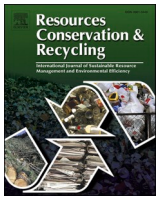
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Regional environmental-economic assessment of building materials to promote circular economy: comparison of three Swiss cantons

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ABSTRACT

National policies are increasingly being introduced worldwide to establish a sustainable economy that includes principles of a circular economy (CE). The construction industry is particularly in focus with such policies, as it is responsible for almost 50% of the worldwide annual resource consumption and waste production. The Implementation of CE policies remains with local actors, and it is important to better understand the regional context of this transition to support policy- and decision-makers.

This paper aims to contribute to the understanding of regional aspects of a CE and identify regional differences in the building materials industry. To identify these different boundary conditions, we formulate hypotheses, which we then test based on various regional case studies. We use an integrated assessment model to assess a regional industry in terms of environmental and economic indicators and combine Material-Flow-Analysis and Life-Cycle-Assessment using an input-output approach.

The results suggest that imports and exports, especially in smaller regions, can hinder the implementation of CE. CE policies should therefore be developed for functional areas rather than political boundaries to effectively manage material flows. This is also in the light of environmental impacts. Consideration of inter-industry linkages in the industry shows that policies should be formulated specifically for the construction processes, as they have the greatest leverage for policy-induced changes within the industry. The financial analysis shows that incentives should be created to minimize the extraction of primary raw materials and to avoid the landfilling of demolition and excavation material.

1. Introduction

Circular economy (CE), as a central aspect of a sustainable economy, is increasingly becoming the focus of national and local decision-makers (European Green Deal, 2020; OECD, 2020). A CE aims to increase material efficiency and minimize the consumption of resources and the associated environmental footprint (Ellen MacArthur Foundation, 2013; European Green Deal, 2020). For this reason, national policies are increasingly being introduced worldwide to establish a sustainable economy that includes principles of a CE (Domenech and Bahn-Walkowiak, 2019; Geng et al., 2009; Mhatre et al., 2021). In Switzerland, various policies and regulations have already been established to minimize resource consumption (BAFU, 2020; (ADWO, 2016)-). Furthermore, there are currently continuing efforts to promote the reuse of waste materials and to avoid the landfilling of potential raw materials (Bau und Umweltschutzdirektion Basel-Landschaft, 2020; UREK, 2020). The construction industry is particularly in focus with such policies, as it is responsible for almost 50% of the worldwide annual resource consumption and waste production (OECD, 2019).

In the construction industry, however, the transition to CE is a major challenge, as it involves a transition from a material-oriented to a service-oriented economy (Halme et al., 2007; Stahel, 2016). This contradicts traditional business models in the building materials industry where economic success is linked to material turnover (Spoerri et al., 2009). Additionally, the transition in the construction industry is highly affected by different barriers in politics and the economy (Diaz Lopez et al., 2019; B. C Guerra and Leite, 2021.; Hart et al., 2019). Since the majority of the construction industry is organized and operates regionally (Opitz, 2018; PWC, 2020), we will need to take a regional approach to promote this transition and to overcome the barriers (Domenech and Bahn-Walkowiak, 2019). This is especially important in a federal state like Switzerland as the constraints for policies are very different in every

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region, especially in terms of resource availability, spatial planning, or economic performance (Scarpellini et al., 2019).

For this reason, the Implementation of CE policies remains with local actors (European Green Deal, 2021; Oliveira et al., 2021; Smol et al., 2017; Virtanen et al., 2019), and it is important to better understand the regional context of this transition to support policy- and decision-makers (Dagilienė et al., 2021; Henrysson and Nuur, 2021). Various studies have already shown that incorrectly formulated policies can have negative effects (Geissdoerfer et al., 2017; Heshmati and Rashidghalam, 2021; Zink and Geyer, 2017). Some studies even show that in specific cases a CE can have greater environmental impacts (Blum et al., 2020; Bracquené et al., 2020) or even create a linear economy lock-in (Coenen et al., 2015; Greer et al., 2021). However, recent studies indicate that the regional aspects of a CE are still understudied (Dagilienė et al., 2021; Henrysson and Nuur, 2021; Scarpellini et al., 2019; Silvestri et al., 2020). The focus of most studies is on the industry or product level at a national scale (Sánchez Levoso et al., 2020). The authors are aware of only a few studies that take a regional approach. However, these usually look at an entire economy and focus on individual countries (Geng et al., 2009; Heshmati and Rashidghalam, 2021) or urban areas as drivers of the circular economy (Dagilienė et al., 2021; Harris et al., 2020). Few studies use the regional approach to study a circular economy with a focus on construction and demolition waste (CDW), waste management and recycling from an environmental perspective.(Lederer et al., 2020; Oliveira et al., 2021). This leaves a gap in the understanding of a regional industry from an environmental and economic point of view.

This paper aims to partly close this gap and contribute to the understanding of regional aspects of a CE and identify regional differences in the building materials industry and thus support decision- and policymakers. We assume that different regional boundary conditions lead to a different structure of a regional construction industry and, accordingly, to different constraints for a CE.

