Towards a Circular Construction Industry: An Empirical Analysis How Construction Companies Transform their Businesses with new Products, Processes, and Business Models

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Summary

Circular Economy is nowadays one of the most trending interdisciplinary research topics in the fields of ecological sustainability, economics, and management science. While a linear economy, our still commonly used economic system, works with processes like ‘take’, ‘make’, ‘use’, ‘dispose’, a Circular Economy aims at keeping products and its resources in a cycle and thus include process steps such as ‘make’, ‘use’, ‘reuse’, ‘remanufacture’, and ‘recycle’. One of the industries, where a transition to a Circular Economy could potentially make one of the biggest impacts, is the construction industry with its vast amounts of primary resources used and its big impact on the environment.

This dissertation contains of two parts: The first one gives a comprehensive overview and introduction of the relevant research motivation, and on the interplay of the four research papers. While the focus on this dissertation lies on how construction companies can transform their businesses towards a Circular Economy with new products, processes, and business models, it is first explained how these affect different organizational levels. Additionally, the theoretical foundation as well as the methodological approach is explained in this section.

In the second part, the four stand-alone research articles analyze through empirical research methods their specific underlying research questions in detail. The first research paper answers the question of the willingness to produce recycled concrete of construction companies and identifies economic and geographical determinants of it. Therefore, a telephone survey was used and combined with regional data. The results show that the market concentration, firm size, partially vertical integration, and economic activity of the region have a significant impact on the willingness to produce recycled concrete. The second research paper examines further the drivers of circular business models and how these models can be operationalized within production processes. In this regard, the role of employees is further examined and how they can influence the set-up times as well as the process quality in construction companies. In this article, an only survey was compiled and analyzed with a structural equation model. Results show that employees do have a significant impact on reducing set-times as well as improving the process quality in construction companies. Furthermore, these improvements also lead to a higher Circular Economy efficiency, which means that a higher share of secondary input materials can be

used, but also a proactive waste reduction during the production is applied. Research paper 3 deep dives into a case study of a single construction company and examines in detail potential value losses and its environmental impact in the production. Therefore, Cost Efficiency Accounting was applied in the construction company for the production of 460 products. The study shows that complex products cause more value losses in production as well have a higher environmental impact instead of non-complex ones. Lastly the article shows, that a material substitution from conventional steel reinforcement to fiber-based reinforcement could benefit in a reduction of the GHG-emissions while not affecting the cost structure of these products. The last research paper answers the question whether construction companies in Germany already have circular products on the market. Therefore, an adapted version of the Material Circularity Indicator was applied to construction products in the database of Ökobaudat. This examination reveals that products with a high circularity score are still an exception, and the majority of the products even have the lowest score.

In summary, the present dissertation gives a deeper insight and understanding of the different levers, drivers and barriers for the transition from a linear to a circular construction industry with a focus on circular business models and efficiency improvements.

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List of Abbreviations

BREEAM	Building Research Establishment Environmental Assessment Methodology
BIM	Building Information Modeling
CDW	Construction and Demolition Waste
CEE	Circular Economy Efficiency
CFI	Comparative Fit Index
CSRD	Corporate Sustainability Reporting Directive
CW_s	Cost Efficiency of a reference object s
C_C	Fraction of mass of a product being collected to go into a composting process
C_E	Fraction of mass of a product being collected for energy recovery where the material satisfies the requirements for inclusion
C_R	Fraction of mass of a product being collected to go into a recycling process
C_U	Fraction of mass of a product going into component reuse
CRU	Components for reuse
C_s^{ideal}	Ideal costs of a reference object s
C_s^{actual}	Actual costs of a reference object s
EECP	European Climate Change Programme
E_C	Efficiency of the recycling process used for the portion of a product collected for recycling
E_F	Efficiency of the recycling process used to produce recycled feedstock for a product
e.g.	*exempli gratia*, for example
EI	Employee Involvement
EMF	Ellen Mac Arthur Foundation
EPD	Environmental Product Declaration
ERP	Enterprise Resource Planning
EU	European Union
F_R	Fraction of mass of a product's feedstock from recycled sources
F_S	Fraction of a product's biological feedstock from Sustained Production. Biological material that is recycled or reused is captured

	as recycled or reused material, not biological feedstock
F_U	Fraction of mass of a product's feedstock from reused sources
F(X)	Utility factor built as a function of the utility *X* of a product
FA	Factor Analysis
GWP	Global Warming Potential
GHG	Greenhouse Gas Emissions
HWD	Hazardous landfill waste
I_R	Proportion of secondary materials used as input
i.e.	*id est*, that is
K_0	Control variable
L	Actual average lifetime of a product
L_{av}	Actual average lifetime of an industry-average product of the same
type	
LCA	Life Cycle Assessment
LFI	Linear Flow Index
M_B	Mass of a product based on the product's reference unit
MC	Main category
MCI	Material Circularity Indicator
MCI_P	Material Circularity Indicator of a OBD product
MCI_{PC}	Material Circularity Indicator of a OBD product category
MCI_{SC}	Material Circularity Indicator of a OBD sub-category
MCI_{MC}	Material Circularity Indicator of a OBD main category
MER	Substances for energy recovery
MFR	Substances for recycling
n	Quantity of products in a category
NWHD	Non-hazardous disposed waste
O_R	Proportion of a product being put to a sustainable use at the end of product life
OBD	Ökobaudat Database
OLS	Ordinary Least Squares
PC	Product category
PSS	Product Service System
R	Sum of Outputs
RP	Research Paper

RMSEA	Root Mean Square of Approximation
RQ	Research Question
RWD	Radioactive disposed waste
SC	Sub category
SEM	Structural Equation Model
SM	Use of secondary materials
SR	Setup Time Reduction
SRMR	Standardized Root Mean Square Residual
TLI	Tucker-Lewis Index
U	Actual average number of functional units achieved during the use phase of a product
U_{av}	Average number of functional units achieved during the use-phase of an industry-average product of the same type
V_B	Mass of virgin feedstock used in a product based on the product's reference unit
W_B	Mass of unrecoverable waste associated with a product
W_{0B}	Mass of unrecoverable waste through a product's material going into landfill, waste to energy, and any other type of process where the materials are no longer recoverable
W_{CB}	Mass of unrecoverable waste generated in the process of recycling parts of a product
W_{FB}	Mass of unrecoverable waste generated when producing recycled feedstock for a product
X	Utility of a product

Part 1:
Introductory Overview of the Dissertation

1 Introduction

1.1 Motivation of the Research Topic

In recent years, the term 'Circular Economy' has picked up tremendous recognition in almost all producing and resource-intensive industries worldwide. The objective of implementing Circular Economy practices is similar in all industries: reducing the environmental impact through a better use of the industry's products and resources. This means that primary resources are preserved, while already extracted resources can circulate longer in the economic system (Fontana et al., 2021). What differs are the preconditions. In the automotive industry, for example, the transition to a Circular Economy overlaps with the electrification of the industry's vehicles, e.g., because of the reuse potential of the batteries (Dräger et al., 2021; Glöser-Chahoud et al., 2021). Battery electric vehicles need to be designed and built in a different way from conventional vehicles in order to compete in price and margin (Fasse & Murphy, 2022). While the needed batteries are very cost intensive and require a high value and functionality, the idea of reusing the battery or recycling its materials after the end of its life is obvious (Baars et al., 2021). In other industries such as the construction industry, on which this dissertation focusses, the need for a Circular Economy stems mostly from that industry's enormous impact on the environment. While the consumption and production of primary raw materials have, at 50%, one of the highest rates in the European Union, the construction industry is also the largest polluter of waste (European Union, 2019). The amount of waste generated in 2014 was 871 million tons and, at 33.50%, made up the largest share of the total EU waste generation. However, compared to the automotive industry, much of the construction waste has a relatively low value and the separation of it is very cost intensive (Katerusha, 2021). Thus, efficient ways to reuse the construction waste need to be evaluated in order to implement a Circular Economy in the construction industry.

