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Author(s):
Meglin, Ronny; Kytzia, Susanne; Habert, Guillaume

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Uncertainty, variability, price changes and their implications on a regional building materials industry: The case of Swiss canton Argovia

Ronny Meglin[a,b,*], Susanne Kytzia[b], Guillaume Habert[a]

[a] ETH Zurich, Dept. of Civil, Environmental and Geomatic Engineering, Zurich, Switzerland
[b] University of Applied Sciences Eastern Switzerland, Institute for Civil and Environmental Engineering, Rapperswil, Switzerland

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ABSTRACT

There is an increasing effort of the cement and concrete industry to increase material efficiency and reduce CO_2 emissions. Several strategies have been identified to achieve this goal, but the implementation of a circular economy (CE) strategy is being pursued most actively by governments and public organizations to increase material efficiency and improve sustainability in the construction industry. This transition to a CE, however, is a process, which features a high multi-dimensional complexity and a fundamental change of a complex socio-technical system. It can be interpreted as a co-evolutionary process between public policies and business models It is, therefore, necessary to understand the existing system and the interactions between business models and public policies to support decision- and policy-makers in the transition towards a CE.

We would like to contribute to this understanding and identify initial implications on which business models and which public policies support a transition towards a CE. The aim of the paper is to provide a novel analysis of the economic structure of a regional building materials industry to identify regional conditions and give first implications on how to implement a CE in a regional context. We use an integrated assessment model to enable a comprehensive environmental and economical assessment of an industry and to generate data for policymaking. This method combines Material-Flow-Analysis (MFA) and Life-Cycle-Assessment (LCA) using an input-output approach. We demonstrate how we can evaluate uncertainties in model application and demonstrate in a case study that our model produces robust results. On this basis, we discuss what additional insights on systems behavior we gain from uncertainty analysis focusing on price data. We use an uncertainty analysis as a basis for identifying implications for business models and policies. In addition, we use the price model in the Input-Output Analysis (IOA) to investigate the impact of price changes on linked sectors. We use an exemplary assessment of the building materials industry in the Swiss canton of A-rgovia as a case study.

First, we were able to show that the model used here is robust and has reasonable uncertainties. Using the results of the Sensitivity-Analysis we could formulate initial indications of how business models are affected by the shift to CE. We have shown that vertical integration of different sectors makes sense regarding a CE to buffer price volatilities, but also to secure the supply of raw materials. Furthermore, the results of the uncertainty analysis and the price model provided us with initial findings, in which sectors policies are most efficient and how price changes affect the downstream sectors. The new approach presented here to capture a regional industry in detail using economic calculations and uncertainty considerations represents an important contribution to better understand a regional industry and to support the process of decision- and policymaking.

1. Introduction

In 2015, approx. 4.4 Gt CO_2-eqivalents greenhouse gas emissions could be attributed to the production of mineral building materials (Hertwich et al., 2020), which corresponds to approximately 9% of the global greenhouse gas emissions of 49 Gt. Therefore, the production of mineral building materials, especially cement, as the hardening component of concrete, is an important driver of climate change. Additionally, the built environment is responsible for an enormously high consumption of natural raw materials and waste production. The construction industry uses almost 50% of the amount of annual world-wide available resources (OECD, 2019), while it produces an average of

* Corresponding author. Oberseestrasse 10, CH-8640 Rapperswil, Switzerland.
E-mail address: ronny.meglin@ost.ch (R. Meglin).

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1.68 kg of construction and demolition waste (CDW) per person and day (Kaza et al., 2018). For this reason, there is an increasing effort of the cement and concrete industry to increase material efficiency and reduce CO_2 emissions (CEMBUREAU The European Cement Association, 2020). Several strategies have been identified to achieve this goal (Favier et al., 2018; Habert et al., 2020). Implementing a circular economy (CE)[1] strategy is pursued most actively by governments and public organizations to increase material efficiency and improve sustainability[2] in the construction industry (BAFU, 2020; Ellen MacArthur Foundation, 2013; European Commission, 2020; Hertwich et al., 2020; OECD, 2020a), going beyond the narrow focus on waste management (Hertwich et al., 2020; OECD, 2020b).

This transition to a CE, however, is a process, which features a high multi-dimensional complexity (Geels, 2019; Markard et al., 2012; Norouzi et al., 2021) and a fundamental change of a complex socio-technical system (Geels, 2019). It can be interpreted as a co-evolutionary process between public policies and business models (Edmondson et al., 2019; Schaltegger et al., 2016). The shift from traditional to sustainable business models is of central importance and drives the transition to a sustainable CE (Bocken et al., 2014; Guerra et al., 2021; Schaltegger et al., 2016; Tunn et al., 2019) and the mitigation of price volatility and supply risks (Ellen MacArthur Foundation, 2013). This is particularly important since a circular economy involves a transition from a material-oriented to a service-oriented CE (Halme et al., 2007; Stahel, 2016). However, this change is highly affected, among others, by institutional barriers (Diaz Lopez et al., 2019; Tazi et al., 2021; Werning and Spinler, 2020), which must also be considered in the regional context (Domenech and Bahn-Walkowiak, 2019). It is therefore necessary to understand the existing system and the interactions between business models and public policies in order to support decision- and policy-makers in the transition towards a CE (Pieroni et al., 2019; Valve et al., 2021).

We would like to contribute to this understanding and identify initial implications on which business models and public policies support a transition towards a CE. The aim of the paper is to provide a novel analysis of the economic structure of a regional building materials industry to identify regional conditions and give first implications on how to implement a CE in a regional context (Dagilienė et al., 2021). The results should then help companies and administrations to incorporate aspects of a CE into business model innovations or to formulate appropriate policies.

We use an integrated assessment model to enable a comprehensive environmental and economical assessment of an industry and to generate data for policymaking. This method combines Material-Flow-Analysis (MFA) and Life-Cycle-Assessment (LCA) using an input-output approach. We use monetary input-output tables (MIOT), which are generated from physical input-output tables (PIOT) in mass units.

