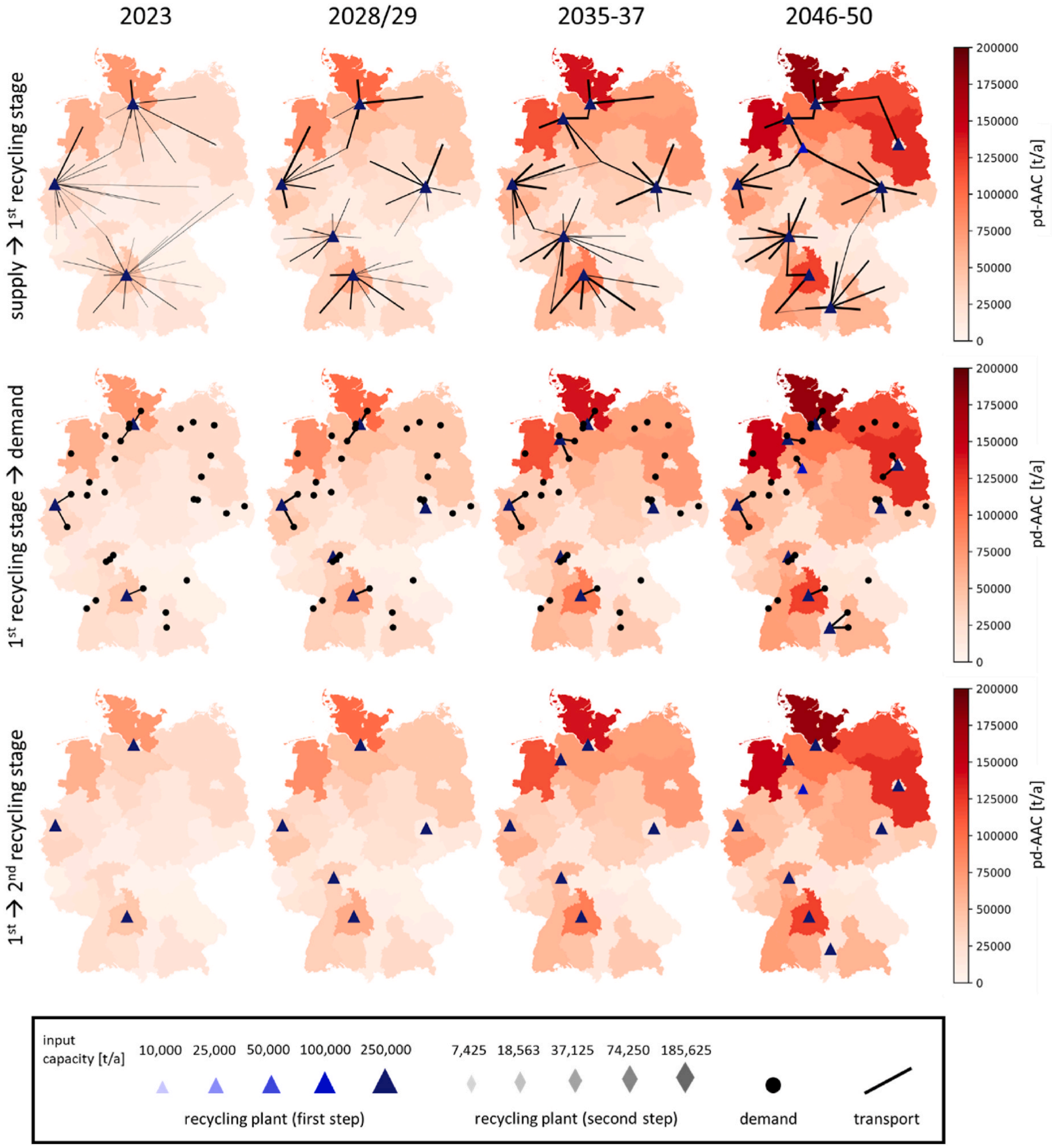

Fig. 1. Optimal pd-AAC recycling network design for Germany in the baseline scenario for the periods 2023, 2028/29, 2035–37, and 2046–50.

worse conditions. Therefore, the variable, fixed, and opening costs (without land costs) for both recycling steps are increased by 50%. Additionally, the revenues are decreased by 50%, and the landfilling costs are reduced to 65 €/t in all regions, corresponding to the minimal pd-AAC landfilling costs given by Aycil and Hlawatsch (2020). Cost inflations are considered like in the baseline scenario.