2. Hypotheses of a CE

To identify the different boundary conditions, we formulate the following hypotheses, which we then test based on various regional case studies:

i A region with few natural resources is more likely to establish a CE due to an increased material efficiency to minimize natural resources consumption (Ness and Xing, 2017; Robaina et al., 2020).
ii Regional differences in environmental impacts result from the outsourcing of the value chain to regions outside the considered region (Franzen and Mader, 2018; Harris et al., 2020, 2021)
iii Waste management is the key process in establishing a CE (Breure et al., 2018; Burlakovs et al., 2017; Lèbre et al., 2017; Mahpour, 2018; Menegaki and Damigos, 2018).
iv A CE leads to an economic benefit (Busu, 2019; Ellen MacArthur Foundation, 2013; Giama and Papadopoulos, 2020).

We want to find out whether these general hypotheses also apply to a regional analysis of a construction industry and whether we can use them to identify policy-relevant differences between the individual regions. The identification of these differences is a key aspect in the formulation of recommendations and policies that contribute to the development of a CE.

3. Methodology

3.1. Integrated assessment model

To test the different aspects of the mentioned hypotheses, we need an integrated assessment model (IAM), which can not only represent the environmental aspects of a CE, but also the economic aspects. However, recent reviews show that still too few models consider the economic dimension of a CE (Ghisellini et al., 2018; López Ruiz et al., 2020). For this purpose, an IAM needs to be developed, which is based on different complementary methods to cover the different levels (Crawford et al., 2018; Loiseau et al., 2012; Moriguchi and Hashimoto, 2016; Säynäjoki et al., 2017; Singh et al., 2021; Teh et al., 2017). Additionally, such a model also has the advantage that it addresses different stakeholders and thus improves communication among them (Di Maio et al., 2017; Mayer et al., 2018).

We developed an IAM to assess a regional industry in terms of environmental and economic indicators and combine Material-Flow-Analysis (MFA) and Life-Cycle-Assessment (LCA) using an input-output approach. We use comprehensive MFA-data of a Swiss database of regional material flows of mineral building materials (Rubli, 2020) in combination with environmental data from the LCA database ecoinvent (Wernet et al., 2016) by using an input-output approach (Meglin et al., 2021). From this combination, we create an environmental extended input-output analysis (EEIOA) that allows us to assess a regional building materials industry for mineral building materials, in our case sand, gravel, cement, concrete as well as excavation material and CDW (see supplementary material) The MFA data is first transferred to a physical input-output table (PIOT). This is made possible by the fact that the processes of the MFA correspond exactly to the sectors of the PIOT. Subsequently, the respective cells of the PIOT are multiplied by the respective prices and costs, resulting in a monetary IOT (MIOT). The environmental impacts are then calculated based on environmental coefficients, aggregated to the individual sub-sectors, by multiplying them with the respective sectors of the MIOT to obtain the impacts per monetary unit.

The system boundary corresponds to the industry and region under consideration. All necessary processes of the value chain of the building materials under study – sand, gravel, cement, concrete as well as excavation material and CDW – from raw material extraction to the EoL-Phase are included except for the use phase (see supplementary material). To include imports in the calculation, we use a Hinterland approach (Kytzia et al., 2004; Schiller et al., 2020). This “Hinterland” is not modeled in detail but provides the necessary imports directly connected to the value. This also allows us to consider the direct (scope 1) and indirect (scope 2 and 3) impacts caused by domestic and foreign production, respectively (WRI/WBCSD, 2011). However, our analysis does not consider the origin of imports and their transport distances. As functional unit, we chose the output of the building materials industry in the region of interest over a specified period.

3.2. Economic and environmental assessment

We economically assess the region based on revenue (income produced by the sector) and value-added (VA). These values can be extracted from the MIOT. The VA represents factor income generated by labor and capital on a regional scale. The economic basic data are obtained from national statistics of the federal government or the respective regional statistics of the canton. Furthermore, we have screened the price lists of about 170 building materials producers throughout Switzerland to calculate average prices (see supplementary material). These prices, as well as costs and internal price structures, were validated in interviews with various producers.

To calculate the environmental impacts, we set up an LCA-Inventory (LCI) based on market data sets (including average transports) of all processes in the value chain of the considered industry using the database ecoinvent (Wernet et al., 2016). For the construction and demolition processes, we use the German database Ökobaudat (BMI, 2020) because no data records are available in ecoinvent. For this purpose, we use the modules A5 (construction) and C1 (deconstruction) (EN 15978, 2012) of the data set "Concrete of compressive strength class C 30/37″ from 2018 (BMI, 2020). Thus, only the respective construction site processes are considered. The transports are considered according to the Swiss market datasets from Ecoinvent. We assume that the German

processes are similar to the Swiss processes, so that this data set provides comparable results. One difference is the energy mix of the two countries, since in Germany a large part of the energy is provided by coal-fired power plants, while in Switzerland hydropower and nuclear power are used. This means that the impact of energy is overestimated, but we assume the differences are negligible in the context of this study. In the case of construction processes, only those processes are included that are related to the mineral building materials considered. Other construction processes, e.g., building installations or interior fittings, are not included. Recycling processes of mixed and concrete granulate are accounted for according to (Tschümperlin et al. 2020) using datasets from ecoinvent. To include the emissions of alternative and secondary raw materials in cement production we use an economic allocation approach based on published average values (see supplementary material). Alternative fuels are allocated according to the average fuel mix of Swiss cement production. Electricity is accounted for in the respective production datasets of ecoinvent according to the average Swiss electricity mix. The detailed environmental impacts of the considered inputs can be found in the supplementary material.

