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The Urban-Industrial metabolism: contribution of waste recycling to the circular economy objectives within the construction sector

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The Urban-Industrial metabolism: contribution of waste recycling to the circular economy objectives within the construction sector

A Komkova[1*], G Habert[1]

[1] Chair of Sustainable Construction, ETH Zurich, 8093 Zurich, Switzerland

*komkova@ibi.baug.ethz.ch

Abstract. The construction and buildings sector is facing an urgent need to reduce GHG emissions and ensure efficient resource utilization while minimizing waste in order to comply with climate change policies and circular economy initiatives. Alkali-activated materials, as an alternative binder to CO_2-intensive conventional cement, show potential in utilizing waste streams from urban environments in their production technology, thereby reducing CO_2 emissions. This study examines two waste streams generated in Switzerland: incineration ashes from municipal solid waste treatment facilities and mineral wool waste from building stock renovation and demolition activities. Geospatial analysis is combined with LCA methods to assess optimal scenarios for waste recycling, utilizing a multi-objective optimization framework based on mixed integer linear programming. The objectives are to minimize the environmental impacts and costs associated with alternative supply chain networks, thereby identifying optimal locations for waste pre-treatment and concrete manufacturing. The proposed scenarios demonstrate reductions of 56% in global warming potential and 29% in costs when compared to the business-as-usual scenario of conventional cement concrete use and waste landfilling. Results show that recycling of urban waste streams in alternative concrete can reduce GHG emissions of industry and heavy transportation sectors by 0.46 mt. CO_2 eq. by year 2030, equivalent to 23% and 4% of the Swiss carbon budget reduction targets for these sectors.

1. Introduction

The construction and buildings sector is responsible for 39% of global GHG emissions, with 10% considered to be embodied emissions [1]. In attempt to minimize these emissions, alternative to CO_2-intensive cement materials with similar mechanical properties and durability aspects are being researched. Another challenge faced by the construction and buildings sector is associated with recycling of waste materials. In Europe, the construction industry generates more than 35% of total waste [2]. During the renovation and demolition of buildings, mineral wool (MW), namely rock wool and glass wool used as insulation materials, are collected and landfilled in many European countries, including Switzerland. Another waste stream within the urban settings is generated from the incineration of municipal solid waste and sewage sludge. Besides energy recovery, the incineration process generates bottom ashes (BAs) that constitute nearly 20% of the input waste by mass, and are currently landfilled in Switzerland. However, recent research has shown that ashes can undergo valuable metal and mineral recovery and later can be used as precursors in alkali-activated materials (AAMs) [3]. AAMs are alternative binders to conventional cement with lower CO_2 emissions [4], which production technology is based on the activation of high alumina-silica precursors with soluble alkaline solutions [5]. Both waste streams examined in this study can serve as alternative precursors in AAM production and are expected to have relatively stable supply in the future. The application of mineral wool as insulation material in the buildings has gained popularity since the 1980s. Considering the service life time of mineral wool as insulation material of 40 years, as well as generic service life of a building of 60 years, an increasing amount of mineral wool waste is expected to become available in the upcoming decades.

We aim to identify optimal supply chain network scenarios for recycling different types of urban waste streams in alternative construction materials, compared to a business-as-usual production of cement concrete and waste landfilling. Furthermore, we aim to quantify potential contributions towards national environmental targets.

2. Methods

Figure 1 illustrates the potential urban-industrial metabolism framework proposed in this study. We analyze the baseline scenario where municipal solid waste bottom ashes and mineral wool waste are landfilled, and cement is used as a binder for conventional concrete production. The baseline scenario is further compared with alternative scenarios where both waste streams are recycled in alternative concrete production. We analyze cases where waste recycling (pre-treatment) can therefore be performed directly at the concrete plants, as well as at a centralized pretreatment plant with subsequent transportation of treated waste to the concrete plants. To identify optimal scenarios for urban waste recycling in alternative concrete, we combine geographic information systems (GIS) with life cycle assessment (LCA), followed by the set-up of multi-objective linear optimization model. Detailed methodological framework is presented in figure 2.