2.4. Implementation

The mathematical model is optimised using the CPLEX solver in the 22.1.1 version, implemented in Python 3.10 via the docplex library. Computation time was approximately 900 s (scenario 0), 750 s (scenario 1), 14 h (scenario 2), and 200 s (scenario 3) on the used machine (AMD Ryzen 9 3900X at 4.00 GHz, 128 GB RAM). The results for all scenarios reached optimality.

3. Results

3.1. Baseline scenario

The results of the optimised network design in the baseline scenario (Fig. 1) show the pd-AAC volumes with a lighter/orange colouring for lower volumes and a darker/red colouring for higher volumes for selected years and periods. Blue triangles specify the optimum recycling plant locations for the first recycling step, and grey diamonds for the second step. Larger symbols and a darker shade correspond to higher input capacities of the plants. Black dots illustrate demand locations (AAC plants), while decentralised demand is not shown since it does not have a specific location. Transports are indicated by black connection lines, which are thicker when larger amounts are transported.

First, it is striking that the pd-AAC amount increases significantly in the considered time frame. Accordingly, the number of first-stage recycling plants also rises. Only three plants are opened in 2023, but five are already active in 2028/29. In 2035–37, the number of recycling plants increases to six, and even nine plants are operational in 2046–2050. The optimised network prefers large recycling plants to benefit from economies of scale in fixed and opening costs. Almost all opened plants have the highest possible input capacity of 250,000 t/a. Only one plant in the last period has a lower but still high capacity of 100,000 t/a (second highest capacity level). Additionally, the network completely avoids closing or relocating plants. Consequently, the first plants are placed so that new plants can reasonably complement them over time. For example, there is a large area without recycling plants in central and eastern Germany in 2023, where new plants are built in the subsequent periods. Strikingly, however, no recycling plants are opened in the middle of Germany (Northern Hesse, Thuringia, and Northern Bavaria). It can be assumed that particularly Northern Hesse and Northern Bavaria have such a low volume that the direct placement of recycling plants there is not advantageous. In addition, a plant in Saxony is preferred to one in Thuringia to minimise the transport distance from Saxony and, in some periods, Brandenburg. Moreover, there are no near AAC plants, and thus, there is less demand for final products in these regions.

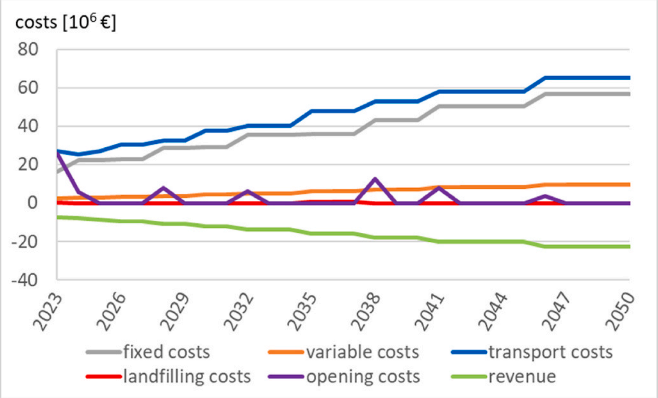

Fig. 2. Development of variable, fixed, opening, transport, and landfilling costs as well as revenues in the baseline scenario in the optimised recycling network until 2050.