The term 'Circular Economy' itself does not have one specific definition but is often associated with activities which recycle products, materials, and resources (Kirchherr et al., 2017). Recycling summarizes in this regard the different levels of the waste hierarchy of the European Commission, shown in Figure 1 (European Commission, 2008). Often, the waste hierarchy shows graphically five different levels of ways to handle waste from products (Knauf, 2015), but there are also more detailed variants of it (Zhang et al., 2022). The different hierarchy levels of the waste pyramid will be explained in the following:

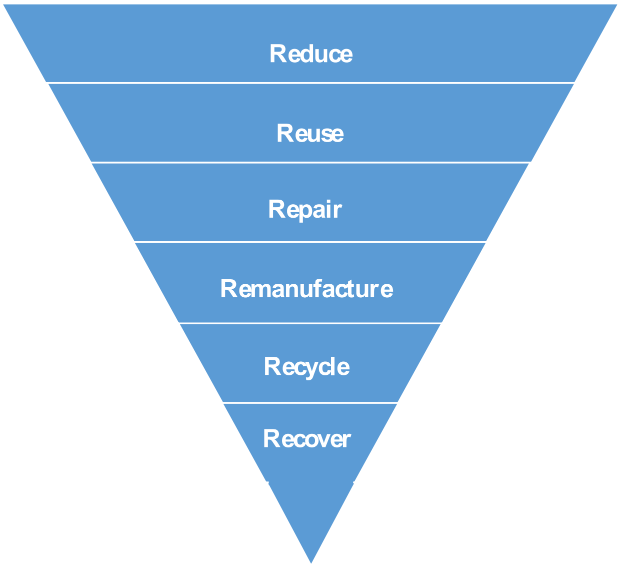

Figure 1: Waste Hierarchy.

'Reduce' is aimed at the initial use of resources, which can be prevented at an early stage and thus will not pass into any product cycle. 'Reuse', on the other hand, means that a product can be used directly for its original purpose at the end of its life cycle. In the case of a reuse, no further effort needs to be put into the product. 'Repair' is similar to a reuse, but in this case, individual parts of the product have to be restored, aiming at lifetime extension and hence reducing total resource consumption by using resources for a longer period of time. In a remanufacturing process, on the other hand, only individual components of the original product are reused or used for a different purpose. If this is either technically no longer feasible or if it is unprofitable from an economic perspective, the product can still be recycled. In this step, an attempt is made to recover as many of the primary materials as possible and to put them to use again. As the final step in the waste pyramid, recovery serves to extract as much energy as possible from the product, e.g. through thermal incineration.

Another perspective is proposed by Bocken et al. (2016), who look at the differentiation between a linear and a Circular Economy in resource flows. They differentiate between three dimensions of resource flows. In the first dimension, the objective is to slow down the material flows, which means that products can be prolonged in their life cycle. This can be achieved in a linear as well as a Circular Economy. In the next dimension, it is also possible to narrow the materials flows by using less material for the same product. Only in the last dimension is the objective to 'close the loop' and to create a circular flow, also known as a Circular Economy. This means that in a Circular Economy, objectives such as slowing down and narrowing material flows are very similar to those of a linear economy. However, a Circular Economy is not only about resource efficiency; rather, it aims for a completely new sustainability paradigm (Benachio et al., 2020; Geissdoerfer et al., 2017; Korhonen et al., 2018). In that regard, research and practitioners are striving to elaborate business models which are designed to keep companies' products in a circle (Bocken et al., 2014; Geissdoerfer et al., 2018; Nußholz, 2018). These new circular business models can be designed with additionally offered services for the customers (Kurdve et al., 2015; Munaro et al., 2020), with take-back mechanisms for a higher product responsibility (Ploeger et al., 2019; Schultmann & Sunke, 2008), or with a better valuation of the waste pyramid (Ghisellini et al., 2018). Based on the motivation, it can be said that the Circular Economy aims to replace the previously prevailing linear economic system with a circular one. Here, the natural resources available for producing products and services are finite, but they can be used multiple times. This means that products and their raw materials are not only produced for single use but can be added back to the system by recycling them.

1.2 Research Model and Associated Research Question

Following this motivation, three main areas for transformation remain which can influence the Circular Economy within the construction industry. First, there are **new products** which are adapting the idea of the Circular Economy and thus keeping the raw materials longer in the system (Bakker et al., 2014; Nußholz et al., 2019). By considering the economy as a circle, this can be realized on the one hand by developing new input materials for the products. This means that instead of using primary raw materials, such as stone, lime, and clinker for the production of concrete, secondary raw materials can be used as a replacement (López Ruiz et al., 2020). Another option is the usage of innovative materials, e.g. carbon fiber-reinforced concrete instead of steel-reinforced concrete, on account of their beneficial environmental characteristics. This could result in a longer life cycle of the product as well as improved characteristics (Ilg et al., 2016; Ortlepp et al., 2018). Lastly, with innovative product designs it is possible for products to be easily separated into their raw materials after their end of life, which improves their circularity by reducing separation and deconstruction efforts (Charef et al., 2021; Hossain et al., 2020).

Second, **new processes** can affect the transition to a Circular Economy as well. Especially in the construction industry, digitalization and automation still lag behind other industries and thus it is worthwhile to analyze processes and to identify avenues for improvement. Prefabrication, where parts of buildings are produced in a production plant and then delivered to the construction site, are one possible solution to closing the gap with other industries (Chen et al., 2010; Minunno et al., 2018). In this context, the interplay between new processes and their executing parts means that employees and machines should not be underestimated. Additionally, automation plays an important role in transforming the construction industry into a Circular Economy. One promising tool can be seen in Building Information Modeling (BIM), where all relevant information of construction products, such as material information and recycling information, can be stored. Environmental information, e.g. from a life cycle assessment (LCA), is regarded as especially useful (Honic et al., 2019; Xue et al., 2021). One application to provide LCA information in the construction industry is that of environmental product declarations (EPD), in which these data are stored and are publicly accessible (Passer et al., 2015).

Third, completely new business models can change the way in which the construction industry operates. Those **circular business models** can either define new value chain architectures or create new revenue streams (Adams et al., 2017; Nußholz, 2018; Nußholz et al., 2019; Yu et al., 2021). New value chains can be built in both ways, from the supply chains as well as on the end-customer side. New suppliers can replace existing ones, for example, when they offer raw materials which are not from a virgin feedstock, but which might have already had a product life before. However, in the case of recycled concrete, these suppliers need completely different competencies, e.g. in crushing and separating the material from demolished buildings (Dahlbo et al., 2015; Ghaffar et al., 2020; Silva et al., 2019). On the demand side of end-customers, construction companies can find new ways to interact with long-time customers and to aquire new ones. In this regard the question remains of how much customers are willing to pay for circular products instead of conventional ones (Boyer et al., 2021). One prominent example, which is changing the revenue streams and is being implementented in the construction industry too, is that of product service systems (PSS). In PSS, a company offers only the usage of the product, but retains ownership of it (Linder & Williander, 2017; Yang et al., 2017). As a result, the customer often pays only a rent instead of paying for the full product.

All three transformation areas 'new products', 'new processes', and 'circular business models', can affect construction companies at different levels, namely, the strategic, the operational, and the intercompany value chain level.