In this paper, we demonstrate how we can evaluate uncertainties in model application and demonstrate in a case study that our model produces robust results. On this basis, we discuss what additional insights on systems behavior we gain from uncertainty analysis focusing on price data. We choose this focus assuming that such economic uncertainties affect the development of business models in the construction sector as well as the effectivity of incentive schemes introduced by public policies. We use an exemplary assessment of the building materials industry in the Swiss canton of Argovia. We will answer the following questions:

(1) What uncertainties are to be expected regarding our MFA and LCA data and how do we rate them?
(2) What uncertainties are to be expected regarding regional price data?
(3) What implications can be drawn from the uncertainty considerations for the evaluation of business models and public policies to support decision-making and promote CE?
(4) What are the effects of price increases in one sector on another downstream sector?

To answer these questions, we first discuss the uncertainty and variability of MFA and LCA data und and evaluate them using a qualitative approach. Second, we want to identify the impact of uncertainties in our price data by performing two typical uncertainty analysis procedures: Sensitivity Analysis (SA) and Monte Carlo Analysis (MCA) (Bamber et al., 2020). Third, we use the IO price model to identify the effects of increasing output-prices. Finally, we interpret and discuss these results concerning the environmental-economic evaluation of the assessment model and try to formulate implications considering the business models of the Swiss building materials industry and public policies promoting a circular economy.

2. State of research

2.1. Circular economy in the built environment

Recent review papers on CE in the construction industry show that most of the studies under review consider product- or building-level, instead of regional or industry level, and work with single methods only (Hossain et al., 2020). Furthermore, it is noticeable that in recent studies, the environmental aspects are investigated far more frequently than the economic background of a CE (Ghisellini et al., 2018; López Ruiz et al., 2020). It seems that the main focus in the construction industry is on resource efficiency (minimize construction waste by recycling), and therefore business and economic aspects are neglected (Lieder and Rashid, 2016; Parchomenko et al., 2019). However, to realize a sustainable CE, not only the environmental but also the economic aspects must be considered (Giama and Papadopoulos, 2020). This is particularly important against the background of a large number of barriers and enablers, that affect this transition (Gallego-Schmid et al., 2020; Hart et al., 2019; Kliem and Scheidegger, 2020). For this reason, a holistic and multidisciplinary assessment methodology must be used, to evaluate the environmental, economic, and social aspects of an industry's value chain and to consider business perspectives, technological developments, and policies (Hossain et al., 2020; Lieder and Rashid, 2016; López Ruiz et al., 2020; Nuβholz et al., 2019; Papageorgiou et al., 2021). Further studies recommend using complementary methods to integrate economic and environmental aspects in an assessment (Crawford et al., 2018; Moriguchi and Hashimoto, 2016; Säynäjoki et al., 2017; Teh et al., 2017). This should make it possible to create a common basis for different stakeholders to evaluate an economy transparently and comprehensively (Reif and Osberghaus, 2020) and to establish an effective and comprehensive collaboration between the stakeholders (Ghaffar et al., 2020).

2.2. Uncertainty & variability

To better understand the data and results and to support interpretation for decision-makers, the identification and communication of uncertainties and variabilities are an integral part of an environmental and economical assessment (Huijbregts, 1998; Igos et al., 2019; Michiels and Geeraerd, 2020; Weidema and Wesnæs, 1996; Yamakawa and Peters, 2009). Depending on the method, however, different uncertainties and variabilities must be considered. In LCA, uncertainties can occur e.g. due to data selection or methodological choices (Cherubini et al., 2018). Especially data uncertainties and uncertainties due to the choice of the

[1] Circular Economy: Regenerative system in which resource input and waste, emission, and energy leakage are minimised by slowing, closing, and narrowing material and energy loops through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling. (Geissdoerfer et al. (2017).

[2] Sustainability: Balanced integration of economic performance, social inclusiveness, and environmental resilience, to the benefit of current and future generations. (Geissdoerfer et al. (2017).

functional unit cause increased sensitivity of the results in LCA studies (Hong et al., 2016; Panesar et al., 2017). Another contentious issue in LCA-Studies is the allocation approach of recycling activities or in the use of secondary raw materials. (AzariJafari et al., 2021; Cherubini et al., 2018; Civancik-Uslu et al., 2019; Häfliger et al., 2017; Heijungs and Guinée, 2007; Jung et al., 2014). In MFA-Studies, uncertainty is particularly caused by the quality of data of physical flows and stocks from different sources (Laner and Rechberger, 2016). However, the mass-balance principle of MFA models also ensures that the data used are consistent, robust, and can reduce uncertainties (Brunner and Rechberger, 2017). In contrast to LCA and MFA studies, uncertainty is hardly reported in IOA studies (Lenzen et al., 2010). Nevertheless, IO-data also has uncertainties that should be investigated as they are important for interpretation (Yamakawa and Peters, 2009). Besides the uncertainty of the base data and assumptions about the homogeneity of the considered region/industry, especially the uncertainty due to the increased aggregation of the data is discussed (Lenzen, 2000; Lenzen et al., 2010; Majeau-Bettez et al., 2016). Some studies have shown in this regard, that the use of MIOTs can lead to contradictory results (Hubacek and Giljum, 2003; Suh, 2004; Weisz and Duchin, 2006) if the data, and especially the price-data, is based on sectors that are too highly aggregated (Merciai and Heijungs, 2014; Weisz and Duchin, 2006). We solve this problem by using comprehensive MFA data from a defined sector (here the Swiss building materials industry) to create a balanced PIOT, that satisfies the basic constraints of IO-Analysis (Miller and Blair, 2009). The PIOT serves as the basis for further calculations of the MIOT. With this, we follow the argumentation of Hoekstra and van den Bergh (2006), that data from the PIOT and the MIOT should be combined to support environmental-economic analysis and policy modeling and that a PIOT is an integration framework for different data sources.

2.3. Business models and transition towards CE

In the construction industry, especially in the building materials industry, the transition to a CE represents a major challenge, as the turnover is coupled with the material throughput (Bocken et al., 2016; Kliem and Scheidegger, 2020; Spoerri et al., 2009). Examples of such a transition are building contractors, who become service agents in materials management of construction sites and so decouple their turnover and profit of the consumption of natural raw materials. However, studies show that there are various barriers to the implementation of such sustainable business models (Guerra and Leite, 2021; Munaro et al., 2020). In addition to regulatory and market constraints, economic constraints are often recognized as one of the main barrier (Abuzeinab et al., 2017; Ghaffar et al., 2020; Tazi et al., 2021). Business models in the Swiss construction sector focus on vertical integration of production and waste management services either including recycling or landfilling of excavated material or construction and demolition waste (Meglin et al., 2019; Opitz, 2018).