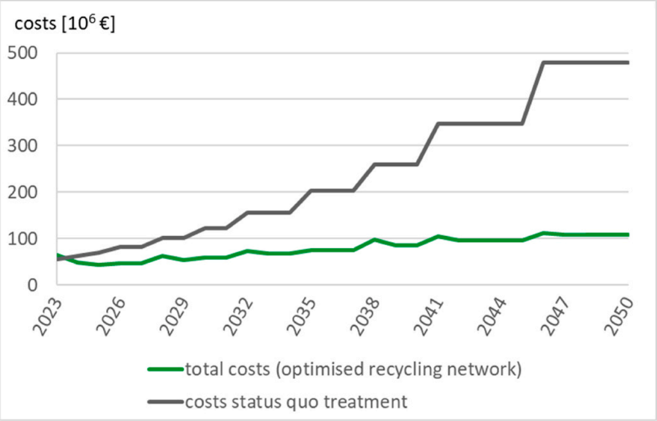

Fig. 3. Comparison of the total costs until 2050 of an optimised recycling network with the status quo ($^{2}/_{3}$ landfilling, $^{1}/_{3}$ recovery).

The increasing volume and number of recycling plants also leads to an increased pd-AAC transport per region, a recycling plant sourcing from fewer regions, and a general reduction in transport distances (supply → 1st recycling stage). Overall, the average pd-AAC transport distance to a recycling plant decreases from 185 km (2023) to 117 km (2046–50). The transport distances from the first recycling step to the demand locations are also relatively low (1st recycling stage → demand). The decentralised demand is supplied when the demand of the AAC plants within a radius of 100 km around the recycling plants is fully served because a lump-sum transport distance of 100 km is assumed. The second recycling step (RC-BCC production) is not part of the cost-optimal solution of the recycling network(1st → 2nd recycling stage). This observation can probably be explained by the additional costs being too high compared to the additional revenue. However, despite not using the second recycling step, the cost-optimised recycling network includes high-quality recycling options with the production of AAC, lightweight aggregate concrete, light mortar, and shuttering blocks which are less cost-intense.

The overall costs of the network and the different cost categories are presented in Fig. 2. Transport costs (blue) and fixed costs (grey) influence total costs the most. They increase steadily over time as expected pd-AAC amounts rise. The share of transport costs in total costs is consistently around 50%, while the share of fixed costs is about 40%. The variable costs (orange) also rise continuously. However, they are significantly lower than fixed costs and transport costs since the relatively high labour costs are attributed to fixed costs, not variable costs. Opening costs (purple) do not incur in most years and are only significantly high initially, as three large recycling plants are opened in 2023. Finally, pd-AAC is hardly landfilled in the optimised network, leading to almost no landfilling costs (red). The revenues (green) offset around 20% of all costs.

Total costs of the pd-AAC recycling network are around 50 M€/a in the first years, ignoring the non-recurring opening costs in 2023 (around 20 M€). The total costs increase significantly in the future, primarily due to strongly rising pd-AAC volumes. Additionally, the inflation considered in the model increases all costs. Thus, the total costs are expected to rise to around 70 M€/a in the early 2030s, potentially reaching more than 100 M€/a in the 2040s (Fig. 3). However, the total costs of the cost-minimised recycling network are significantly lower than the costs of the

Table 5
Explanation how parameters are included in the sensitivity analysis and why some are not.