Following this explanation, the research model of this dissertation targets the different obstacles to improving the Circular Economy in the construction industry, as shown in Figure 2:

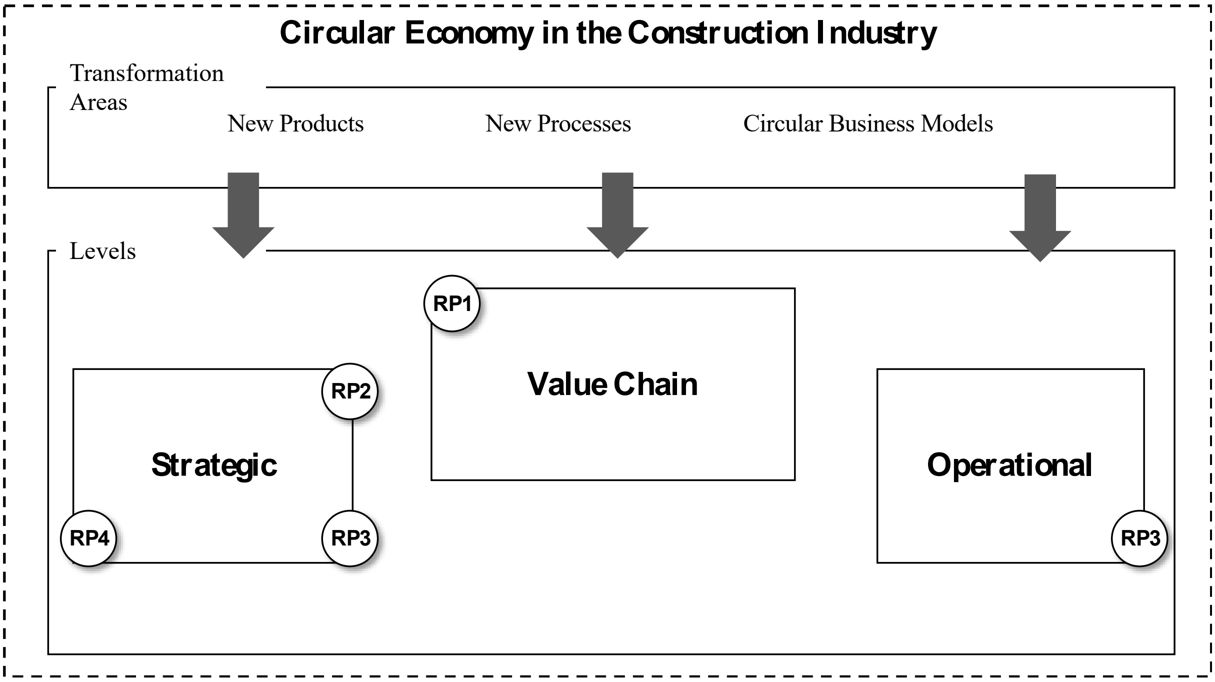

Figure 2: Research Model

Specifically, the following overarching research questions guide this dissertation:

- How can construction companies contribute to transforming their industry into a Circular Economy with new products, new processes and circular business models?
- How can company characteristics be changed in order to transform the strategic, operational, and value chain decisions?

To answer these research questions, this cumulative dissertation consists of four research papers, each of which focusses on different aspects of the research model.

In the **first research paper (RP1)** "Circular Economy in Construction – An Empirical Evaluation of the Willingness to Produce Recycled Concrete in Germany", an examination of the case of recycled concrete took place. The focus was set on analyzing how the business model and the production processes of construction companies would change if their primary input material were to be changed to recycled input material. Following this, RP1 tackles two areas of transformation in this dissertation on the level of value chains (Figure 3). The purpose of RP1 is the identification of the economic and geographical determinants of the production readiness of recycled concrete, with a focus on Germany. Due to this coordinative task within supply chains with new processes and business models, the specific research questions of RP1 were:

- RQ1: Which factors influence the willingness to produce recycled concrete?
- RQ2: Which measures are necessary to establish a Circular Economy for concrete?

For this purpose, a telephone survey of ready-mix concrete producers was conducted and the resulting data were combined with regional economic and geographical conditions and empirically analyzed.

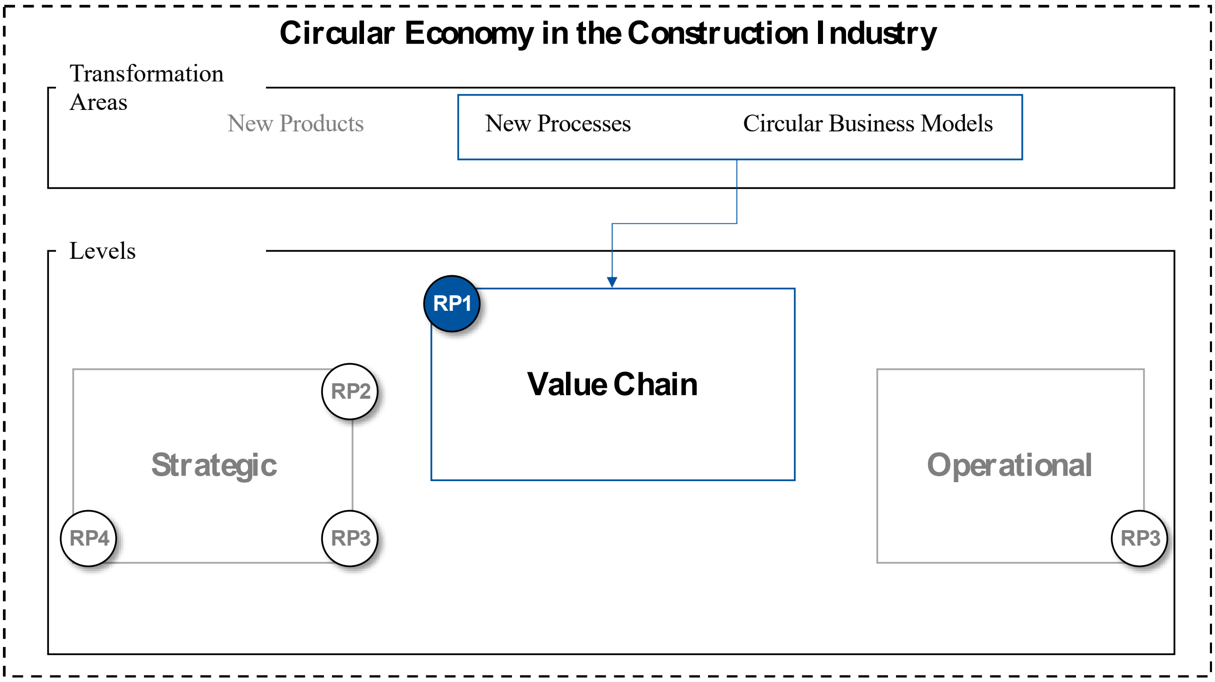

Figure 3: Research Model for RP1.

In the **second research paper (RP2)**, “Who Drives Circularity?—The Role of Construction Company Employees in Achieving High Circular Economy Efficiency”, the objective was chosen to gain an intra-company view of construction companies, and how these improve Circular Economy efficiencies through new processes and new business models. Important factors under investigation are employee involvement at the operational level, e.g., in production processes, and how this involvement can be strategically steered, as shown in Figure 4. Therefore, the related research question was:

- RQ: How does employee empowerment affect the efficiency of Circular Economy factors in the construction industry?

For this purpose, a company survey was conducted and analyzed with a structural equation model.

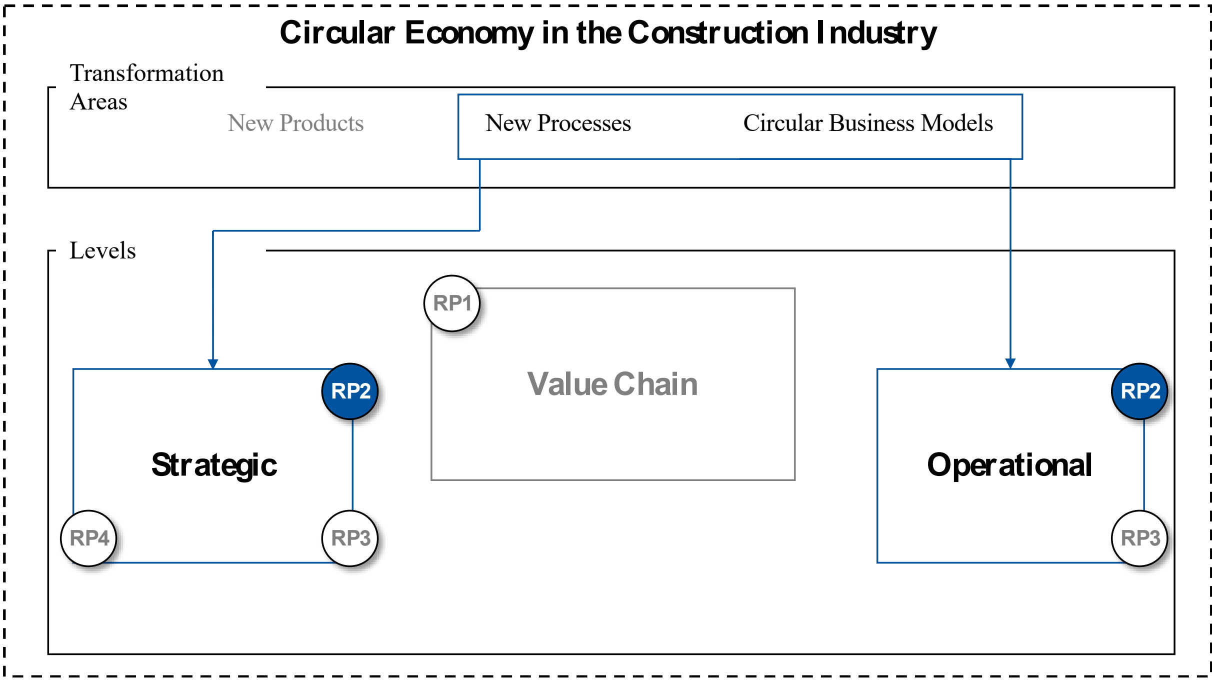

Figure 4: Research Model for RP2.