3. Integrated assessment model for the swiss building materials industry

We have developed a model that maps and assesses the Swiss building materials industry for mineral building materials (sand, gravel, cement, and concrete). It combines comprehensive MFA-data from a Swiss database of regional material flows of mineral building materials (Rubli, 2020) with environmental data from the LCA database ecoinvent (Wernet et al., 2016) using an input-output approach to create an environmental extended IOA (EEIOA).

We do so because the single methods have different system boundaries, benchmarks, calculating techniques, and scopes and are not able to completely capture and assess a complex system of a CE (Meglin et al., 2021). For example, an MFA is used to capture technical processes on a mass basis of a socioeconomic system and investigate its dependencies in a defined boundary but data availability is a significant problem (Brunner and Rechberger, 2017; Krausmann et al., 2018). A LCA is a bottom-up decision-support tool encompassing all the impacts of a product system from cradle to grave to promote cleaner production (Frischknecht, 2020; Jolliet et al., 2016)). Potential truncation errors due to the choice of the system boundary and complicated allocations are sources of error to be considered when performing an LCA (Reap et al., 2008-; Suh, 2004). IOA, on the other side, is a top-down economic tool for analyzing interindustrial interdependencies in an economy describing the distribution of goods and services in an economy (Miller and Blair, 2009; Suh, 2010). Since IOA data are mostly compiled from national statistics, the resolution of the data is rather low, so that sometimes simplifications and assumptions have to be made, which can influence the results significantly (Aguilar-Hernandez et al., 2018; Weisz and Duchin, 2006). However, since these single methods are accepted and widely used by the professional community, we will use them in combination to overcome individual shortcomings and to combine the different levels of interests (product level, regional level).

A simplified illustration of the assessment model and the calculation steps is presented in Fig. 1. First, MFA data is translated into the PIOT by assigning the respective mass flows of the MFA to the corresponding processes in the PIOT. This is made possible by the fact that the PIOT's processes correspond exactly to the MFA processes (see MFA-Model and general PIOT in the supplementary material). In a second step, the individual elements of the PIOT are multiplied by average prices (Table 2 in section 4.2) to obtain a MIOT for the selected industry. Finally, the MIOT is extended with environmental coefficients, which were aggregated to the individual sub-sectors, so that the environmental impacts per sector and monetary unit can be determined. This method aims to obtain comprehensive environmental and economic data that can be used for decision-making in the creation of policies regarding the transition to a circular economy.

Yet, transforming the PIOT into a MIOT not only changes the unit in which flows of goods and services between processes are represented from mass units to monetary units. It also changes the position of service flows for waste management within the IO matrix (see Fig. 2). In general, a PIOT only represents mass flows related to goods and services in the economic system. For waste management services, the direction of the related mass flow (solid or liquid wastes) does not represent costs and revenue of processes/industry involved. The process "Demolition", for example, provides a waste management service for the construction of buildings and infrastructures. In the MIOT, it is represented as flow between demolition (service provider) to buildings/infrastructures (as clients). The PIOT, however, focuses on material flows. It considers the mass flow of CDW as output of buildings/infrastructure and input to the process "Demolition". To represent the economic interdependencies between all processes/industries, all waste management services must be changed from outputs from waste generating processes/industries to outputs from suppliers of waste management services. An example can be seen in Fig. 2 below, where the material flows in the PIOT are assigned to input-flows of the sector "Demolition", but in the MIOT to the output-flows (revenue). This step is necessary to represent the actual economic situation of a service-oriented CE and to allocate the impacts to the corresponding sector accordingly.

To assess the impact of price changes on the industry, we can use the IO price model (Holub and Schnabl, 1994). With this, we can investigate how the industry in question reacts to an isolated change in individual prices, given a constant quantity. It is based on the general form of Leontief's input-output analysis and the general formula for n sectors (Leontief, 1986):

$$\mathbf{X} = (\mathbf{I} - \mathbf{A})^{-1} \times \mathbf{Y},$$

where $\boldsymbol{X}$ is the output-vector $(n \times 1)$, $\mathbf{I}$ is the identity matrix $(n\ x\ n)$, $\boldsymbol{A}$ the $(n \times n)$ technology-matrix, and $\boldsymbol{Y}$ the vector of final demand $(n \times 1)$. The formula is then modified as follows:

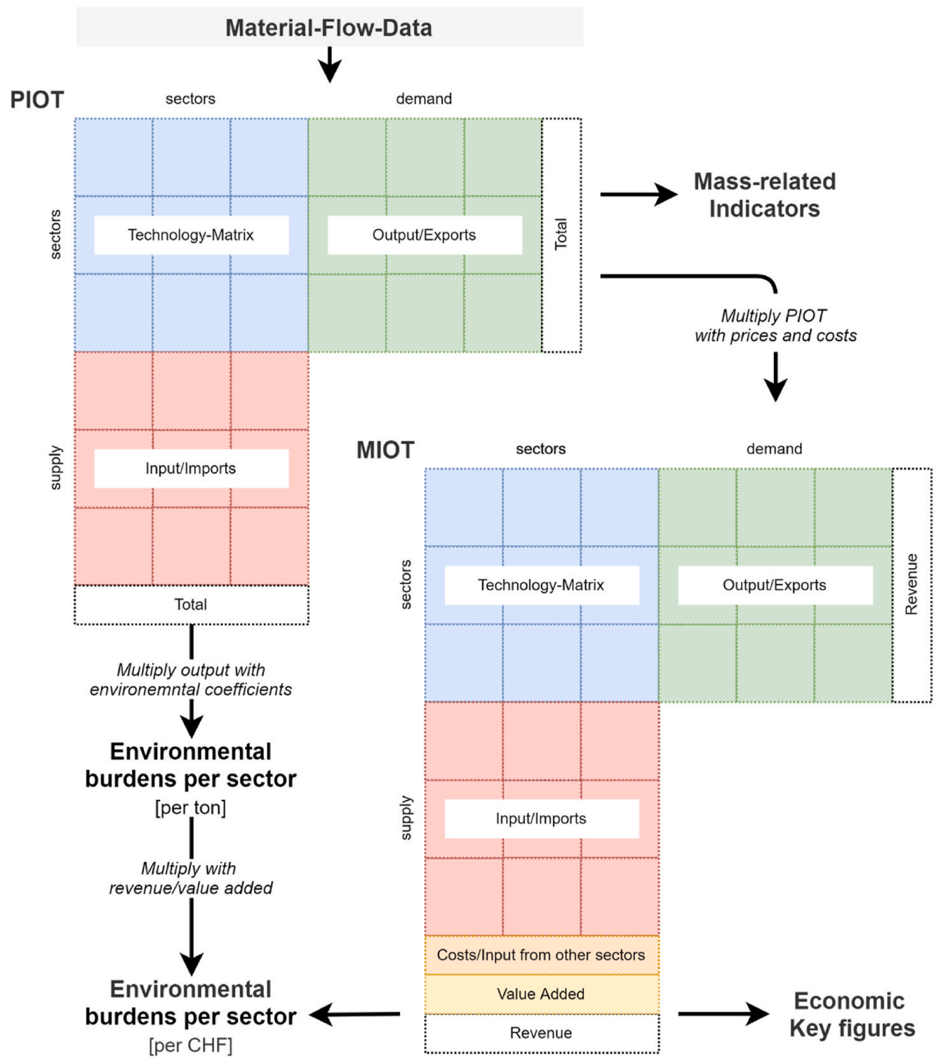

Fig. 1. Simplified illustration of the assessment model presenting the calculation steps and the data obtained (PIOT: physical input-output table; MIOT monetary input-output-table).

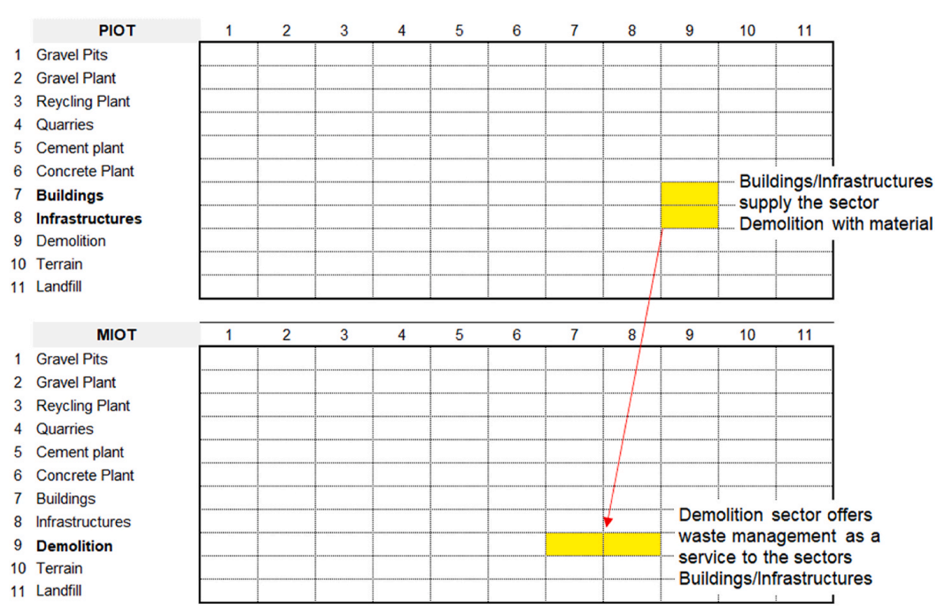

Fig. 2. Change of flow direction when transforming the PIOT (top) into a MIOT (bottom) using the example of construction and demolition waste.

$$\mathbf{p} = (\mathbf{I} - \mathbf{A}')^{-1} \times \boldsymbol{w}\boldsymbol{P}_w$$

where $\boldsymbol{A}'$ is the transposed $(n \times n)$ technology matrix, $\boldsymbol{p}$ is the $(n \times 1)$ price vector of output prices, $\boldsymbol{w}$ is the $(n \times 1)$ vector of input coefficients, and $\boldsymbol{P_w}$ is the $(n \times 1)$ price vector of the primary factor. We calculate the price changes by varying the individual price factors in the vector P_w, which results in a change of prices in vector p in the linked sectors.

4. Analysis of uncertainty and variability

In this paper, we look at the uncertainties and variabilities in two parts. In the first part, we take a qualitative look at the MFA and LCA data. We do this because, on the one hand, the database that serves as a basis for our MFA data has already conducted an uncertainty analysis, to which we would like to refer; on the other hand, there are many studies on the analysis of uncertainties in LCA that examine the relevant aspects. In the second part, we will quantitatively consider and evaluate the uncertainties caused by price data using a Monte-Carlo Analysis and a Sensitivity Analysis.

4.1. Qualitative analysis of MFA and LCA data

We perform the qualitative consideration of uncertainties and variabilities using the types and criteria of uncertainty published by Huijbregts (1998) and Weidema and Wesnæs (1996). The pedigree matrix developed by Weidema & Wesnæs will allow us to look at the uncertainties of the data used, even without complex calculations. The respective aspects are evaluated by scoring them from 1 to 6. The score 1 corresponds to the best value with no uncertainty (e.g., verified data from the same location) and 6 to the worst value with a high uncertainty factor (e.g., broad estimations from unknown locations). In addition to data uncertainties, uncertainties, and variability due to geographical and temporal aspects are also considered. Table 1 shows the types of uncertainty and variability and the corresponding scores for the MFA and LCA data.

Parameter-Uncertainty describes the lack of knowledge of the true values of data or data gaps. For the assessment, we use the MFA database "KAR-Model" which is an institutionalized database of regional and interregional material flows of various cantons in Switzerland (Rubli, 2020). It covers all the materials under study (sand, gravel, and concrete) since 2010. The data used in the KAR model comes directly from the cantonal authorities and companies, but some assumptions must be made for few missing data points. Therefore, we give the MFA data a rating of 2 in both indicators. This corresponds to verified data partly based on assumptions. We use ecoinvent version 3.6 (Wernet et al., 2016) as a database for our environmental coefficients. The data are mostly based on measurements of all corresponding processes under study and are periodically controlled/updated. In addition, experts review the data periodically. For some data sets, assumptions must be made, if no measurements are available. Therefore, the LCA-data is rated with a 2 or 3 (non-verified data based on assumptions) for reliability and 1 (verified data) for completeness.

Table 1
Types and Indicators for uncertainty and variability and the corresponding scores for the MFA and LCA data.