Parameter	Considered?	Explanation
variable costs	yes, ±10%	variable costs for both recycling steps are considered at the same time
fixed costs	yes, ±10%	fixed costs for both recycling steps are considered at the same time
opening costs	yes, ±10%	opening costs for both recycling steps are considered at the same time
transport costs	yes, ±10%	transport costs for all routes and all commodities are considered
landfilling costs	yes, ±10%	landfilling costs for all regions are considered
revenues	yes, ±10%	revenues for purified pd-AAC and RC-BCC are considered at the same time
supply	yes, ±10%	the supply in all regions is considered
demand	yes, ±10%	demand from AAC plants and decentralised demand are considered at the same time
inflation rate	yes, ±10%	inflation rates for all cost categories are considered
discount rate	yes, ±10%	discount rate is considered for all costs and revenues at the same time
transport distance	no	transport distances are not subject to uncertainties as precise route-specific data is used
efficiency	no	the impact of changes in efficiency on variable costs can only be determined in a detailed cost analysis
capacity	no	capacities are not subject to uncertainties as opening and fixed costs are calculated for given plant capacities
maximum landfill amount	no	the maximum landfill amount is irrelevant for the optimised network as landfilling is widely avoided and equation (3) is not binding

status quo of pd-AAC treatment, which is assumed to be $^{2}/_{3}$ landfilling and $^{1}/_{3}$ recovery (e.g. backfilling) in Germany (Bauhaus University Weimar, 2010; UBA, 2019; Aycil et al., 2023). Even assuming that recovery does not cause any costs, the landfilling costs are around 55–70 M€/a in the first years. These costs are expected to increase immensely due to the increasing pd-AAC volumes and the exceptionally high inflation rate of landfilling costs (Fig. 3). Thus, status quo pd-AAC treatment without recycling is expected to cause costs of 120 M€/a in 2030, 260 M€/a in 2040 and 480 M€/a in 2050, summing up to around 6800 M€ until 2050. In contrast, the cost-optimised recycling network only causes costs of approximately 2200 M€. Thus, the savings potential when establishing pd-AAC recycling in an optimally designed recycling network sum up to 4600 M€ (68%) until 2050.

3.2. *Sensitivity analysis*

The results are subject to uncertainties, mainly of the input data. These are based on cost calculations, research, and assumptions, not field data. Therefore, the relative influence of different input variables on the results is determined in a sensitivity analysis (Table 5).

Variable, fixed, opening, transport, and landfilling costs, revenues, supply, demand, inflation, and discount rates are considered. These parameters are increased and decreased by 10% compared to their baseline scenario value. The associated change in the new cost-optimal network with its calculated total costs shows the model's sensitivity to this parameter. The variation of variable, fixed, and opening costs is simultaneously applied to the costs at both recycling steps (pd-AAC processing and RC-BCC production). Additionally, investigating the sensitivity of the inflation rate means all inflation rates are changed concurrently. Changing inflation rates of individual cost categories would have a similar effect as changing the costs themselves.

Results of the sensitivity analysis show that the total costs are most sensitive to changes in the supply (Fig. 4), as a changed supply directly affects transport, variable, fixed, and opening costs. Moreover, the largest recycling plants have already been built in the baseline scenario, so only small additional economies of scale occur with increased supply. Transport and fixed costs show high sensitivities according to their high share in total costs.

Variations of inflation and discount rates change the total costs by ±2.5-3-5%. These rates affect the total costs differently than the other examined parameters. The impacts of a change only become noticeable over time but are much more significant towards the end of the time horizon as inflation and discount rates have an exponential influence on total costs. Thus, the overall sensitivity considering all periods is significant but not as high as for fixed costs and supply. Revenues show an expectable sensitivity equal to their contribution to total costs. A variation of variable costs, opening costs, landfilling costs, or demand does not change the total costs significantly. Besides, a 10% change in demand does not influence the optimal solution at all.