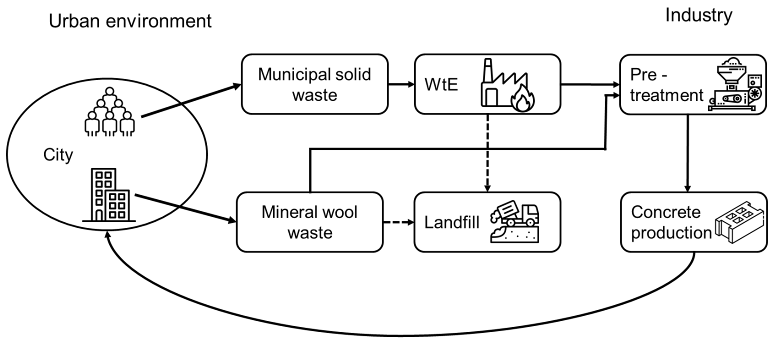

Figure 1. Proposed waste recycling within the Urban-Industrial metabolism framework.

2.1. Geospatial analysis and LCA

To identify the shortest transportation distances between the actors in supply networks, we used origin-destination matrixes in QGIS. While quantities and locations of ashes are known from the annual reports of incineration plants, to identify the locations and quantities of annually generated mineral wool waste, we applied bottom-up building stock model using the swissBUILDINGS3D 2.0 geospatial data on building geometries, merged with data from the Federal Register of Buildings and Dwellings (GWR). Buildings were arranged into cohorts, where building typology and year of construction/renovation determine the amount of MW in each building element, with assumptions described in [6]. Furthermore, we selected 12 potential locations for centralized waste pretreatment, among which the optimal location was later identified in the optimization model.

The LCA methodology was then used to quantify the impacts of transportation, as well as of manufacturing the concrete mixes with cement as a binder (baseline scenario), and concrete with waste used as precursor in AAMs (alternative scenarios) [3]. The functional unit has been defined as the total amount of concrete produced in Switzerland using available waste materials as a binder, compared to conventional cement concrete with equivalent mechanical properties. The CO_2 eq. emissions associated with waste transportation, pretreatment, and manufacturing of concretes were estimated using the IPCC 2013 method within the Ecoinvent v3.6. database using SimaPro software.

The supply chain networks have previously been analyzed using mixed integer linear programming (MILP) with two individual objectives, differentiating between decentralized and centralized waste recycling scenarios [6]. In the current study, we apply a multi-objective linear optimization model, focusing on minimization of environmental impacts and costs, where decentralized and centralized recycling can be selected at the same time. Here, we construct a Pareto frontier using a set of identified optimal solutions, showing the trade-offs between costs and CO_2 emissions. Finally, we discuss the implications of meeting the demand for conventional cement concrete with supply of waste-based construction materials at a regional/country level and examine the potential contribution of proposed urban-industrial metabolism scenarios towards the Swiss carbon budget emission reduction targets.

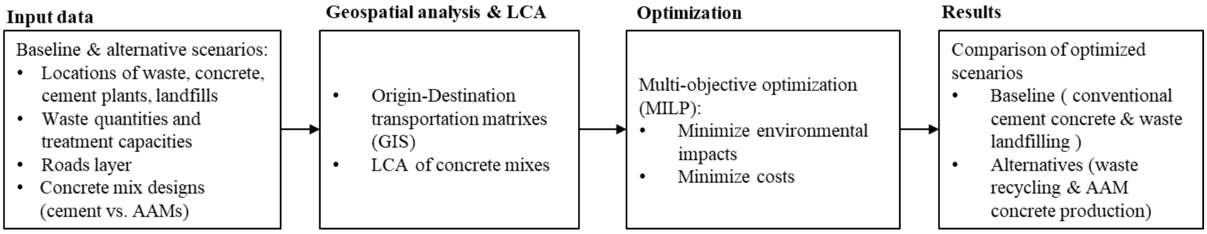

Figure 2. Methodological framework.