Types of uncertainty according (Huijbregts, 1998)	Uncertainty indicator according (Weidema and Wesnæs, 1996)	Score/remarks	
		MFA	**LCA**
Parameter-Uncertainty	Data Reliability	2	2–3
	Data Completeness	2	1
Model-Uncertainty		See below	n/a
Uncertainty due to choices		n/a	See below
Temporal variability	Temporal correlation	1	2
Spatial variability	Geographical correlation	1	2–3
Variability of sources	Further technological correlation	1	2–3

Model-Uncertainty describes the uncertainty caused by the calculations in the model, especially for LCA when linear relationships are assumed. We assume that these assumptions correspond to the reality for the processes and materials considered here and thus do not go into detail about these uncertainties. Since we only model short-term influences (e.g., policy-induced changes), we assume that the system under consideration can absorb these changes without significant adjustments to the system (Frischknecht, 1998). For MFA calculations, if sufficient data are available (see "Parameter-Uncertainty"), the uncertainty is reasonable, since the fundamental law of mass balance guarantees that the input always equals the output (including all stock changes). This helps to minimize uncertainty by finding data gaps and wrong data. The creators of the database investigated the uncertainty of the database and the underlying MFA model. They performed a Monte-Carlo Simulation (Schneider, 2020) and a Sensitivity-Analysis (Schneider, 2016) and showed, that the underlying model is robust and the uncertainty is mainly in the range of ±15%, with some parameters having an uncertainty of ±25% (e.g., processing of gravel-rich excavated material). Even though these uncertainties are relevant, they are not considered in detail, since the objective of the assessment model is based on a regional view and therefore the data must be evaluated according to an average regional data set for which certain uncertainties must be accepted. Nevertheless, this must be considered when interpreting the results.

Uncertainty due to choices refers to the selection of basic boundary conditions when conducting an assessment. In this case, it is only applicable to the LCA study, where especially the selection of the functional unit, the system boundary, and allocation methods must be mentioned. In our case, the focus is on an explicit industry in a defined region, which is also represented in the system boundary (Fig. 3) where all necessary processes of the value chain of the building materials are integrated (excluding the use-phase of the building, including imports from a supplying "hinterland" region). The functional unit is defined as the "output of the building materials industry in the defined region over a specified period".

The environmental impacts of alternative and secondary raw materials in the cement production are allocated according to an economic allocation using average values found in the literature (see supplementary material). We use this economic approach instead of a physical approach (e.g., mass) because waste management services for CD&W are important in the CE transition. The economic rationale for using and providing these services can only be captured if they are considered as outputs of waste management processes (demolition/recycling, landfill) and inputs for construction processes (buildings/infrastructures). The uncertainties caused by the above-mentioned choices can be significant but are not specifically calculated in this paper. We would like to refer to various studies that specifically investigate and discuss these uncertainties (Cherubini et al., 2018; Civancik-Uslu et al., 2019; Häfliger et al., 2017; Panesar et al., 2017; Sayagh et al., 2010).

Temporal variability and spatial variability refer to the uncertainties due to temporal and regional differences in the data. In the context of this study, we use data that are regularly updated or reviewed. The MFA data are from 2018, while some of the LCA data are slightly older, but extrapolated to the corresponding year of the datasets (2019). Thus, we give the MFA data a ranking of 1 and the LCA data a 2 due to the extrapolation. Regarding the spatial variability, we rate the MFA data with a 1, since the data originate exactly from the regions we consider. The data sets from Ecoinvent for the ecological impacts are also largely based on data from Switzerland. For a few data sets, e.g., for transport or the construction process, we must refer to data from Germany or Europe, which, however, have comparable regional boundary conditions, so that the data are rated with a 2–3.

Variability of sources, the uncertainties caused by different technologies, is rated the same as the regional variability. As we are conducting

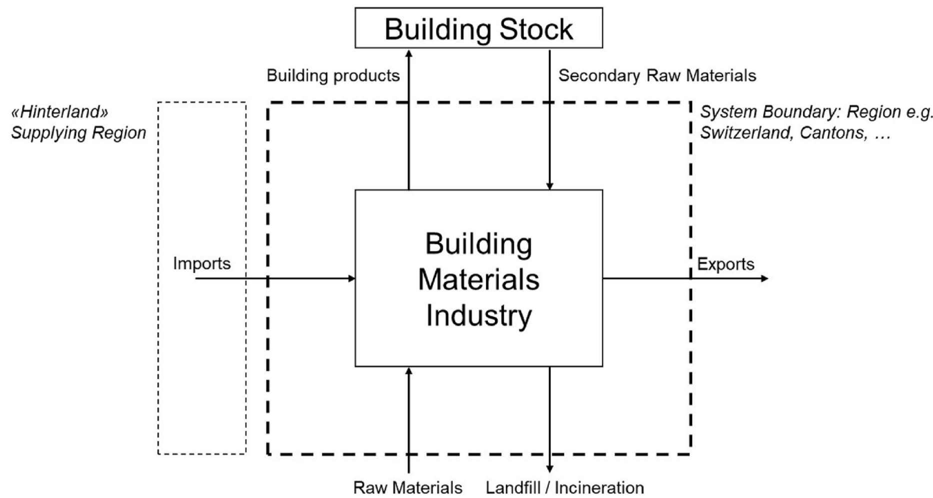

Fig. 3. System Boundary of the assessment model.

a regional analysis and not comparing products from different production sites, the impact of the variability of sources will be considered negligible.

4.2. Quantitative analysis of prices and costs

In our case, the input parameters for the quantitative uncertainty analysis are the financial data used for our assessment model (Table 2). These are based on the one hand on average building material prices of around 170 building materials producers throughout Switzerland published in public pricelists for the year 2018. On the other hand, the costs and prices of the construction process are estimated using national construction expenditures (Bundesamt für Statistik BFS, 2020a) and the Swiss construction price index (Bundesamt für Statistik BFS, 2020b). For further calculations, it must be considered that no price or cost pass-through is considered in the base model. This means that, for example, rising cement prices do not influence the concrete price. We calculate this pass-through of prices separately in the price model.

4.2.1. Sensitivity analysis

With the help of SA, we can identify which input parameters have the largest impact on our output and whether an interaction effect is present (Iooss and Saltelli, 2020). We will vary this data by ±10% step by step and calculate the sectoral and overall revenue of the industry to identify the price/cost with the most impact on the overall result.