Some model parameters are not included in the sensitivity analysis. First, changing the distance is irrelevant as road distances without uncertainty are used for most transports (except for transports to AAC plants). Moreover, changed distances would have the same impact as changing the transport costs (which is analysed) since the distance is only used in multiplications with transport costs (see equation (1)). The efficiency is also not included in the sensitivity analysis. An adjusted efficiency changes variable costs since more or less material is sorted out. Additionally, the revenues change as the amount of valuable output varies. However, variable costs and revenues are already considered in the sensitivity analysis. Moreover, the exact impact of a change in efficiency on variable costs can only be determined in a detailed cost analysis (as many different aspects like waste treatment costs and amount of valuable output change) and not within a recycling network modelling. Additionally, the opening and fixed costs are calculated for given plant capacities. Thus, the capacities are not subject to

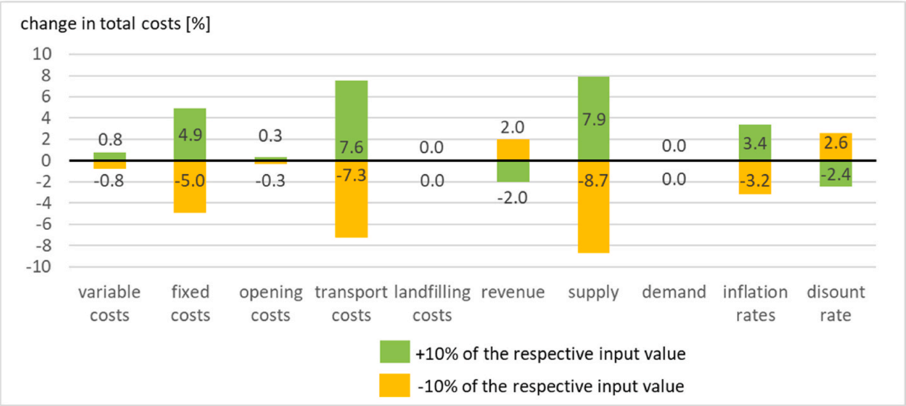

Fig. 4. Results of the sensitivity analysis of total costs, including all cost parameters, revenue, supply, demand, and inflation/discount rate.

Table 6
Overview of all scenarios considered in the scenario analysis, including the parameters change compared to the baseline scenario (scenario 0).

	variable/fixed/ opening costs 1st recycling step	variable/fixed/ opening costs 2nd recycling step	revenue purified pd-AAC	revenue RC-BCC	demand RC-BCC	landfilling costs
scenario 1	–	−3 %/a	–	+50%	+50%	–
scenario 2	–	−6 %/a	–	+100%	+100%	–
scenario 3	+50%	+50%	−50%	−50%	–	65 €/t