Research paper 3 (RP3), "Value losses and Environmental Impacts in the Construction Industry – Tradeoffs or Correlates?", examined the question of whether an improvement in manufacturing efficiency also reduces environmental impacts. Thus, the research questions were:

- RQ1: How can Cost Efficiency Accounting help to identify products that allow companies to reduce their environmental impacts?
- RQ2: To which degree do value losses during the production stage correlate with their environmental impact in the construction industry?

In this article, the methodology of Cost Efficiency Accounting was applied to a quantitative case study of a German precast construction company. Besides the operational introduction and evaluation of this measurement system, strategic decisions such as material substitution were analyzed in terms of value losses and environmental impacts. In Figure 5 it can be seen how RP3 is reflected in this dissertation:

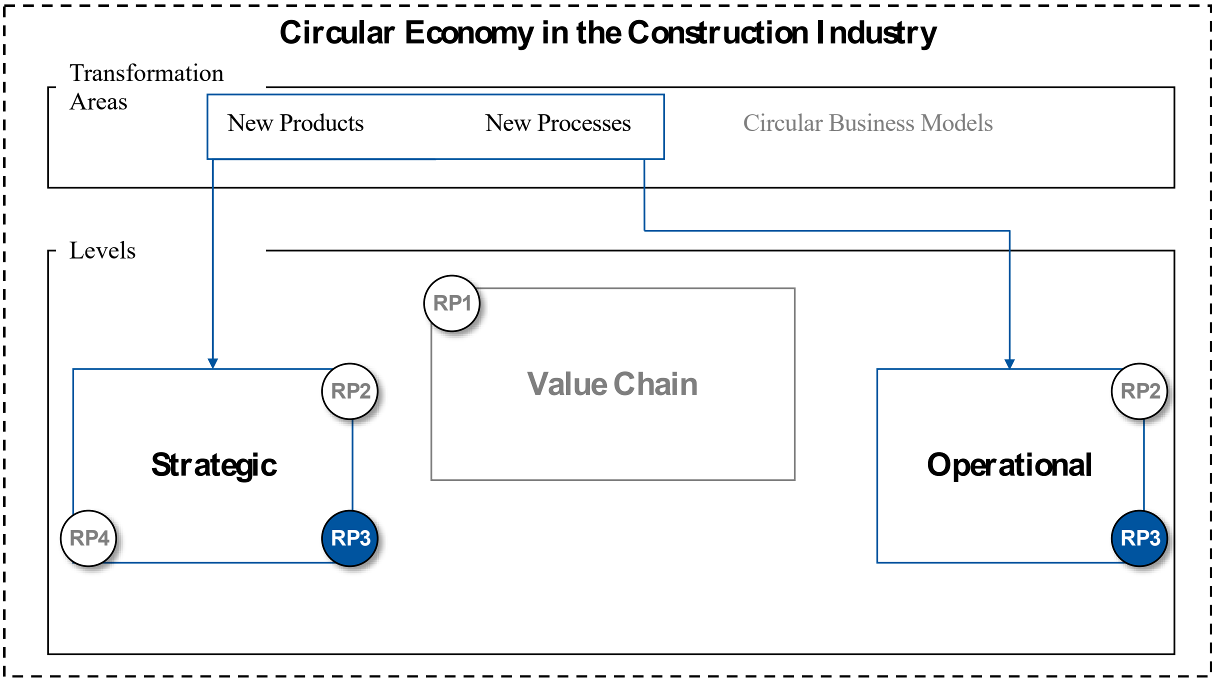

Figure 5: Research Model for RP3.

The last **research paper 4 (RP4)**, “Measuring circularity: evaluation of the circularity of construction products using the ÖKOBAUDAT database”, the circularity of construction products in Germany was evaluated. The objective was to check construction products’ circularity based on their environmental product declarations and to compare different product types regarding their circularity. The underlying research question was:

- RQ: How do different construction products or product groups listed in OBD (“Ökobaudat”) perform in terms of circularity measured with a circularity indicator?

For answering this research question, the Material Circularity Indicator (MCI) was adapted and applied to the OBD database. On the basis of this analysis, strategic decisions based on a company’s product portfolio can be made to improve circularity. Figure 6 shows this relationship in the research model of this dissertation:

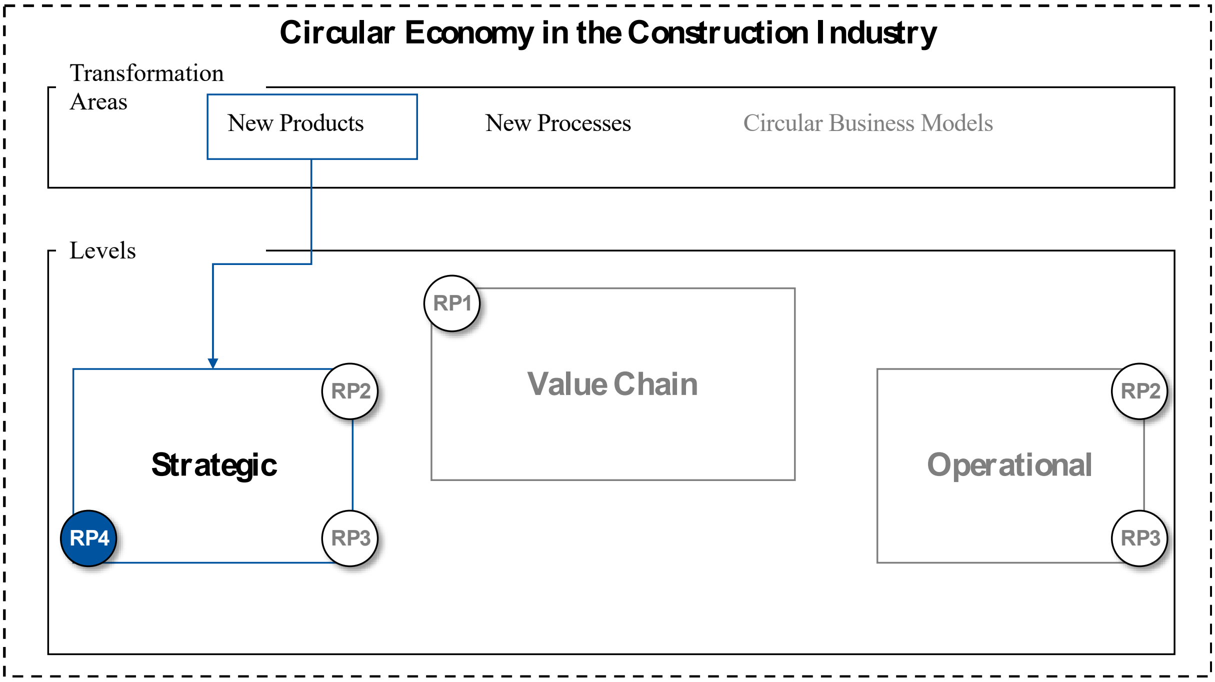

Figure 6: Research Model for RP4.

Table 1 provides an overview of the four articles with their authors, research questions and publication status:

Table 1: Overview and Actual Status of Research Papers.