4.2.2. Monte-Carlo Analysis

In Monte Carlo simulation, a distribution of the desired output is calculated by randomly changing the input parameters several times according to the respective distribution (Covello et al., 2012). This should show which input parameters have the highest uncertainties and how these must be interpreted in the context of the overall result. In this paper, prices and costs are varied according to their calculated or estimated standard deviation (see Table 2), assuming a normal distribution. The calculations are performed 500 times to obtain a reasonable distribution.

Table 2
Prices and Costs of products and processes.

material/processes	Price/Cost [1000 CHF]	Standard Deviation
Cement Raw Materials	0.016	0.0016
Gravel in gravel pit	0.015	0.0031
Excavation material for deposit	0.012	0.0036
High Quality Gravel	0.021	0.0036
Cement	0.125	0.0125
Concrete	0.062	0.0041
Excavated material for re-use	0.005	0.0005
Construction of buildings (structural engineering)	0.102	0.0431
Construction of infrastructures (civil engineering)	0.177	0.0883
Demolition	0.063	0.0156
Excavated material for re-use at site	0.005	0.0005
Recycled aggregates	0.010	0.0025
Construction and demolition waste at gravel plant	0.017	0.0079
Landfill fee	0.040	0.0040
Energy for cement production	0.012	0.0012

5. Results

In the following sections, the results of the SA, MCA, and price model are presented and discussed. The assessment of the building materials industry in the Canton Argovia for the year 2018 serves as a case study. The key figures used for the assessment can be seen in Table 3. In this study, we focus on the overall economic results of the assessment (Table 4). For this reason, we do not go into the detailed results of the economic and environmental assessment here. These can be found in the supplementary material. The overall economic results in Table 4 represent the reference values for the following uncertainty calculations.

5.1. Sensitivity analysis

Fig. 4 illustrates the results of the SA in the form of a tornado chart. It shows the impact of price changes on the revenue of the respective sectors when changing prices by ±10%.

The price changes of ±10% do not cause any significant changes in

Table 3
Key figures used for the assessment for the canton of Argovia (Rubli, 2020).

2018	Argovia
Population	678 200
Demand for mineral building materials [m^3 per capita]	4.7
Accumulation of excavated material [m^3 per capita]	4.2
Accumulation of demolition material [m^3 per capita]	0.7
Accumulation of construction and demolition waste [m^3 per capita]	0.6
Mining gravel/sand [m^3 per capita]	3.6
Deposited excavated material [m^3 per capita]	5.2
Deposited excavated material from canton [m^3 per capita]	3.9
Imported excavated material [m^3 per capita]	1.8
Exported excavated material [m^3 per capita]	0.4
Cement production [t]	580 000

Table 4
Results of the economic assessment of the building materials industry of the canton Argovia in 2018.

	Revenue [1000 CHF]
Gravel Pits	137′657.29
Gravel Plant	112′998.43
Recycling Plant	20′010.19
Quarries	45′897.90
Cement plant	409′875.00
Concrete Plant	166′480.66
Buildings (structural engineering)	365′825.49
Infrastructures (civil engineering)	272′077.37
Demolition of buildings/infrastructure	64′754.40
Terrain	1′205.00
Landfill	30′147.47
Σ	1′626′929.20

the revenue of the industry. Since the changes amount to a maximum of 2.5%, we can assume that the model is robust to changes in the input parameters. Only three prices stand out which have a greater influence on total sales. These are on the one hand the construction prices for buildings and infrastructures and on the other hand the cement price. This is plausible, as these correspond to the input for the highest-revenue sectors of the industry in this region. For example, Argovia is home to 2 of the 6 Swiss cement plants, which causes a correspondingly high turnover of the cement industry.

5.2. Monte-Carlo Analysis

The results of the MCA show that the greatest uncertainty is found in the prices of the construction processes (Fig. 5). This has different reasons. On the one hand, the data basis for construction prices is poor, so that there are only a few data points with large variation. On the other hand, construction prices are highly project- and region-specific, so that there are large uncertainties in this regard. The goal here should be to improve the data basis and thus reduce the uncertainty. Fortunately, the remaining sectors show little uncertainty. Only the cement sector still shows slightly increased uncertainties. Here, too, only a few data are available, so that a standard deviation of 10% was set. The reason for this is that cement prices, like construction prices, are partly determined on a project- and region-specific basis, and there are also framework contracts with companies for which the prices are unknown and larger discounts are assumed. In general, it must be said that prices are based on public price lists of manufacturers. These prices are seldom requested but adapted to a specific project. Furthermore, there are strong differences in the regions. In regions with high construction activity, the prices, e.g., for concrete, are correspondingly higher than in regions with low construction activity. For the assessment here, average values were used for Switzerland, which causes a certain uncertainty but is acceptable regarding the focus and the level of concern of the study.

5.3. Price model

The results of the price model can be seen in Table 5. The prices were increased by 10% in isolation from each other to identify the resulting price changes in the dependent sectors. This way, the effects of price pass-through can be identified downstream of the value chain. For example, an increase in the output price in the gravel pit (column 1) leads to an increase in the price in the gravel plant by 6.6%. Further price increases are also caused in the concrete plant (1.4%), construction of buildings (1.7%), and construction of infrastructures (0.5%). In general, price pass-through is found to be very low with most of the changes under 2%. This indicates that small price changes triggered by policies, for example, have only a minor impact on the value chain of mineral building materials. This must be considered when formulating policies, e.g., levies on the extraction of gravel, to ensure their effectiveness. Our results show that construction of building is more sensitive to price changes along the value chain of concrete production than construction of infrastructures. Price changes in the recycling plant have a much stronger effect on demolition prices than on concrete prices indicating the importance of waste management services for generating revenues for recycling plants in the status quo.