We have chosen indicators that are used in most of the studies in the field and therefore allow a comparison with other studies (Bovea and Powell, 2016). To account for the emissions of processes and products we use the global warming potential (GWP) according to the IPCC 2013 over 100 years (Stocker, 2014) measured in kg CO_2 equivalents. The consumption of primary – renewable and non-renewable, energy is summarized according to the cumulative energy demand (CED) indicator (Frischknecht et al., 2015). Additionally, we use the end-point indicator of the ecological scarcity (Frischknecht and Büsser Knöpfel, 2013; Knoeri et al., 2013), which is used especially in the Swiss context of this study and is supposed to simplify communication with Swiss policymakers. It is a Single-value indicator measured in eco points that weighs environmental impacts (e.g., climate change, resource depletion) according to the ecological objectives of the respective country. Note, that values for ecological scarcity were not available for construction and demolition processes.

3.3. Assessment of regional circularity

There are a variety of indicators that describe the degree of circularity of a product or economy (Moraga et al., 2019; Saidani et al., 2019). However, most indicators are set at the micro-level (i.e., a product) and primarily measure aspects of material efficiency and waste prevention. We would like to calculate the degree of circularity of a separate regional industry. For this purpose, we use indicators that are generally applied in regional economics: Leontief multipliers calculated based on IOTs (Dubois, 2015; McLennan, 1995). They are derived from the physical or monetary Leontief inverse matrices ⟦(I-A_(P or M))⟧ ^ (-1) (Holub and Schnabl, 1994a, 1994b) of the input-output analysis and indicate how much additional turnover is generated by an additional output of a specific process/industry and thus which processes/industries are pivotal to economic activity in a region (Lenzen, 2003; Wen and Wang, 2019). We assume that in a regional circular economy, the linkages between the individual sectors will increase because linear value chains are replaced by circular value chains. This would result in higher Leontief-multipliers of the single processes but also in sum as direct and indirect effects between the respective sectors will increase as well. Three different multipliers can be calculated. The single value within the IOT describes the change in the output of the respective sector that is directly and indirectly required to produce one additional unit. The sum of the column values indicates what all sectors must, directly and indirectly, produce for the sector under consideration to produce one additional unit. The sum of the rows, on the other hand, indicates what the sector under consideration must produce in total for all sectors to be able to produce an additional unit for final demand. In the context of this study, we focus on the single values and the column sum. We use these values to quantitatively assess the linkages between sectors and identify industry hotspots.

4. Case study regions

To test the previously mentioned hypotheses, we need regions that have a significantly different structure in the industry under consideration. We have chosen the Swiss cantons of Argovia, Thurgovia, and Zurich. Despite their spatial proximity (see Fig. 1), these have in part very different characteristics (Table 1). The canton of Argovia has a high availability of raw materials and landfill volume on the one hand, but also a high construction activity with a high share of single-family homes in low-density areas. Furthermore, it is home to two of the six Swiss cement plants. The canton Zurich has even a higher construction activity, but mostly multiple family homes in high-density areas (cities and agglomeration). Zurich has high availability of raw materials but only restricted landfill volume. Thurgovia, with the lowest population of the three regions considered, has a low availability of raw material and landfill volume, as well as comparably low construction activity.

4.1. Data of material flows

The material flows originate from an institutionalized database of several cantons for gravel, excavated material, and demolition material (Rubli, 2020). We additionally use data provided by studies that examine the material flows of the Swiss building stock in detail (Gauch et al., 2016; F Guerra and Kast, 2015.; Rubli, 2016). In Fig. 2 you can see the fundamental distinctions between the regions. Argovia and Thurgovia, despite their lower construction investments, demand more building materials per capita than Zurich. This can be explained by the fact that in Zurich a high share of newly constructed buildings is a replacement of multi-story buildings and require fewer materials per tenant than new buildings on Greenfield sites, as in Argovia and Thurgovia, especially as the share of single-family detached homes is higher in Argovia and Thurgovia. This also correlates with the accruing excavated material. The high availability of resources and landfill volumes in Argovia is reflected in the numbers of gravel excavation and excavated material landfilled, which is the highest among these three regions. The high landfill volume also leads to the fact that Argovia imports more excavated material than the other regions. Zurich, on the other hand, exports excavated material because it has less free landfill volume. Most of the excavated material in Zurich is deposited in open gravel pits. In Switzerland, however, this is considered recycling or recultivation. In Thurgovia, on the other hand, most of the excavated material is disposed of in landfills or used as terrain adjustment. What is noticeable in all regions, however, is that an extremely small proportion of excavated material is washed (processed) to obtain gravel. Especially in Thurgovia, due to the low gravel extraction, you could expect that gravelly excavation material is processed to obtain gravel and to avoid imports. However, the figures show a contrary picture. This is probably due to the fact that the washing of gravel is currently still less profitable than the import and longer transports of primary gravel from neighboring regions. This already indicates that the first formulated hypothesis may not be valid. It is evident in all regions that CDW is largely recycled. Especially in Argovia, more CDW is processed than is generated in the region, which shows that Argovia plays an important role as an import region for the neighboring cantons (including Zurich). The data thus indicate that imports play a major role in the value chain for Argovia. Argovia serves as a hub for CDW, which is processed and then exported back to the surrounding regions, and for excavated material for the domestic recultivation of gravel pits. The high recycling rate can be explained on the one hand by scarce landfill volume, but also by successful regulation on the part of the authorities. In 2016, a regulation was introduced, which mandates the recycling of CDW as long as it is technically possible (ADWO, 2016)-. Unfortunately, recycled CDW is often used for low-quality applications, such as lean concrete (Galbenis and Tsimas, 2006; Hiltbrunner, 2017). However, this policy seems to be