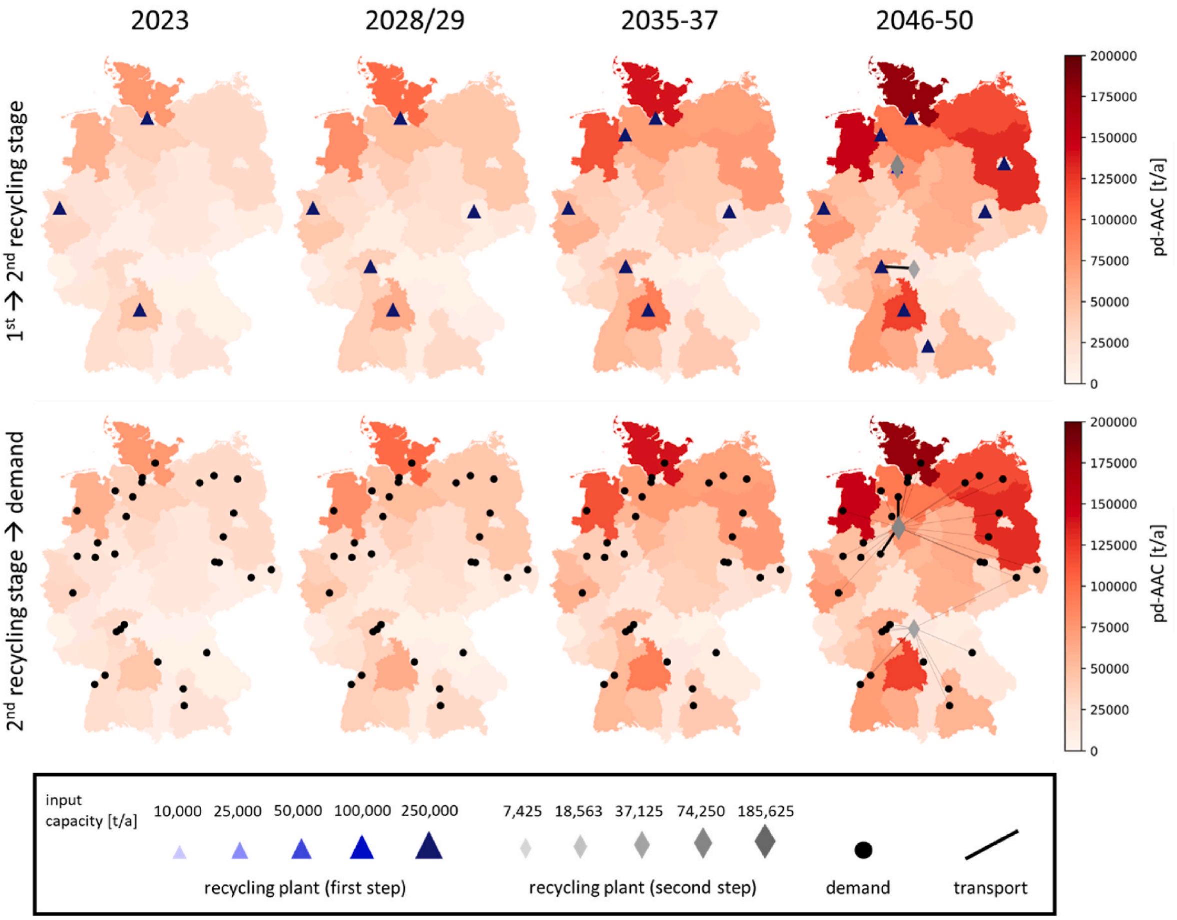

Fig. 5. Optimal German pd-AAC recycling network in scenario 2 (heavy support for RC-BCC production) for the periods 2023, 2028/29, 2035–37, and 2046–50.

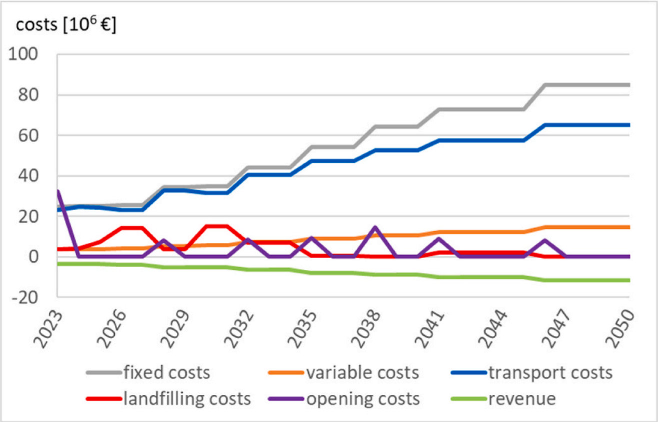

Fig. 6. Development of variable, fixed, opening, transport, and landfilling costs as well as revenues in the optimised recycling network until 2050 in scenario 3.

uncertainties. Finally, the maximum landfill amount is irrelevant for the optimised network as landfilling is widely avoided, and equation (3) is not binding. Therefore, a 10% change in this parameter would not lead to any change in the result.

3.3. Scenario analysis

Three scenarios were considered to investigate how the optimal network structure behaves under changed framework conditions (Table 6).

In scenario 1, the RC-BCC production is supported (+50% demand, +50% revenue, −3 %/a variable/fixed/opening costs). However, the optimal solution of this scenario equals that of the baseline scenario. No RC-BCC plants were opened, and the total costs of the network remain unchanged.