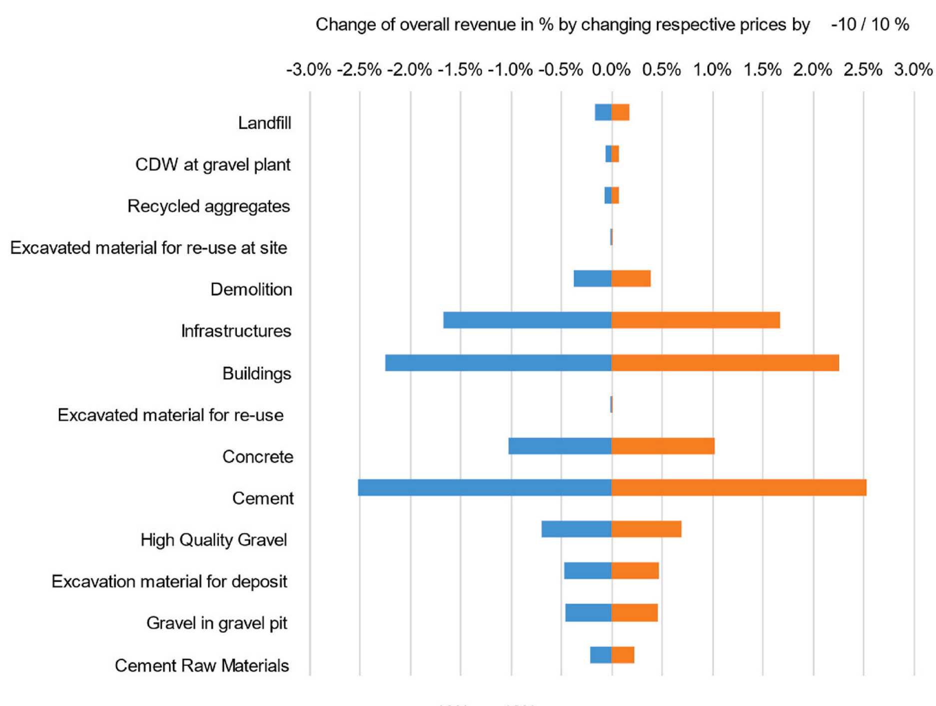

Fig. 4. Results of the Sensitivity-Analysis representing the change in % of the overall revenue when changing prices/costs by ±10%.

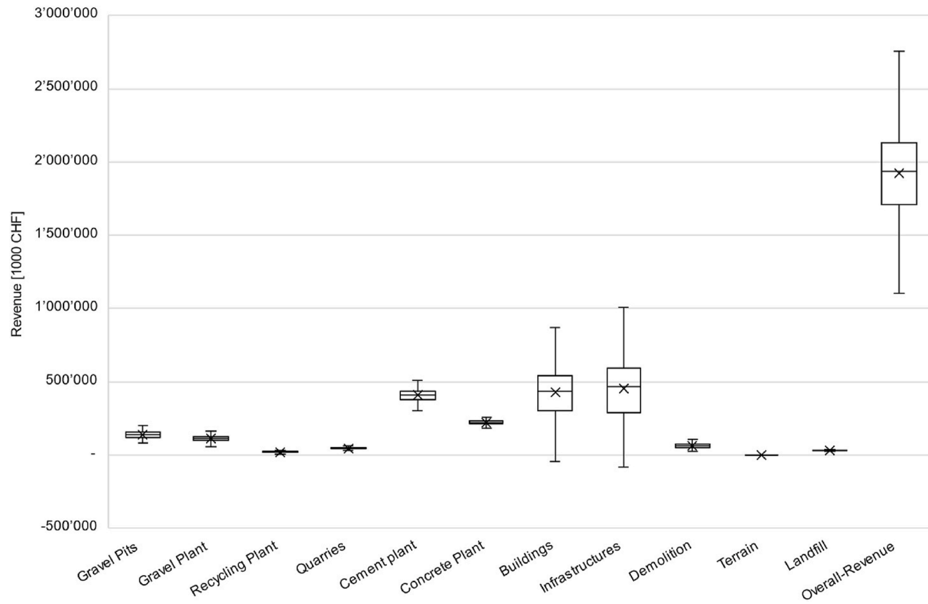

Fig. 5. Results of the Monte-Carlo-Analysis.

Table 5
Effects of changing output prices in the respective sectors (columns) on the output prices of the linked sectors (rows).

		1	2	3	4	5	6	7	8	9	10	11
1	Gravel Pits	10.0%	–	–	–	–	–	–	–	–	–	–
2	Gravel Plant	6.6%	10.0%	–	–	–	–	–	–	–	0.1%	–
3	Recycling Plant	–	–	10.0%	–	–	–	–	–	–	–	–
4	Quarries	–	–	–	10.0%	–	–	–	–	–	–	–
5	Cement plant	–	–	–	0.9%	10.0%	–	–	–	–	–	–
6	Concrete Plant	1.4%	2.1%	0.1%	0.3%	3.3%	10.0%	–	–	–	0.0%	–
7	Buildings	1.7%	1.2%	0.2%	0.3%	1.5%	4.6%	10.0%	–	0.6%	0.0%	0.6%
8	Infrastructures	0.5%	0.8%	0.3%	0.0%	0.2%	0.5%	–	10.0%	0.8%	0.0%	0.4%
9	Demolition	–	–	1.6%	–	–	–	–	–	10.0%	–	0.2%
10	Terrain		–	–	–	–	–	–	–	–	10.0%	–
11	Landfill	–	–	–	–	–	–	–	–	–	–	10.0%

6. Implications of uncertainty, variability and price changes

6.1. *Implications for business-models*

Based on considerations of price fluctuations, the SA results can provide initial indications of which business models are robust in a transition to a circular economy, but also which combinations of individual sectors would be interesting for a circular BM. For example, we assume that a combination of construction activity (buildings and infrastructures) with the demolition sector would result in a more robust BM, as the demolition process can counteract the larger price fluctuations and dependencies of the construction process. A similar beneficial combination could be seen in concrete production and demolition. The concrete sector has greater price dependencies, which can be reduced by securing the supply of demolition material that can be used as secondary gravel. Cement production represents a special case. Apart from the supply of cement, it has few links to the other sectors of the construction industry. To create a more robust BM, most cement manufacturers in Switzerland are expanding their business with concrete production or the manufacture of concrete products. Another approach, which is particularly important regarding the development of sustainable low-carbon cement, is the supply of secondary raw materials. A plausible combination, also given price fluctuations, could be the integration of excavation activities or demolition processes, which can provide important secondary raw materials. This is also important in the face of a projected decline in concrete demand (Heeren and Hellweg, 2019), as reduced production can be compensated for with a waste management service.