#RP	Title	Research Question(s)	Authors	Publication Status	Presen-tations
RP1	Circular Economy in Construction – An Empirical Evaluation of the Willingness to Produce Recycled Concrete in Germany.	RQ1: Which factors influence the willingness to produce recycled concrete? RQ2: Which measures are necessary to establish a Circular Economy for concrete?	Dräger, Katerusha	**Planned to submit:** Journal of Cleaner Production	Abfall-wirtsch-aftstage Münster 2019
RP2	Who Drives Circularity?—The Role of Construction Company Employees in Achieving High Circular Economy Efficiency	RQ: How does employee empowerment affect the efficiency of Circular Economy factors in the construction industry?	Dräger, Letmathe	**Published in:** Sustain-ability 15 (9), 7110	POMS 2019
RP3	Value losses and environmental impacts in the construction industry –	RQ1: How can Cost Efficiency Accounting help to identify products that allow companies to reduce	Dräger, Letmathe	**Published in:** Journal of Cleaner	POMS 2018, VHB 2019

	Tradeoffs or Correlates?	their environmental impact? RQ2: To which degree do value losses during the production stage correlate with their environmental impact in the construction industry?		Production 336, 130435
RP4	Measuring circularity: evaluation of the circularity of construction products using the ÖKOBAUDAT database	RQ: How do different construction products or product groups listed in OBD perform in terms of circularity measured with a circularity indicator?	Dräger, Letmathe, Reinhart, Robineck	**Published in:** Environ-mental Sciences Europe 34, 13

2 Theoretical Concepts

The Circular Economy in the construction industry is a highly interdisciplinary field of research, thus there is a wide variety among the different research streams and their underlying theories. Within this dissertation, the focus lies on how companies in the construction industry can build their business within the Circular Economy. On this basis, there are four underlying theoretical concepts which are applied in this dissertation. In this chapter, the concepts of Natural Resource-based View, Lean Construction, Cost Efficiency Accounting, and the MCI will first be elaborated.

2.1 Natural Resource-based View

The Natural Resource-based View, developed by Hart (1995), is an extension of the classical Resource-based View of Barney (1991), which can be seen as a strategic framework for companies to achieve long time competitive advantages. But compared to the Resource-based View, where the focus lies on company-related resources such as value, rareness, inimitability, and substitutability, the Natural Resource-based View adds as a competitive advantage for companies in their relationship to natural resources out of the natural environment (Hart, 1995). This is particularly relevant for concepts like the Circular Economy, which focusses on the objective of keeping materials and resources as long as possible in the loop (Kalmykova et al., 2018).

In the framework of the Natural Resource-based View, Hart (1995) introduces three strategic capabilities which will ensure a long-term competitive advantage through activities which include environmental considerations. The first capability is pollution prevention, which is intended to reduce waste streams in companies. Following this, an improved utilization of inputs means a higher efficiency. Besides this, pollution prevention can already cut emission and thus reduce the costs of liability costs from regulations. Second, product stewardship, which means internalizing the environmental impacts that a product has over its lifetime. As an approach for measuring the environmental impacts, methodologies like LCAs are considered, which include all the environmental impacts of a product. Additionally, product stewardship also includes take-back mechanisms, where the relationship between a product and its producing company does not end with it being sold to a customer. Mechanisms like take-back can ensure that the product and its materials find their way back into the company after the product's end of life. By doing this, companies have the incentive to reduce environmentally hazardous businesses, to redesign products and product systems, as well as to lower the life cycle costs of a product. Third, sustainable development enhances a company's business activities and also those of its supply chain and customers. Especially within global supply chains, the range of sustainable practices can vary substantially. Thus, companies should also give more attention to less developed geographic regions.

2.2 Lean Construction

Lean Management and the principles behind it originated in Japan after the Second World War and have gained worldwide recognition and imitation through their consistent implementation by Toyota in the 1970s (Womack et al., 1990). During this period, the supply of raw materials and the build-up of inventories were critical bottlenecks that made it necessary to increase production performance (Diekmann et al., 2005). These bottlenecks gave rise to various approaches in companies, such as just-in-time production, total quality management, continuous improvement, and zero inventories. Womack et al. (1990) describe the principles involved as follows:

- Specifying value is crucial to prioritize the customer's perspective. Therefore, a company should identify the customer's needs and their willingness to pay for the product or service.
- Identifying the value stream entails recognizing all activities that generate value for the customer. Eliminating activities that do not add value is necessary as they are considered waste and do not contribute to what the customer desires.

- Enabling product flow necessitates a process-oriented approach, where a company ensures that it produces products and operates in a way that avoids slow departmental decisions. Aligning all process steps reduces waiting times for machinery and employees, minimizing value losses.
- Pull of the customer means that a company delivers the product at the right time as per the customer's needs. Applying principles such as just-in-time is essential in this regard.
- Managing towards perfection emphasizes continuous improvement and transparency in products and processes to identify and eliminate waste.

Over the decades, the focus in the implementation of these principles has been set on reducing waste, ensuring continuous improvement, and reducing cycle times (Gurumurthy & Kodali, 2011; Holt et al., 2000; Kurdve et al., 2014). However, because the lean management philosophy was developed within the manufacturing industry, these principles have had to be adapted to the construction industry, because both industries have different characteristics (Diekmann et al., 2005). For example, the construction of a building is often project-oriented instead of flow-oriented. Furthermore, in construction projects, many different companies have to work at the same time, which often results in increased coordination efforts. Another important factor is the usage of products from the construction industry, which often tend to be immobile rather than mobile. In order to accommodate those special characteristics, two aspects have to be reconsidered (Diekmann et al., 2005). First, even greater emphasis has been placed on involving employees who receive further training at every level of the hierarchy and who are encouraged to become proactively involved (Holt et al., 2000). Second, repeatable work processes need to be defined to ensure a high level of standardization. In addition, a high level of prefabrication must be achieved to ensure delivery quality (Chen et al., 2010).

2.3 Cost Efficiency Accounting

Cost Efficiency Accounting is a concept developed by Letmathe (2002), and is particularly relevant for research that examines efficiency gains in production through reducing value losses. The concept was chosen for this dissertation because it enables the measurement of value losses, such as time and materials. Additionally, the concept is easy to adapt and to implement in specific cases, e.g. for construction companies, where it ensures a robust theoretical foundation and still ensures that it can be implemented in practice. Cost Efficiency Accounting uses a single efficiency indicator: the cost efficiency of a reference object, e.g. a process, a product, or an organizational unit. It is defined as the ratio of ideal and actual costs of the reference object:

$$CW_s = \frac{C_s^{ideal}}{C_s^{actual}} \tag{1}$$

with: CW_s Cost Efficiency of a reference object s

C_s^{ideal} Ideal costs of a reference object s

C_s^{actual} Actual costs of a reference object s

Ideal costs define an "artificial" construct that characterizes an ideal production in which no value losses exist. The main driver is an ideal consumption, i.e. the consumption of all inputs (materials and capacities) equals their optimal levels. Simply speaking, all materials will be part of the final products, machines run at their optimal speed, and humans work at (long-term) cost-optimal productivity levels. For Circular Economy purposes, that would also imply that all products and resources could circle endlessly in the economy, like a perpetual motion machine (Cullen, 2017). Even though these kinds of machines and value flows do not exist in reality and some losses always occur, the "idealization" always shows the direction for improvements. Ideal costs are further calculated by multiplying ideal consumptions by their planned cost rates. The ideal consumption can be defined individually but should mostly contain the areas "time" (capacity consumption of machines and human labor) and "material/resources" (Letmathe, 2002). These areas are relevant for increasing the resource efficiency as well as improving Circular Economy practices (di Maio et al., 2017). In Cost Efficiency Accounting, deviations from ideal costs will be traced back to inefficiencies, or waste, in these areas. Those areas include (for the following, see Letmathe, 2002):

- All procured material is completely used to produce the final products, which means no material is wasted at all, i.e. through cuttings, shrinkage, or theft. Referring to the construction industry, it means that materials such as concrete would only be needed in the desired volume of the final product, e.g. walls or stairs. Also, steel for reinforced concrete will always be cut into the ideal length and. in the end, there is no residual steel left.
- Undesired by-products, such as solid waste and sewage, are not built up during the production process, because they do not add value to the final product. This is even true for by-products, which could have a value in themselves but do not contribute

to the defined and planned final product of the production process. With this assumption, water and waste management are no longer relevant.