2.2. *Multi-objective optimization framework*

The multi-objective optimization model has been set up in GAMS. Two objective functions aim to minimize environmental impacts E (1) and costs C (2) associated with transportation networks, waste recycling and concrete manufacturing. The weighted sum method has been used to assign weights to each objective function in order to create a set of Pareto optimal solutions.

The optimization model for waste recycling includes options of transporting waste from waste source i directly to concrete plants j, as well as to centralized recycling plants k, with subsequent transportation to concrete plants. The transportation distances are denoted as d and quantities of materials as q, with total waste generated q_w. In this model, m denotes vector of other AAM binder mix constituents, including activators and co-precursors.

The emission factor f and cost factor c of transportation t are fixed and equal to 0.16 kg CO_2 eq. and 0.1 CHF per tonne and km travelled. As both waste streams undergo pretreatment, including milling, grinding and sieving, the environmental impacts associated with electricity consumption for these processes e_w are expressed in kwh, while emission and cost factors are fixed, being f_w equal to 0.12 kg CO_2 eq. per kwh and c_w equal to 0.16 CHF per kwh, respectively. While mineral wool waste requires additional grinding machinery acquisition, the investments are made by the concrete producers or the centralized recycling plants, implying lower marginal costs for the latter.

The optimization problem is subject to constraints (3)-(7) on the capacity b of concrete plants and pre-treatment plants, where ∂_k is a binary variable indicating whether the recycling plant is operating or not. Furthermore, we assume that all waste produced at a source location a_i, will be fully utilized.

The two-objective objective optimization problem is defined as follows:

$$\begin{aligned} min\, E = {} & \textstyle\sum_i \sum_j d_{i,j} * q_{i,j} * f_t + \sum_i \sum_k d_{i,k} * q_{i,k} * f_t + \sum_k \sum_j d_{k,j} * q_{k,j} * f_t \\ & + \textstyle\sum e_w * q_w * f_w + \sum q_m * f_m \end{aligned} \tag{1}$$

$$\begin{aligned} min\, C = {} & \textstyle\sum_i \sum_j d_{i,j} * q_{i,j} * c_t + \sum_i \sum_k d_{i,k} * q_{i,k} * c_t + \sum_k \sum_j d_{k,j} * q_{k,j} * c_t \\ & + \textstyle\sum e_w * q_w * c_w + \sum q_m * c_m \end{aligned} \tag{2}$$

s.t. $$\textstyle\sum_j q_{i,j} + \sum_k q_{i,k} = a_i \tag{3}$$

$$\textstyle\sum_i q_{i,j} + \sum_k q_{k,j} \leq b_j \tag{4}$$

$$\textstyle\sum_i q_{i,k} \leq b_k * \partial_k \tag{5}$$

$$\textstyle\sum_j q_{k,j} \geq b_k * \partial_k \tag{6}$$

$$\textstyle\sum_{i,k} q_{i,k} = \sum_{k,j} q_{k,j} \tag{7}$$

3. Results

In this chapter are presented results of the multi-objective optimization and compared with the baseline scenario. We examine the contribution of the identified environmental benefits associated with proposed urban-industrial metabolism towards the Swiss climate strategy, specifically towards carbon budget reduction targets.

3.1. Optimal scenarios for waste recycling

In total, 812,000 tonnes of BAs were produced in year 2020, and nearly 70,000 tonnes of MW waste will be generated in year 2030, together allowing to produce nearly 4.5 mil. m^3 of AAM concrete. The sets of Pareto optimum solutions, where environmental impacts and costs were minimized for BAs and for MW waste are presented in Figure 3. The optimized scenario 1 (S1) of BAs (figure 3a) is associated with the lowest GWP, being 324,563 tonnes CO_2 eq. per year, that is achieved at a cost of 201 mil. CHF. In this case, BAs are transported from municipal solid waste incinerators (MSWI) directly to concrete plants for pretreatment and further manufacturing of alternative concrete. S2 represents a point where total costs are reduced by 3%, while emissions increase by 0.05%. Here, a small fraction of BAs waste is transported to centralized recycling plant located in canton Zurich with subsequent distribution to concrete plants (Figure 5). S1 of MW (figure 3b) corresponds to 32,604 tonnes CO_2 eq. and 21.2 mil. CHF, where all waste are transported to concrete plants for direct pretreatment, leading to highest investments in pretreatment machinery. S2, on the other hand, results in 4.5% lower total costs and 2.9 % higher GWP, where MW is transported directly to centralized pretreatment plant in canton Zurich, with subsequent distribution to neighboring concrete plants. It should be noted that waste transportation together with waste recycling constitute only up to 12% of the total AAM costs and less than 5% of total GWP, where the main impacts of AAMs are attributable to alkaline activators and co-precursors.