6.2. *Implications for policymaking*

In Switzerland, various approaches are currently being discussed on how to promote a CE in the construction industry. In the canton of Basel-Land, for example, a tax on the disposal of CDW is being considered, with a charge of up to CHF 50 per ton of non-contaminated material to be landfilled (Bau und Umweltschutzdirektion Basel-Landschaft, 2020). This policy aims to "force" the companies to recycle more CDW. Similar policies have already been implemented in other countries (Söderholm, 2011). An example of this is the aggregate levy (Ettlinger, 2017) and the landfill tax (Elliott, 2016) in the United Kingdom. The question, therefore, arises what influence such a policy measure can have on the building materials industry. We believe that the SA can provide initial indications of the sectors in which policy measures are more effective, or where barriers are to be expected. Studies have already shown that single measures seem to be ineffective and that it is necessary to combine measures to effectively promote change (Dewick et al., 2019; Domenech and Bahn-Walkowiak, 2019; Söderholm, 2011). Similar conclusions can be drawn from the SA results presented here. The sector "Landfill" seems to be extremely robust to price changes. For a change of ±10%, the total revenue changes by less than ±0.2%. Two conclusions can be drawn from this: (i) The introduction of a levy on landfilling will not lead to a significant reduction in the economic efficiency of landfills, since the price will most likely change only slightly, and (ii) there is a risk that the levy will achieve only low effectiveness since the influence of the levy on the landfill price is small. This would result in only a small incentive for the recycling of construction and demolition waste. In contrast, cement production shows a higher sensitivity to price changes. This could be a further argument in favor of a CO_2-taxation. The tax-induced price changes and the resulting pressure on cement manufacturers can be used as an incentive for innovative low-CO_2-cements and for using secondary raw materials and fuels, thus closing materials cycles, and increasing material and energy efficiency. On the other hand, it can also worsen the economic situation of the region under consideration, as higher cement prices are passed on to the construction prices, thus favoring imports from other regions/countries. In the worst case, this could lead to a reduction in economic output or lower value added by the building materials industry. The results of the price model, on the other hand, show that prices are only partially passed on. An increase in the cement price, for example, would only lead to an increase in the output price of 3.3% in the concrete plant, and only 1.5% and 0.2% respectively in the two construction processes.

This shows that different measures are necessary for different sectors. For price-insensitive sectors such as “Landfill”, low levies are not sufficient. Only a much higher levy or even a landfill ban would lead to a significant change in the business model of landfilling CDW or excavated material. In cement production, levies would probably already have a more significant effect. It still needs to be investigated, however, whether a levy would raise the price of cement to an extend that changes behavior in the construction industry. At present, the cost of building materials represents only a small part of the construction costs, so that the builder has only a small incentive to use sustainable cement. This statement is of course only valid in rich countries like Switzerland. In developing countries, the situation is quite different due to different construction methods and standards. Finally, it must be noted that the different sectors and dynamics within them require a policy mix that is long-term and adaptable (Kern et al., 2019; Wilts et al., 2016), while also considering sequentially to respond to changing constraints (Meckling et al., 2017).

7. Conclusion

“Uncertain aftermaths” and “inadequate awareness, understanding, and insight” are main barriers to implementing a CE (Mahpour, 2018, p. 226). With the novel approach of the uncertainties presented here and the resulting implications for the building materials industry, we want to take a step towards a better understanding of a transition to a circular economy.

In the first step, we were able to show that the model used here is robust and has reasonable uncertainties. This confirms that the combination of MFA and LCA with an IO approach leads to a reliable assessment of a region (Brunner and Rechberger, 2017; Säynäjoki et al., 2017). We were able to show in a qualitative discussion that the MFA and LCA data we used will not cause significant uncertainties at this level of consideration. The quantitative analysis of our financial data also shows no major uncertainties. Only the construction prices cause high uncertainty. This is on the one hand due to the poor data basis, but also due to regional price differences. It must also be noted that average and public price data are used for the analysis, which leads to a certain degree of uncertainty. However, due to the rather broad regional view in this study, this is not considered to be significant. A limitation, which is caused by the model calculation, is the missing passing on of the prices to the next process. This means that, for example, rising cement prices are not passed on to the concrete plants in the model calculation. This pass-through is calculated separately in the presented IO price model and shows that this propagation of uncertainty is low and of negligible importance in this regional analysis.

In a second step, we were able to use the uncertainties and sensitivities to formulate initial indications of how business models are affected by the shift to CE. We have shown that vertical integration of different sectors makes sense regarding a CE to buffer price volatilities, but also to secure the supply of raw materials. For example, mining sectors could counteract a potential resource scarcity by processing demolition waste and using it as a raw material. Market fluctuations can also potentially be mitigated by offering waste management services to decouple their operations from material throughput. These insights provide significant value to the industry by enabling prioritization and supporting the implementation of circular business models. The development of such circular business models represents a fundamental shift, but it is necessary to achieve a sustainable transition to CE.

Furthermore, we have tried to draw conclusions based on the results, in which sectors policies are most efficient. Using a recent example of a proposed landfill fee in Switzerland, we have shown that an increased fee is unlikely to have a negative impact on the sector’s revenue, but also that there is a risk that this policy will have a small effect as the sector’s influence in the building materials industry is relatively low. However, using the example of the CO_2 tax in cement production, we can assume that the influence of this policy is greater since the influence of the cement price is weighted more heavily in the building materials industry. Furthermore, we were able to show the effect of price increases on the downstream sectors. For example, a moderate increase in the price of cement would lead to a noticeable rise in the price of concrete, but a significant increase in construction costs is not to be expected. These results provide initial indications of which policies should be applied to which sectors and can help formulate effective policies that are tailored to specific aspects and have clear objectives.

It must be noted that these findings are based on a broad view and can only provide initial indications. The transition to a closed-loop CE is complex and involves different levels with diverse actors and includes several feedback loops (Foxon, 2011; Geels, 2010; Kliem et al., 2020). The application of sensitivity analysis is one way to better understand this complex behavior (Pianosi et al., 2016).

The new approach presented here to capture a regional industry in detail using economic calculations and uncertainty considerations represents an important contribution to better understand a regional industry and to support the process of decision- and policymaking.

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CRediT authorship contribution statement

Ronny Meglin: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Visualization. **Susanne Kytzia:** Supervision, Validation, Writing – review & editing, Project administration, Funding acquisition. **Guillaume Habert:** Supervision, Writing – review & editing.

Declaration of competing interest

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

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