- No scrap or rework is necessary, because the final product already has all relevant quality specifications with no defects. This also means that recycling processes, which are relevant in the Circular Economy to ensure a cycle, are not required in Cost Efficiency Accounting.
- The entire output conforms to all relevant quality specifications, which will lead to a zero-defect production. If this assumption is given, the gross output quantity (actual output quantity) will equal the net output quantity (useful output quantity).
- Additionally, there is no supervising and quality inspection needed, because all products have already been produced to exactly the specifications required. The same principle applies to the production processes, where no improvements can be made, since no waste of materials or any scrap occurs.
- Changeovers and setup times either do not exist or does not consume any time or cause interruption to the production processes.
- The same applies to processing times. Each product will be produced within exactly the cost-optimal processing time with no interference from machine breakdowns or waiting times.
- After the product has been produced, it will be delivered just-in-time to the customer, which means stocks and inventory will not build up. Additionally, raw materials or semi-finished products can directly be used for further processing.
- There are no time losses during production: Unplanned interruptions to machines and shop-floor workers are excluded, and time fluctuations are not considered.

These attributes define ideal standards which cannot be accomplished completely in practice. For example, in most cases it is impossible to eliminate setup times entirely or to install a just-in-time system with no inventory. Under these circumstances, a perfect cost efficiency of “1” can never be achieved. Cost efficiency losses result from any deviation from the ideal production. By aiming at the elimination of all non-value adding activities and resources, there is an unambiguous direction for improvement. Since cost efficiency is a dimensionless indicator, the cost efficiencies for each of those areas can be aggregated. Hence, they can be compared within a single process or production of a product and show directly in which area the highest improvements can be achieved. Another advantage of this universal indicator is that it does not have to deal with the underlying cost data, a fact which lowers the complexity of its interpretation and facilitates direct improvements on the shop-floor.

2.4 Material Circularity Indicator

The last theoretical concept applied in this dissertation is the Material Circularity Indicator (MCI) of the Ellen McArthur Foundation (Ellen MacArthur Foundation & Granta Design, 2019; Ellen MacArthur Foundation, 2015). This indicator measures product circularity based on product and resource flows. While there are also other indicators that have been developed to measure circularity on the product level (Heisel & Rau-Oberhuber, 2020; Kristensen & Mosgaard, 2020; Linder et al., 2017), the MCI aims to steer companies towards reducing virgin input materials, adding more renewable materials, reducing value losses in production, as well as increasing a product's durability (Ellen MacArthur Foundation, 2015). Thus, this indicator is able to provide an overarching picture of circular products (Elia et al., 2017). Furthermore, Saidani et al. (2019) confirm that the MCI provides robust values for measuring circularity on the product level. Moreover, many researchers have also started to apply this concept for measuring circularity, thus improving the comparability of their findings (Bhochhibhoya et al., 2022; Rocchi et al., 2021). The objective of the MCI on the product level is to evaluate circularity, based on three basic drivers, with the following equation:

$$MCI = 1 - LFI * F(X) \qquad (2)$$

with: *MCI* Material Circularity Indicator of a product
LFI Linear Flow Index
F(X) Utility Function of a product

First, within the calculation it is considered how linear the product flow is (LFI). This means that a product whose input materials are completely from a virgin feedstock, is considered to be a fully linear product. On the other hand, products with no virgin feedstock, but with materials collected from recycling, and/or from reused components, can be considered to be a circular product.[1] Second, it is considered how long the product will be used compared to an industry average (F(X)). This consideration benefits products

[1] In this case it also depends on the degree of the recycling efficiency. In practice, the percentage of a fully circular product ranges between 0 and 100 percent.

which are longer in use and thus have a longer durability. This specific driver is important for scaling the value of a product, because with a long durability various use phases still maintain a high value. Third, the indicator considers how intensively a product is used compared to its industry average. This particular driver further enables companies to evaluate their business models and to influence how long a product can be used.

3 Research Methodology

The research gap and the overarching research question have revealed that more evidence from empiricism is required. For that reason, this dissertation uses surveys in RP1 and RP2 as well as a case study in RP3 and an exploratory analysis in RP4 as its methodologies in order to ensure high external research validity. This multi-methodological approach enables the inclusion of different perspectives of the research questions and the various views of the Circular Economy. In the following chapter, the choice of the different methodologies as well as the data collection and data analysis of all four research papers are elaborated.

3.1 Choice of Methodology

Surveys, especially online-based ones, have several advantages compared to other research methodologies such as interviews or case studies. First, they give the researcher access to a larger population, which can be used in quantitative analyses (Wright, 2006). Therefore, they are often used to discover relationships between groups or organizations and to try to generalize a statement or an objective (Gable, 1994). This advantage is used in RP1 in a telephone survey and RP2 in an online questionnaire to collect company-related information and to apply it to the construction industry. A second benefit that this dissertation took advantage of in RP1 and RP2 is the saved time (and cost) for the researcher as well as the answering person (Wright, 2006). Interviewing the same sample size would require a lot more time and cost effort in order to gain the same information as a survey does. Additionally, the answering person can choose in a survey the best time slot for completing a questionnaire and thus is more likely to respond.

Case studies are generally useful when the researcher tries to answer “how” or “why” questions, such as this dissertation does in RP3 (Yin, 2014). But in contrast to other methodologies, such as experiments, a case study does not require the control of behavioral events, since phenomena in the real world cannot be controlled completely (Yin, 2014).

However, for research topics which should be applicable to companies in the construction industry, it makes sense to do the research directly within a company. One major objective of RP3 was to examine how Cost Efficiency Accounting can be applied within a construction company. For that reason, a single case design was chosen. Single case designs are especially useful when a common case, i.e. everyday situations which are easy to duplicate, is under investigation (Yin, 2014). This was the case in RP3, where the case company was a medium-sized construction company in Germany, which could be seen as representative of many other companies in this sector. Even though a common criticism of using this methodology is that the validity decreases, RP3 ensured the highest validity possible through a very structured approach. First, multiple sources of data were used to establish a high construct validity (see Chapter 3.2). Additionally, the case study was built as a quantitative case study to ensure objectivity in the analysis. Second, logic models and rival explanations were used and discussed for a high internal validity (Chapter 3.3, Chapter 4.3). Third, the theoretical foundation within the case study is well defined, as described in Chapter 2, to address the external validity for a single case study.

In RP4 we performed an explorative analysis with data from the public available database OBD in order to answer the research question. This approach is especially useful when exploring data with a novel approach, as was done in RP4 with the adapted circularity indicator.

Table 2 summarizes the methodological approach for the different research papers, including the data collection and data analysis:

Table 2: Methodological Approach for RP.