Therefore, the support is doubled in scenario 2 (+100% demand, +100% revenue, −6 %/a variable/fixed/opening costs). In this scenario, RC-BCC plants are opened, but only from 2040 onwards due to the decreasing costs over time (Fig. 5). In the period 2046–2050, even two RC-BCC plants are used, one with an input capacity of 37,125 t/a and one with 74,250 t/a. The network structure in the first stage remains unchanged compared to the baseline scenario. The additional RC-BCC plants increase variable, fixed, and opening costs. However, the revenues also increase significantly since the RC-BCC is sold. Thus, the total costs are reduced in the entire time horizon from 2.221 M€ to 2.141 M€ (−3.6%). Overall, the RC-BCC production is only used when extensive support and high technological progress are available. This implication results from the (currently) very high costs of RC-BCC production. Energy costs, in particular, have a significant impact due to the high energy intensity of the process and drive up costs - especially when heating with electricity, which is desirable from an environmental perspective. Furthermore, an investment is required for an RC-BCC plant that is considerably higher than for first step recycling plant.

Scenario 3 represents a stress scenario for recycling (variable/fixed/opening costs +50%, revenues −50%, landfilling costs reduced to 65 €/t). In this scenario, landfilling is used more than in the baseline scenario, but the limit of 30% is still not reached in any period and the recycling rate remains high at 96.9% (99.9% in the baseline scenario). The total costs increase considerably from around 2200 M€ to approximately 3100 M€ due to the significantly higher recycling costs (Fig. 6). In addition, revenues are lower and total landfilling costs are higher as more pd-AAC is landfilled. However, the recycling network structure remains mostly unchanged compared to the baseline scenario. Opening a new plant is sometimes postponed to save the fixed costs of one period. Additionally, the location of a few plants changes slightly. However, the largest capacities are still preferred, and up to nine plants are built to recycle most of the pd-AAC. Overall, recycling remains the preferred option for pd-AAC treatment even when facing unfavourable framework conditions.

4. Discussion and limitations

The model results depend decisively on the used input data. The input data are primarily based on calculations from previous studies (Steins et al., 2021, 2023a; Persyn et al., 2022) and are supplemented by assumptions. Field data is not yet available for pd-AAC recycling. Furthermore, it should be considered that inflation rates can fluctuate strongly over such a long horizon and that a change has an exponential effect on the costs of subsequent periods. All in all, the input data are associated with relevant uncertainties that can impact the result. Therefore, the actuality of the input data, including recycling costs, transport distance, and demands, should be reviewed and updated as the establishment of pd-AAC recycling progresses. However, the sensitivity and scenario analyses show that no fundamental change in the result is expected even with significantly changed framework conditions. In particular, recycling will still be preferred to landfilling, even with considerably higher costs. Thus, the current result and the associated implications can be considered relatively robust.

This study's modelling focuses on cost minimisation. Ecological criteria are not considered but are of great importance, especially in the case of modelling and optimising a recycling process. If, for example, greenhouse gas (GHG) emissions are minimised instead of costs, the optimal solution could change significantly. Transports cause significant GHG emissions, while many aspects of the fixed costs (operating labour, interest payments, insurance, overhead costs, general expenses) are not associated with GHG emissions. Thus, GHG minimisation of a pd-AAC recycling network could lead to the opening of more and smaller plants to reduce transport impacts without considerably higher fixed impacts. Consequently, the structure of the network would change towards more decentralised recycling.

Additionally, RC-BCC production is more favourable concerning GHG emissions than in terms of costs. If renewable energy is used to produce the RC-BCC, no other recycling option can achieve similarly high GHG savings of up to 0.77 kg CO_2-Eq/kg pd-AAC compared to landfilling (Stemmermann et al., 2024). Therefore, it can be expected that RC-BCC production will be used much more in the GHG-minimal recycling network than in the cost-minimal one. An expansion of the still comparatively low demand for RC-BCC in this study (e.g. by inclusions other concrete production plants) would also be beneficial to exploit the full potential of this recycling option. An optimisation of the network according to ecological criteria should be researched to confirm these reasonings. Moreover, a multi-criteria objective function may be appropriate since practical decisions often need to consider costs and sustainability aspects, including GHG emissions, at the same time. This way, the different optimisation aspects can be balanced, and individual weights can be used depending on the decision maker's preferences.