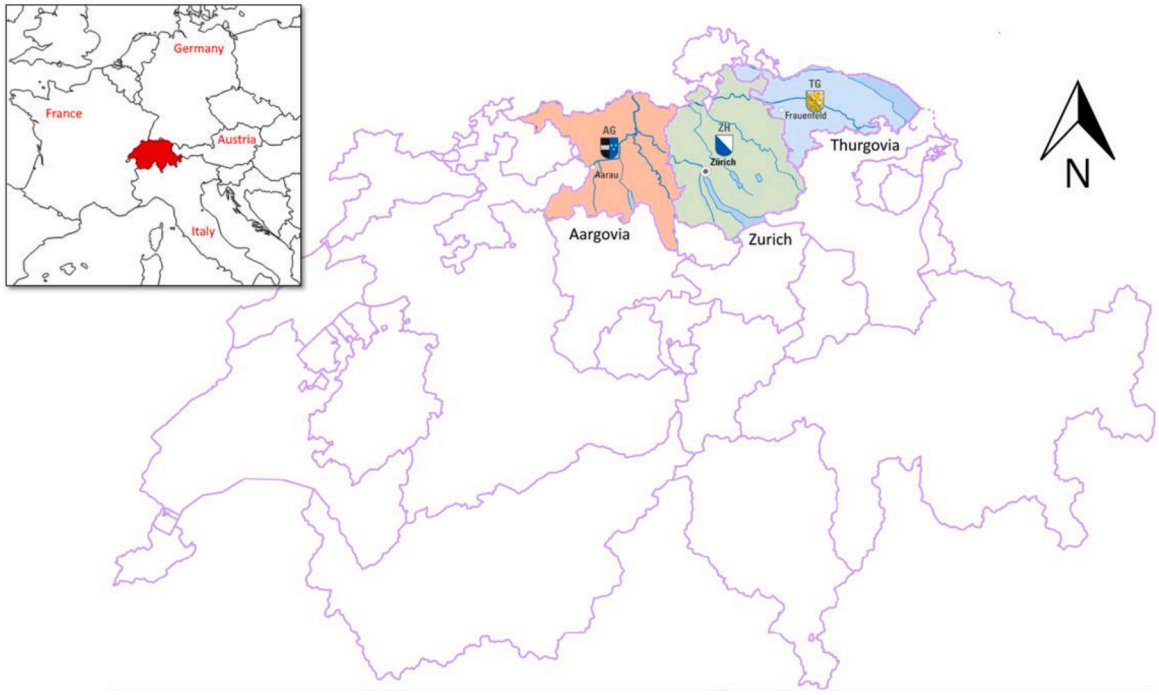


Fig. 1. Location of the regions under consideration in Switzerland.

Table 1
Characteristics of the regions under study; data from the federal statistics office (Bundesamt für Statistik BFS, 2020, 2021), KAR-Modell (Rubli, 2020) and cantonal statistics (Kiefer et al., 2020; Oetiker, 2020; Walser, 2019).

	Argovia	Zurich	Thurgovia
Population (2018)	678′200	1′521’000	276′500
Population density (capita per km^2)	486.1	915.8	320.3
Gravel extraction (m^3 solid, 2018)	2′427’080	3′015’995	376′000
Solid rock mining (m^3 solid, 2018)	912′857	–	–
Recultivation / landfilling with excavated material (m^3 solid, 2018)	3′174’025	2′635’829	804′000
Construction and demolition waste (CDW) landfilled (m^3 solid, 2018)	34′000	80′400	30′000
approved remaining gravel volume (million m^3 solid)	15.07	16.81	unknown
Construction investments (million CHF, 2018)	3351	8803	1799
Buildings	679	1615	201
Infrastructures			

successful and appears to confirm hypothesis (iii).

5. Results

5.1. General physical and monetary results

Based on the data from Section 4, it can already be estimated that the region of Argovia produces the most building materials. In fact, Argovia produces about 48 tons per capita per year, while about 7.8 tons of material per capita are imported. Thurgovia, as the region with the least resources among the three regions considered, produces about 37 tons per capita per year, while about 8.6 tons per capita are imported. Zurich, the region with the most inhabitants and the highest construction activity, produces about 26 tons per capita and imports about 4.4 tons per capita per year. However, the exports of the respective regions also play an important role. Argovia exports a large part of the cement produced (over 80%) to other Swiss regions, including to the two regions under consideration. This is important above all for the value added, but also for the environmental impact (see 5.3). The same applies to excavated material and CDW, which is exported from Zurich and Thurgovia to neighboring regions, e.g., to Argovia, for processing or landfilling. In Zurich about 30% and in Thurgovia just less than 20% of the excavated and demolition material accrued is exported. However, due to a lack of data, the exact destination of these exports is unknown. Nevertheless, this exchange of material between the regions must be considered when interpreting the results to avoid double counting and misinterpretation.