#RP	Methodology	Data collection	Data analysis
RP1	Survey	Telephone survey, geographical coordinates, Dafne database	Ordered logistic Regression
RP2	Survey	Online questionnaire	Structural Equation Model
RP3	Case Study	On the shop floor, ERP System, Interviews	Cost Efficiency Accounting; Linear Regression (OLS)
RP4	Explorative Analysis	EPDs, Ökobaudat	Adapted Circularity Indicator

3.2 Data Collection

In **RP1**, the data were collected from German construction companies, based on primary and secondary Nace Rev. 2 allocation. The company data, including the telephone numbers for the telephone survey, had been extracted from the database Dafne, which is operated by Bureau Van Dijk - A Moody's Analytics Company and contains the annual reports information of companies located in Germany as well as their contact information. 1267 production sites of ready-mix concrete were identified within the chosen Nace allocation, and these companies were organized into 412 enterprises. 117 companies took part in the telephone survey - these companies operate a total of 457 concrete production sites. Thus, the survey had a response rate of 28.39% when considering the enterprises and 36% when considering the concrete production sites, which is above the threshold for conventional surveys. To ensure the high response rate and the comparability of the survey, a structured call process was developed, as shown in Figure 7:

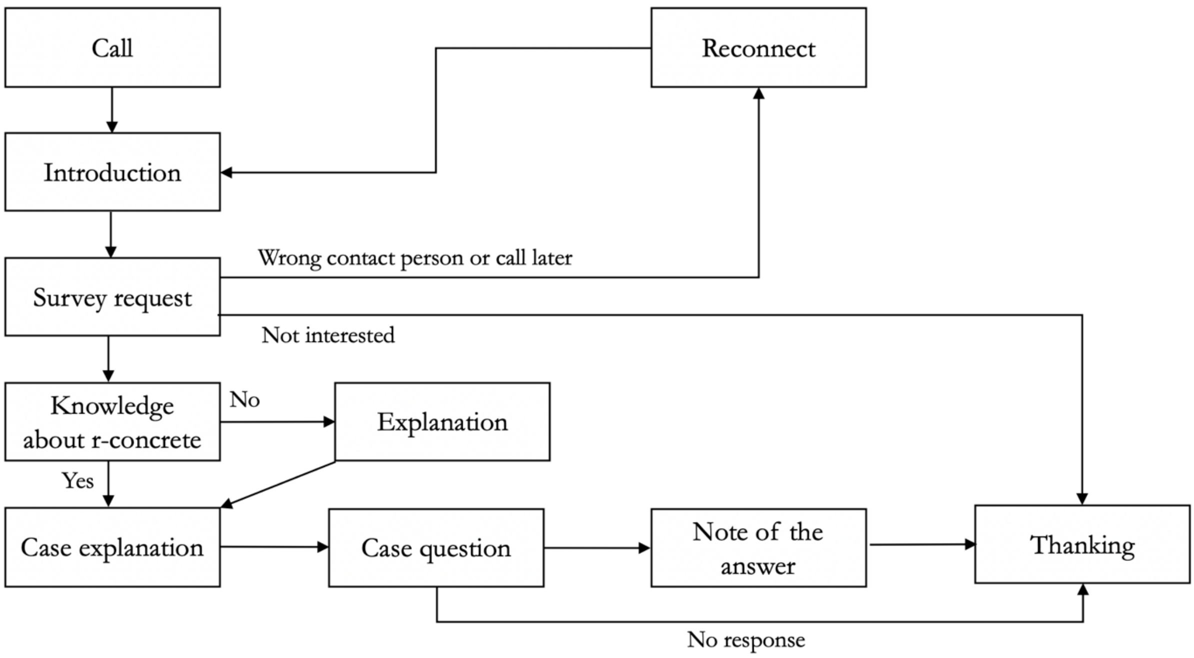

Figure 7: Protocol of the Telephone Survey.

After the introduction process, where the objective and the background of the research question were explained, a single question was asked which was relevant for the dependent variable in order to determine the potential willingness to produce recycled concrete in a fictive situation. The situation and the following question were defined as follows: *Imagine that a customer contacts you to order recycled concrete. You would be willing to accept such an order with a comparable quantity of conventional, ready-mixed concrete.*

How likely would it be - on a scale of 1, definitely not, to 5, definitely - that you would accept this order?

The answers were recorded on a 5-level scale of the Likert-type to ensure comparability and a quantitative analysis. In order to avoid an interpretation-related distortion of the answers between participants, the quantitative significance of the answers was pointed out to interviewees - e.g. answer option 2 would indicate a likelihood of accepting the order of roughly 25%:

- 1: Definitely not (≈0%)
- 2: Probably not (≈25%)
- 3: Possibly (≈50%)
- 4: Probably (≈75%)
- 5: Definitely (≈100%)

As one company can operate several concrete sites, it was asked whether the answer applies to all the concrete plants of the company. If the answer did not apply to all the company's concrete plants, the contact person for each site was contacted separately. In order to keep the responses comparable, the telephone survey process was standardized, as shown in Figure 7. To increase the response rate, the companies that could not be reached were called again two weeks after the initial call. The other data needed for RP1 were collected from the Dafne Database and complemented by the geographical location data of each production facility.

In **RP2,** the data were also gathered from a company survey to test the hypothesis. The survey contained questions of four constructs. Each construct, i.e. employee involvement, process quality, setup-time reduction, and Circular Economy efficiency, had four to six questions. Again, the questions could be answered within a 5-level Likert scale. The questionnaire was implemented via soscisurvey to ensure the highest security standards. After a validation by industry and research experts, the questionnaire was sent to construction companies which had recorded activities in the following Nace Rev. 2 areas:

- 233 - Manufacture of ceramic building materials,
- 235 - Manufacture of cement, lime and gypsum,
- 236 - Manufacture of products from concrete, cement and plaster,
- 237 - Processing and processing of natural stone and stone,
- 239 - Manufacture of grinding tools and abrasives and other products made from non-metallic minerals,

- 381 - Collection of waste,
- 382 - Waste treatment and repair,
- 383 - Recovery,
- 41 - Building construction,
- 42 - Civil engineering,
- 43 - Preparatory construction site work, construction installation and other finishing trades.

Given the environment of the case study of **RP3**, different data sources were combined for the analysis. First, to specify the scope of the study, interviews with the production and facility managers of the examined companies clarified which production process would be useful for the examination. Second, data on the produced products were collected on the shop-floor. This included the actual production times, rework times, waiting times, complexity, quality, and interruptions. Lastly, data from a company's ERP-system was added to obtain the planned production times, the amount of concrete per product, the used steel per product, and the geometrics of the products. The data sources are shown in Table 3:

Table 3: Sources of Data.

Data	On the shop floor	ERP-System	Interviews
Time	Actual production times; rework; waiting times	Planned production times	Processes
Material	-	Concrete; steel; geometrics	-
Value losses	Complexity; quality; interruptions	-	Areas of value losses; interruptions

Additionally, external data, specifically the Environmental Product Declaration (EPD) from the German "Institut Bauen und Umwelt", were used to evaluate the Global Warming Potential of the examined products. Within three consecutive months, data on 460 produced products were collected.

RP4 used the publicly available data source of environmental data for construction products OBD. This database is hosted by the German Federal Ministry of the Interior and Community and contains relevant EPDs in line with DIN EN 15804 (Bundesministerium des Innern, 2020). Further, external validity is secured through a third-party validation according to DIN EN ISO 14025. Following the RQ of this respective RP, the objective was to evaluate the circularity of construction products. Therefore, material flows were taken into account, but energy use, for example, was left out due to the conceptual limitations of the MCI (Ellen MacArthur Foundation, 2015). Table 4 shows the seven indicators which fulfilled this criterion in the OBD-database:

Table 4: Relevant Data used of OBD-Database.

Notation	**Description**	**In- / Output**
CRU	Components for reuse	Output
HWD	Hazardous waste for landfill	Output
MER	Substances for energy recovery	Output
MFR	Substances for material recycling	Output
$NHWD$	Disposed non-hazardous waste	Output
RWD	Disposed radioactive waste	Output
SM	Use of secondary material	Input

3.3 Data Analysis

Different statistical and non-statistical methods were used to analyze the data. Given the data structure of RP1, the dependent variable “potential willingness to produce recycled concrete” is measured as an ordinal scaled variable. An ordinal logistic regression was chosen for the analysis because it describes the causal relationship between the ordinal response variable and one or more independent variables (Fagerland & Hosmer, 2016). RP2 uses a covariance based structural equation model to test the proposed hypothesis in combination with a factor analysis and a structured path analysis (Lee et al., 2011). The examined and tested variables were Circular Economy Efficiency, Process Quality, Setup-time Reduction, and Employee Involvement. In RP3, ordinary least squares (OLS) regressions are used to examine the relationship between the dependent variable “time variation” and the independent variables “concrete”, “volume”, “steel”, and “complexity”. Additionally, Cost Efficiency Accounting was used to evaluate and analyze the value losses of the produced construction products. Lastly, in RP4, the data from the OBD with a Circularity Indicator for products were analyzed by adapting the MCI of the Ellen McArthur Foundation (Ellen MacArthur Foundation, 2013). The indicator uses the material flows in an input-output perspective and calculates for products a circularity score compared to the industry average and product lifetimes.