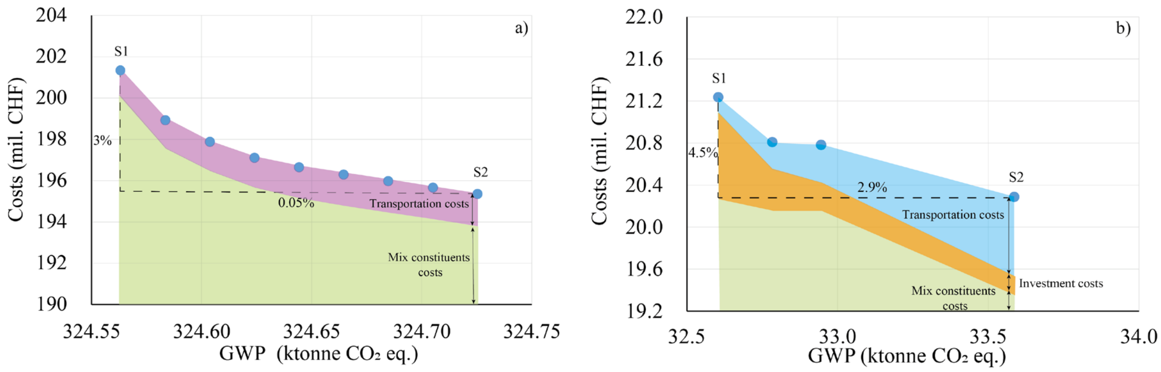

Figure 3. Pareto optimal solutions based on the multi-objective optimization of GWP and costs of supply chain networks for BAs (a) and MW (b).

The baseline scenario where both waste streams are landfilled and 1.48 mil. tonnes of conventional cement are used for concrete production, is associated with 0.82 mil. tonne CO_2 eq. and 0.3 mil. CHF. The landfill fee is assumed to be 150 CHF/t and costs of cement are 100 CHF/t. Figure 4 illustrates mineral wool generation in Switzerland at a regional (canton) level. The quantities of MW were identified at the individual building level and later aggregated into 5 km grids, which were used as sourcing sites for transportation optimization. Mineral wool is assumed to be sorted manually from the rest of C&D waste and transported in 16-32 t trucks, with filling capacity of 50%.

By utilizing both BAs and MW waste as precursors in alternative concrete, the optimal scenarios would reduce GHG emissions by 56% and costs by 29% compared to the baseline scenario. Furthermore, figure 5 shows that the use of both waste streams in concrete production would minimize dependency on cement, implying that individual production capacities of cement plants can be decreased by 8% to 66%, depending on the plant.