In Fig. 3 the resulting monetary results are visibly divided from the point of view of production and the point of view of demand. At first glance, we might assume, that the figures confirm the principle already mentioned in the building materials industry that more material turnover leads to greater economic success. In Argovia, more material is "moved" per capita than in the other regions considered, which leads to greater revenue (production value) per capita and correspondingly greater value-added per capita. The canton of Zurich generates the least revenue and value-added per capita since this region produces and demands the fewest building materials per capita. However, a closer look at the individual sectors reveals that the basic structure of the economy is similar in the regions considered, despite different boundary conditions. The revenue/value-added ratio is relatively similar with 2.86 in Thurgovia, 2.84 in Argovia, and 3.01 in Zurich. This indicates that the proportion of the regional value-added is relatively stable, no matter how much material is moved. This seems to be since in all three regions, the majority of building materials are produced from primary raw materials and the value-added there is similar. Based on the population, revenue and value-added are highest in Zurich and lowest in Thurgovia. The share of overall imports in material turnover is also relatively similar with 16% (Argovia and Zurich) and 23% (Thurgovia). Regarding imports and exports, however, a detailed look at the individual sectors reveals differences. A significant share of revenue is generated by cement exports and is only offset by a small share of imports (e.g., supplementary cementitious materials). In the other two regions, on the other hand, a large part of the production value is utilized by cement imports to the concrete plants. Exports play only a minor financial role in these two regions.

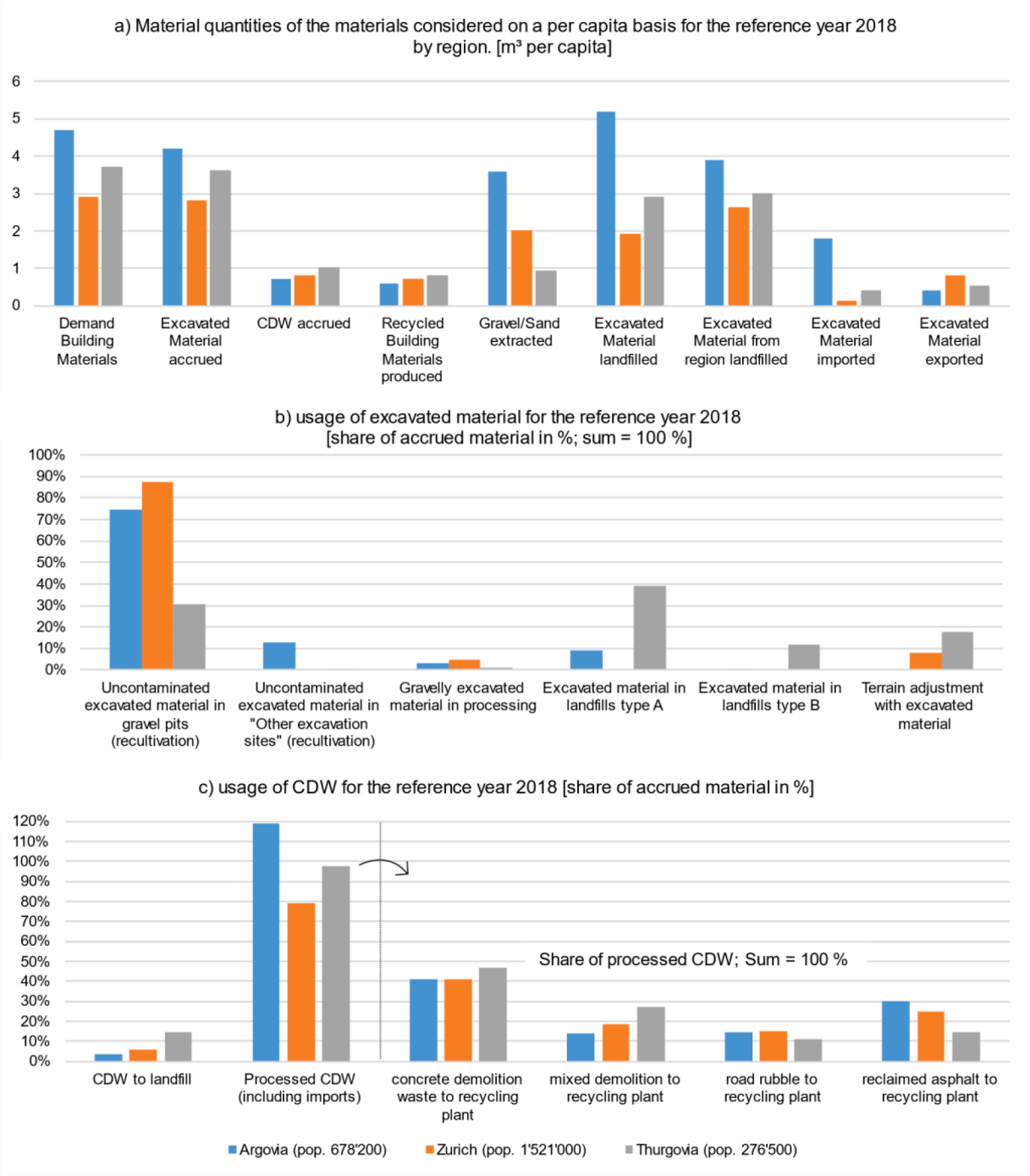


Fig. 2. key values for mineral building materials in the regions under consideration for the reference year 2018 (Rubli, 2020); a) Material quantities of the materials considered on a per capita basis by region in m^3; b) usage of excavated material in% of the total accruing excavated material; c) usage of CDW in% of the total accruing CDW; Underlying data used to create this figure can be found in the supplementary material.