The decentralised demand is calculated from maximum input material substitution with pd-AAC in the entire production of the light mortar, lightweight aggregate concrete, and shuttering block production. This strong assumption leads to a demand of 1,800,000 t/a pd-AAC powder and 600,000 t/a pd-AAC granulate, which might be considerably less in practice. However, there are further alternatives besides these three recycling options, including using the pd-AAC as supplementary material in concrete or for producing floor screed. While these alternatives are ecologically less attractive than the previously mentioned recycling options (Volk et al., 2023), they would nevertheless be available for a cost-minimising recycling network. Therefore, the assumption of a high decentralised demand is reasonable.

The pd-AAC supply must always be treated in the same period it arises, as storage between periods is not allowed. In practice, storage is only conceivable in the short term due to the large quantities to be treated. It is also not practicable to leave the pd-AAC at the demolition site. Only temporary storage at a landfill and processing in a subsequent period would be conceivable. However, this alternative is not modelled due to additional landfill management efforts and transport costs.

Impurities in pd-AAC can be problematic. In particular, plastics, timber, and glass can affect the quality and performance of the recycling products and have to be sorted out prior to recycling. Moreover, varying chemical compositions of the pd-AAC primarily influence the RC-BCC production where the lime input has to be adapted as a consequence. However, the modelled processes and costs of the recycling process include intensive purifying by air separation and near-infrared sorting. The literature research on the different recycling options showed that sufficient qualities can be achieved. However, establishing the recycling options on a large scale with high throughputs still needs to prove a successful handling of impurities.

5. Conclusion

This paper developed a new capacitated, multi-period, and multi-stage model for pd-AAC recycling network optimisation in Germany. The cost-minimised recycling network prefers large recycling plants to use economies of scale in the pd-AAC treatment. However, RC-BCC production plants (second recycling stage) are not opened due to high costs. Instead, pd-AAC powder and granulate are directly used for different recycling purposes. With increasing pd-AAC volumes in the future, the network opens new recycling plants to treat all pd-AAC. Landfilling is mainly avoided. An increasing number of recycling plants leads to reduced transport distances in the future, almost reaching 100 km on average. The transport costs account for around 50% of the total costs, while fixed costs sum up to about 40%, and revenues offset nearly 20% of the total costs. Variable, opening, and landfilling costs are pretty low. Pd-AAC recycling costs for the whole period until 2050 sum up to 2200 M€ and, thus, have a significant savings potential compared to the status quo, which would cause costs of 6800 M€.

Future research can use field data to optimise the model when pd-AAC recycling is established, and robust data is available. Furthermore, the regional focus can be expanded to optimise, for example, a European or global pd-AAC recycling network. Due to differences in demand or costs, international transports and storage could be beneficial and should be included in future work. The mathematical modelling is formulated in such a general way that international transports can be depicted when the data is adapted. However, the storage would have to be added to the model. Additionally, the model can be transferred to other use cases. Generally, all similar recycling processes are suitable for model transfer, especially those involving construction materials. With its multi-period formulation, the model can deliver the highest added value in situations with increasing (or decreasing) future supply and changing costs. Moreover, future research could investigate stochastic modelling of similar settings to consider uncertainties directly in the model.

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CRediT authorship contribution statement

Justus J. Steins: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Manuel Ruck:** Writing – review & editing, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **Rebekka Volk:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Investigation, Funding acquisition. **Frank Schultmann:** Writing – review & editing, Supervision, Resources, Project administration.

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.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2024.143580.

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