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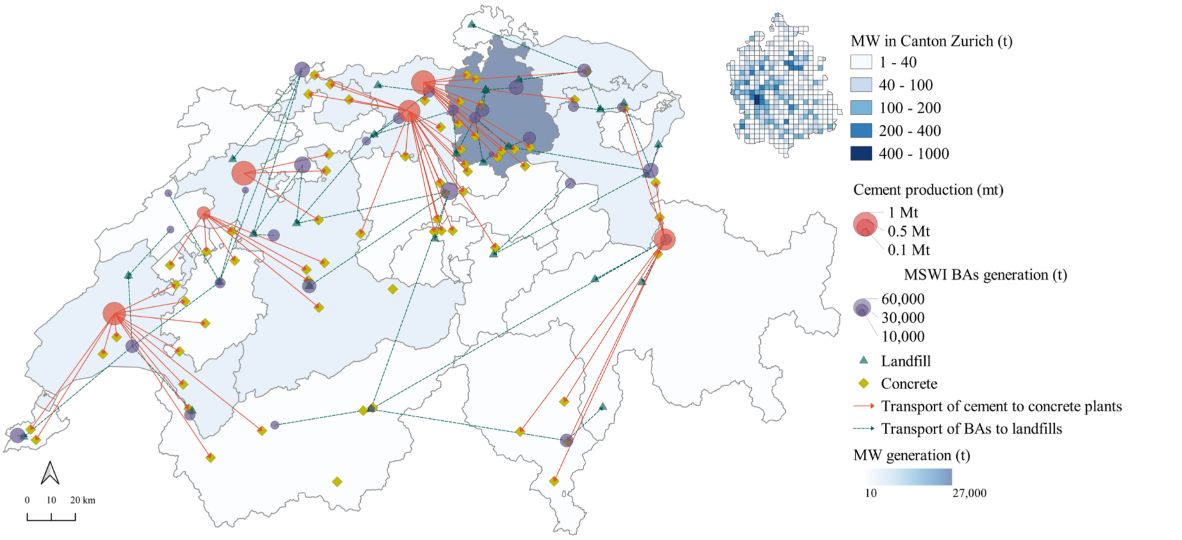

Figure 4. Baseline scenario. Waste is transported to landfills and cement is used in concrete production.

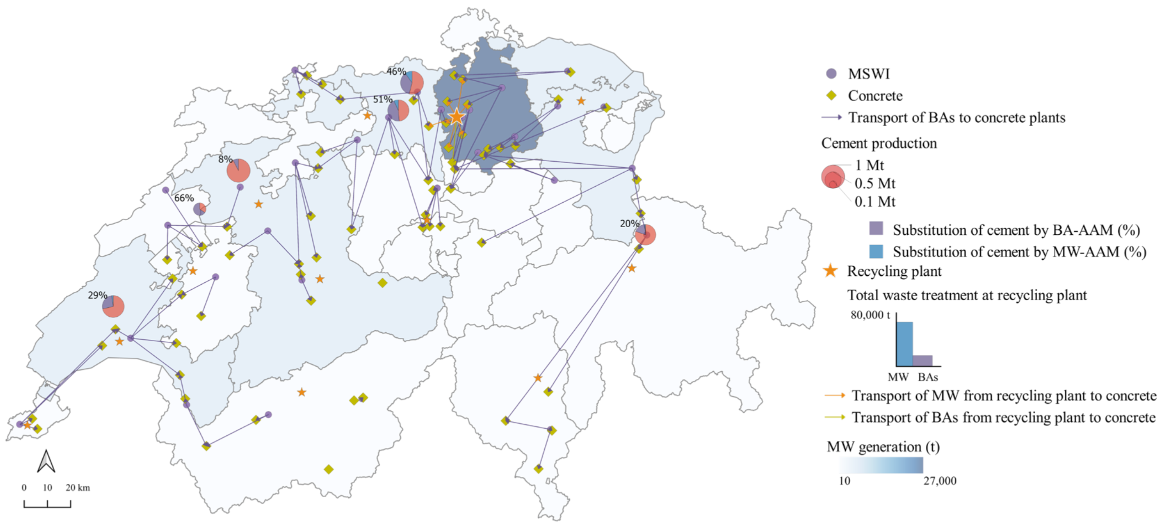

Figure 5. Optimized scenario S2. All MW waste is transported to the optimal centralized recycling plant with subsequent transportation to concrete plants for AAM concrete production. The pie charts denote cement supply share (%) that can potentially be substituted by using both waste streams.