5.2. Results of the Leontief-inverse matrices

Fig. 4 represents the physical and monetary Leontief inverse matrices of the respective regions as heat maps. The detailed matrices can be found in the supplementary material.

5.2.1. Physical Leontief-multiplier

The physical multipliers show in which upstream sectors additional production is triggered when the output of the respective sector is increased by one unit of mass. A higher multiplier means that the value chain is longer in comparison. This is particularly visible in the processes (6) concrete plant, (7) and (8) construction of buildings and infrastructures, and (9) demolition since changes in the material flows in these sectors trigger the complete value chain. Furthermore, it is evident in these sectors that the more material originates in the region, the higher the multiplier. Thus, the multiplier is highest in Argovia, while it is lowest in Thurgovia, the canton with the least mineral resources. It is also noticeable that Argovia generally has higher multipliers, as the cement industry is part of the value chain and contributes significantly to the material flows. Additionally, the importance of the individual sectors for the entire regional construction industry can be estimated. For example, Argovia shows a lower multiplier of the sector landfill (11)



Fig. 3. Allocation of the production value from the point of view of production (left) and demand (right); top: Argovia, middle: Zurich, bottom: Thurgovia; Underlying data used to create this figure can be found in the supplementary material.

than in the other regions, since in Argovia the majority of the CDW is processed and not landfilled. Argovia, however, shows the highest multiplier in sector (3) recycling plants, as the recycling rate in this region is higher than in the other regions.

5.2.2. *Monetary Leontief-multiplier*

The monetary multipliers show us which cash flows are triggered in the upstream sectors if we increase the investments in the respective sector by one monetary unit. Only in this way can the change from a material-based to a service-oriented economy be mapped. If we look at



Fig. 4. Results of the physical (left side) and monetary (right side) Leontief inverses of the cantons Argovia (top), Zurich (Middle), and Thurgovia (Bottom), represented as Heat-Map, high interlinkage = green, low interlinkage = red; Underlying data used to create this figure can be found in the supplementary material.

the monetary values, we see that there are far fewer links in the industry than in the physical view. Here, the predominant material-related business model of the construction industry becomes apparent. For example, recycling plants (3) do not have a monetary upstream chain. The recycling plants offer a co-production of recycled materials and a waste management service. Comparable to the physical multipliers, concrete production (6) shows that the domestic origin of raw materials leads to a higher multiplier. In Argovia, for example, the multiplier for concrete production is significantly higher at 1.71 than in Thurgovia at 1.07. In the construction processes, the multipliers are also higher than in Zurich and Thurgovia since the supply of primary gravel to the industry represents a financial advantage.

5.3. Environmental impacts

If we look at the environmental impacts (Fig. 5), the predominance of the cement industry becomes apparent. For all three environmental indicators, Argovia shows the highest values for direct scope 1 impact per capita, which is largely due to the cement industry and its CO_2 emissions and energy consumption. In Zurich and Thurgovia, on the other hand, direct emissions are lower, again due to the absence of the cement industry. In contrast, in these two regions, cement imports cause much higher indirect emissions. In summary, we see that Argovia has the highest total environmental impacts per capita, which is on the one hand due to the cement industry, but also due to higher mining activity and landfilling. The second-highest impact per capita is in the Thurgovia region. The reasons for this are the increased material demand per capita due to increased Greenfield construction activities with a high share of single-family detached houses, as well as the higher activities in connection with the landfilling of excavated material. In Zurich, less material is demanded due to the different construction activities, and less material is landfilled due to the lack of landfill volume. All of this results in lower environmental impacts. However, it should be noted that double counting of impacts may occur in this evaluation. The indirect emissions in Zurich and Thurgovia could be partly assigned to the direct emissions of the cement industry in Argovia (or vice versa) since both regions are very likely to purchase cement from the two plants in Argovia. However, since no MFA data is available in this respect, a separation is not possible. Furthermore, it must be noted that, as described in ss, no data on the ecological scarcity indicator are available for the construction processes. For this reason, the values are slightly underestimated in all regions.

6. Discussion

To identify relevant constraints and conditions for a CE, we

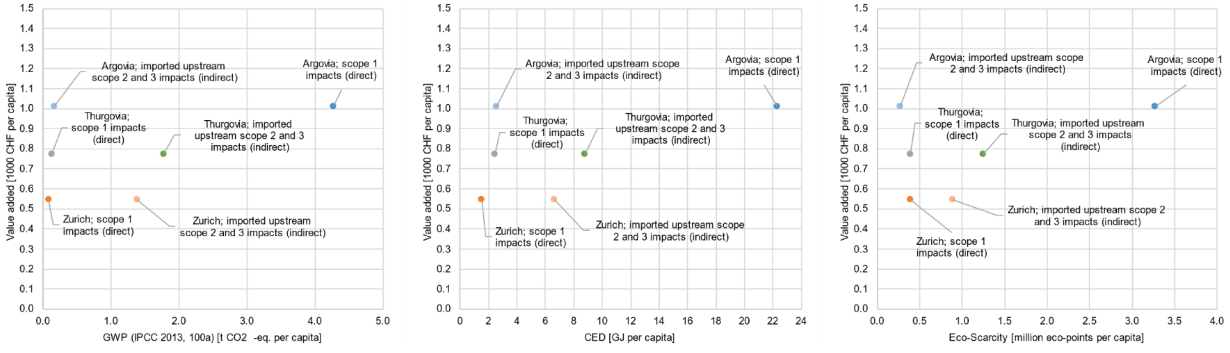


Fig. 5. Environmental Impacts per capita in relation to the value-added of the respective regions distinguished between scope 1 and upstream scope 2/3 impacts; top: GWP; middle: CED; bottom: Eco-scarcity.

formulated different hypotheses and tested them on three regions in Switzerland, which have different characteristics in terms of resource availability and construction activity.

6.1. A region with few natural resources is more likely to establish a CE due to an increased material efficiency to minimize natural resources consumption – not confirmed for the considered regional industry

Based on the results, it is not apparent that, in terms of building materials, a region with few resources is more likely to establish a CE. Argovia, with high availability of resources, shows the highest physical multipliers in most sectors within the industry. Thurgovia, with the lowest available resources, on the other hand, shows the lowest physical multipliers. The figures show that Argovia processes the most CDW although it has the most primary raw materials available. Thurgovia, on the other hand, landfills a very large proportion of excavated material that could be used for gravel extraction, although it has the fewest primary raw materials. This contradicts the first hypothesis. This is mainly due to spatial reasons in the regions considered. The regions are directly neighboring and maintain a lively exchange of building materials. Furthermore, the regions covered here are relatively small and transport distances are short. This does not create the necessary (financial) pressure to implement a CE. Thurgovia, as a resource-poor region, is therefore not primarily supplied with recycled materials, but by importing primary building materials from the neighboring regions of Zurich or Argovia. This is a limitation of the regional view of the model, which is based on data from the cantons and cannot directly represent the interregional exchange. However, this also leads to the conclusion that the management of building materials and CDW should not only be considered within political boundaries, as it is done now, but must take place supra-regionally within functional boundaries (e.g., urban areas with their supplying neighboring regions) to carry out effective resource planning. This finding is supported by other studies (Augiseau and Kim, 2021; Kliem et al., 2021; Schiller et al., 2017, 2020).

6.2. Regional differences in environmental impacts result from the outsourcing of the value chain to regions outside the considered region – confirmed for the considered regional industry

The results confirm this hypothesis. It is evident, that the structure of the industry has a significant influence on the impacts, in the sense that the absence of high-emission industries reduces the direct emissions. Argovia has the largest impacts as it is home to two of the six Swiss cement plants. A comparison with the two other regions shows that the cement industry is decisive in the environmental assessment of the regions (Meglin et al., 2021). In Zurich or Thurgovia, the direct emissions are much lower since there are no significant CO_2 and energy-intensive processes. Only the transport- and vehicle-intensive processes of gravel extraction and construction are located there. However, the reduced direct impacts in Thurgovia and Zurich are "compensated" by indirect impacts due to imports of cement. The recycling of CDW or excavated material does not seem to have a significant influence on the regional environmental impacts, which is shown by the higher emissions in Thurgovia compared to the emissions in Zurich. Rather, the predominant type of construction and the associated material requirements have a significant influence (Gallego-Schmid et al., 2020). This is evident from the fact that Zurich requires less building material due to most new replacement buildings and thus has lower impacts.

It should be noted that average transport distances were used in our assessment. It can be assumed that transport distances will increase in regions with a high proportion of imports and that this will result in higher emissions. However, since the regions considered here are neighboring, we assume that the increased emissions are negligible. It should also be noted that double counting may occur since a certain proportion of the imported cement comes from the plants in Argovia. In this context, the question arises as to who is responsible for the accruing impacts. Various approaches are being discussed, especially for greenhouse gas emissions, including the "production-based principle" or the "consumption-based principle" (upstream responsibility) (Steininger et al., 2016, 2020). In the production approach, only the direct impacts that occur within the boundaries of the region under consideration would be considered, while in the consumption approach the imported impacts would also be taken into account. The decision as to which approach should be chosen is outside the scope of this paper, but we can provide the data for transparent accounting and appropriate policies. However, the different approaches can cause significant differences in the calculated environmental impacts, which in turn can be used as a basis for policies and thus have a significant influence on regional development in the long term (Harris et al., 2020).

6.3. Waste management is the key process in establishing a CE – not confirmed for the considered regional industry

The high recycling rates due to policy measures in Switzerland indicate that waste management and landfilling are important processes towards CE. However, it should be mentioned that it is not clear whether the policy is responsible for the high rates or whether the lack of landfills and the associated costs promote the recycling of CDW. Indeed, the Leontief multipliers do not indicate that landfilling is the most important process in the construction industry considering a CE. In all regions considered, the physical and monetary multipliers are lower than the construction processes in the respective regions. Only in Zurich is the physical multiplier of the landfill sector comparable to the construction processes, which is due to an increased landfilling of CDW. However, the construction processes (incl. demolition) play a more decisive role. These processes show a high degree of linkage with the other sectors of the construction industry, especially when viewed from a physical perspective. This means that these processes probably have the greatest leverage for change in the transition to CE, as they trigger all other sectors. Furthermore, regions with a high level of construction activity and large availability of raw materials, such as Argovia, show the highest multipliers. This indicates that the linkages are stronger and therefore a CE is more likely to be realized. This could be because in Argovia the necessary infrastructure is better developed and the proximity to the concrete and cement plants offers more possibilities for the establishment of a CE. Thurgovia is home to only a few companies that tend to import material. A more linear business model still prevails there, as it could be that the economic benefit of recycling CDW is not given and the spatial proximity to sectors that drive recycling is missing. The presence of the complete value chain can therefore be seen as an advantage in a regional industry to establish a CE.