3.2. Contribution to circular economy targets

The circular economy aims to ensure the efficient use of resources by minimizing waste and environmental degradation. The open loop recycling of MSWI ashes and mineral insulation waste in alternative concrete production can divert nearly 0.9 mil. tonnes of waste from landfills in Switzerland. Furthermore, the valorization of waste in alternative to cement binder can help to achieve annual GHG reduction targets set within the Swiss carbon budget [7]. Figure 6 illustrates that production of AAMs as an alternative to cement-based construction materials can contribute 23% towards the GHG reduction target of the Swiss industry by the year 2030. Here, the industry GHG emissions are based on energy consumption of all industry and industrial processes [7], where cement sector alone contributing 2.41mt CO_2 or 31% to the industry's carbon budget in 2020 [8]. Furthermore, the optimization of transportation networks implies a 4% contribution towards the GHG reduction targets of the transportation sector, specifically of heavy trucks. The use of alternative construction materials can also contribute towards reduction targets of carbon budget defined for the embodied emissions of the Swiss building stock [9].

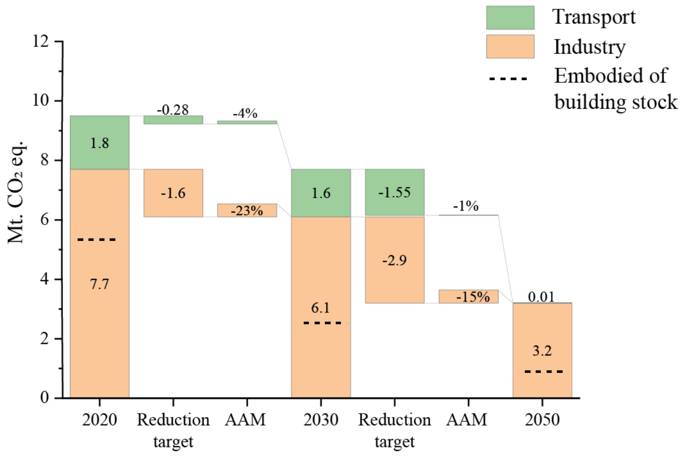

Figure 6. Contribution of AAMs to the carbon budget reduction targets.

4. Conclusions

The proposed methodology allows to identify optimal supply chain network designs for the recycling of urban waste streams in alternative concrete. Results show that due to economies of scale, centralized recycling is more cost-effective for mineral wool, with small fraction of ashes also being transported to the same optimal recycling plant, while GHG emissions are minimized within the direct symbiosis between waste generation sites and concrete producers. Furthermore, the use of available waste can potentially substitute current annual demand for cement by nearly 30%. Recycling of urban waste streams can contribute 27% towards Swiss carbon budget reduction target of examined sectors by 2030. The results of this study can provide indications to policy-makers on open loop recycling strategies within circular economy settings and nudge the establishment of new urban-industrial symbioses.

Acknowledgments

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References

[1] United Nations 2021 Global Status report for Buildings and Construction 2021: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector *United Nations Environ. Program.*

[2] European Commission 2020 *Circular Economy Action Plan for a Cleaner and More Competitive Europe*

[3] Huang G, Ji Y, Li J, Hou Z and Jin C 2018 Use of slaked lime and Portland cement to improve the resistance of MSWI bottom ash-GBFS geopolymer concrete against carbonation *Constr. Build. Mater.* **166** 290–300

[4] Komkova A and Habert G 2023 Environmental impact assessment of alkali-activated materials: Examining impacts of variability in constituent production processes and transportation *Constr. Build. Mater.* **363** 129032

[5] Provis J L and van Deventer J S J 2014 *Alkali Activated Materials* vol 13 (Dordrecht: Springer Netherlands)

[6] Komkova A and Habert G 2023 Optimal supply chain networks for waste materials used in alkali-activated concrete fostering circular economy *Resour. Conserv. Recycl.* **193** 106949

[7] Swiss Federal Office of Energy 2021 *Energy Perspectives 2050+*

[8] Cemsuisse 2021 *Kennzahlen 2021*

[9] Priore Y D, Habert G and Jusselme T 2023 Exploring the gap between carbon-budget-compatible buildings and existing solutions – A Swiss case study *Energy Build.* **278** 112598