6.4. A circular economy leads to an economic benefit – not confirmed for the considered regional industry

A look at the results of the economic assessment does not indicate that CE leads to a significant benefit in the context studied here. The data show that value-added accounts for a similar share of revenue in all three regions, although some of the regions have very different characteristics. A deeper look at the Leontief Multiplier shows that the different availability of resources does not have a significant impact on the financial linkages of a regional building materials industry. This can be explained by the fact that the prevailing system in all regions still corresponds to a rather linear business model. In all three regions, most of the materials in demand are produced with primary raw materials. In addition, it must be mentioned that recycled gravel, which is produced from demolition material, still has a much lower value compared to concrete or cement and therefore has little impact on the financial performance of the industry. In contrast, the cement industry in Argovia contributes a large share to the region's revenue and value-added. This is not the case in the other two regions considered. Another barrier in this context is the high profitability of waste management services and

landfilling, which hinders the effective implementation of a CE. Furthermore, the monetary Leontief multipliers show that the construction processes have the greatest economic leverage. The Leontief multiplier is highest for building construction with 2.06 in Argovia, while it is lowest for Zurich with 1.82. This means that in Argovia, each investment of one monetary unit results in a total output of 2.06 units due to direct and indirect effects, while in Zurich only 1.82 units result. This again indicates that the presence of the complete value chain of the construction industry provides an economic advantage.

It must be mentioned that in this assessment average prices and costs for all regions were used. However, the prices in the respective regions and partly also from project to project are different. This would lead to slightly differing results. Due to the geographical proximity of the regions, we assume that these differences are negligible in the context of this assessment. However, for studies of remote regions, e.g., regions in Western Switzerland compared to Eastern Switzerland, these differences would have to be considered separately.

7. Conclusion

In a recent report, the European Commission stated, that it "*is for Public Authorities, first and foremost, to assess the obstacles to the transition towards a more circular economy and, based on that assessment, decide upon the implementation of the applicable incentives to address them*" (Katrakis et al., 2021, p. 30). However, for public authorities to be able to take the appropriate measures, they need a transparent data basis and knowledge about the boundary conditions prevailing in the relevant regions and industries (B. C Guerra and Leite, 2021.; Hart et al., 2019).

In this study, we were able to take an important step in this direction and show which regional boundary conditions have which effects on an industry. To do so, we developed an IAM to assess a regional industry and evaluate it based on physical and monetary metrics. We have formulated four general hypotheses in the context of a CE and, based on three example regions in Switzerland, we have evaluated the status of a CE in a regional industry and identified obstacles. Based on those hypotheses, we were able to evaluate the status of CE and identify obstacles in three sample regions. From these findings, we can now formulate indications that can be used for the development of effective CE policies.

The results suggest that imports and exports, especially in smaller regions, can hinder the implementation of CE. CE policies should therefore be developed for functional areas rather than political boundaries to effectively manage material flows. This is also in the light of environmental impacts. Although the outsourcing of high-emission processes in the value chain significantly reduces direct emissions, these are offset to a large extent by indirect emissions. In this case, too, the consideration of functional areas would enable a fair and transparent accounting of the environmental impacts. Consideration of inter-industry linkages in the industry shows that policies should be formulated specifically for the construction processes, as they have the greatest leverage for policy-induced changes within the industry. However, this means a change in the usual approach, as currently the focus is more on waste management. The financial analysis shows that the use of secondary building materials is still not profitable enough. Therefore, financial incentives should be created to minimize the extraction of primary raw materials and to avoid the landfilling of demolition and excavation material.

The findings here also indicate a need for further research. Further regions should be investigated, on the one hand to confirm the applicability of the obtained findings, but also to investigate what influence the mentioned limitations have on our results. For example, we have studied regions that are very close to each other and have a lively exchange of building materials. An investigation of different regions without economic connection could bring new insights and confirm our results. However, the analysis of prices and costs should be more differentiated to achieve the necessary level of detail. Furthermore, based on the results, the question must be asked to what extent the physical and monetary multipliers can be used to assess circularity. While there are significant differences in the physical multipliers between the regions, the differences in the monetary multipliers are very small, which can be explained by various boundary conditions, such as the low prices for secondary building materials or the still prevailing linear business models in the construction industry. Further studies with comparisons of different regions or industries (e.g., steel industry) should verify the applicability of the Leontief multipliers as an indicator of circularity. In addition, a study of different industries would be desirable. We assume that the model is also applicable to other regional heavy industries, where the process steps can be divided into raw material extraction, intermediate product, and end product. Thus, a comparison with a heavy industry where recycling of waste materials already works, e.g., the steel industry, could confirm our results but also give indications on how to overcome the mentioned barriers and how a CE can achieve a greater financial benefit. In addition, this view can also help to look at recycling in a larger regional context and show examples of how policymakers can overcome political boundaries for the implementation of measures. Regarding these measures, we also see the need to develop and test innovative policy instruments to promote CE in a regional industry under the constraints described here.

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The authors declare no conflict of interest.

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Supplementary materials

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