4 Key Findings of Research Articles

This chapter provides a short summary of the key findings from the four research articles and shows how the articles address in the different areas of this dissertation's research-model- specific aspects, which were described in Chapter 1.2. The detailed articles can be found in Part 2 of this dissertation.

4.1 Research Article 1

The goal of RP1 was to identify which factors influence the potential willingness to produce recycled concrete and which measures are necessary to ensure this change. While this affects the whole supply chain of the concrete industry and the business models of the ready-mix concrete producers, we surveyed 117 companies in the industry. The results were combined with geographic data on the companies' production sites as well as company-related data, such as their vertical integration. The evidence for the tested hypotheses is summarized in Table 5:

Table 5: Evidences of RP1.

#	**Hypothesis**	**Evidence**
H1	The willingness to produce recycled concrete increases with rising regional market concentration.	Supported
H2	The willingness to produce recycled concrete increases with rising firm size.	Supported
H3	The willingness to produce recycled concrete decreases if the concrete producer also manufactures or mines natural stone, sand and gravel.	Supported
H4	The willingness to produce recycled concrete increases if the concrete producer also undertakes the demolition work at the construction site.	Not supported
H5	The willingness to produce recycled concrete increases if the concrete producer also undertakes the waste collection.	Supported
H6	The willingness to produce recycled concrete increases if the concrete producer also undertakes the waste recycling.	Not supported
H7	The willingness to produce recycled concrete increases with rising economic activity of the region.	Supported
H8	The willingness to produce recycled concrete increases with rising distance from the supply area of the concrete production plant to the disposal site.	Not supported

H9	The willingness to produce recycled concrete increases with rising distance from the concrete production plant to the sand, gravel and stone supplier.	Not supported

These results yield that the regional market concentration, the firm size, upfront vertical integration, and the economic activity of a region increases the willingness of firms to produce recycled concrete. In that regard, interesting insights can be drawn from this dissertation. First, producers of ready-mix concrete depend besides other factors strongly on the activity of their respective region (H1 and H7) rather than their supply chain (H8 and H9). Second, they are willing to adapt their business models into circular business models via a higher vertical integration. The results regarding vertical integration show more evidence of upfront integration (H3) compared to later integration (H4, H5, and H6) which could possibly be explained by ready-mix concrete producers perceiving more influenceability in their input material than in the end of life of their products (Torres-Guevara et al., 2021). Lastly, the firm size as a significant indicator (H2) can explain why the demand for recycled concrete is still not being driven sufficiently by customers in order to move the industry towards a higher use of recycled materials. Besides the testing of the hypotheses with the original calculated data, a scenario analysis was added with the predicted probabilities across the response categories, shown in Figure 8:

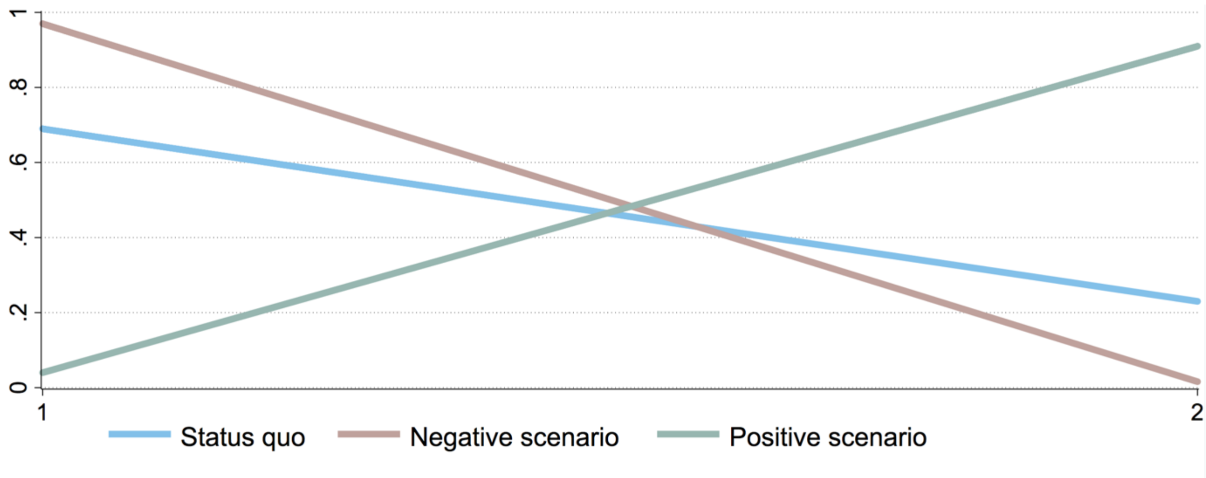

Figure 8: Predicted Probabilities across Response Categories.

Status quo: all parameters set to mean values.

Negative scenario: HHI=10, population=100000, production of gravel=1, waste collection=0, employees=5. Positive scenario: HHI=70, population=1000000, production of gravel=0, waste collection=1, employees=20. Category 1: definitely not or probably not; category 2= probably or definitely.

The positive scenario (green line) varied with a higher market concentration, a higher number of employees, and added waste collection as an operational area, while in the negative scenario (red line) the market concentration as well as the employee size shrank, and the companies had additional operations in the primary raw material activities instead of in waste collection. The scenario variations show that the probability of producing recycled concrete increases to almost 100% in the positive scenario, while the negative scenario indicates no production of recycled material at all.

4.2 Research Article 2

After ascertaining the interconnections of the supply chain for producing recycled ready-mix concrete, the research focus of RP2 lies on the question of what the drivers of circular business models on a strategic level are and how the models are operationalized into processes which enable construction companies to transition into a Circular Economy. Therefore, the role of employees in production processes within the construction industry was observed and the way in which employees influence the process quality and setup time reduction. Furthermore, the analysis answered the question of how a better process quality and a reduced setup time can increase Circular Economy efficiency. For this examination, a structural equation model was applied. The elaborated hypotheses were all statistically supported and thus indicate the high importance of employees as drivers of the transition (see Table 6).

Table 6: Evidences of RP2.

#	Hypothesis	Evidence
H1a	Employee involvement in construction companies increases the process quality in manufacturing processes.	Supported
H1b	Employee involvement in construction companies reduces setup times during manufacturing processes.	Supported
H2a	A high process quality in manufacturing processes increases circular efficiency.	Supported
H2b	A low setup time during manufacturing processes increases circular efficiency.	Supported

The support for the first hypothesis demonstrates that involved employees in construction companies help to increase the process quality in construction processes through a higher empowerment (H1a). In the construction industry, the impact is probably even stronger compared to other industries due to its high degree of manual work. The current and ongoing trends towards more prefabrication of construction products also underlines the need for maintaining a high process quality (Jang & Lee, 2018; Tam et al., 2015). Strongly empowered employees can specifically reduce the amount of scrap, rework, and process-time interruptions, because they know the materials; they work with them and they operate within the processes. They are also best able to identify inefficiencies and waste sources and can find ways to prevent them. Furthermore, they can find and suggest ways for improvements, e.g. via a higher reuse of input materials or auxiliary materials, and thus can be a driver of circular improvement (Kurdve & Bellgran, 2021). Additionally, the result of the second hypothesis shows that a higher employee involvement decreases the setup times, because employees are enabled to use special tools or to redesign jigs (H1b). On the one hand, this positively influences the amount of waste generated during production because it enables the workers to handle the products with the right machinery in the right time. On the other hand, due to a faster setup time, companies can switch more easily between production programs and can thus produce environmentally friendly products besides conventional ones. Consequently, this leads to the result that a high process quality and a low setup time can both increase the Circular Economy efficiency in the production processes of construction companies (H2a and H2b). A high process quality is important for reducing the amount of waste in construction companies because only materials which are necessary for the products enter production. This shortens the material cycle, one of the objectives of Circular Economy efficiency (Bocken et al., 2016). Additionally, with a lower setup time it is possible to react more flexibly to circular approaches and circular products, which also increases Circular Economy efficiency. Increased Circular Economy efficiency can be characterized by a higher share of secondary input materials, proactive waste reduction, application of useful measurement indicators, and already including these features in the design phase.

4.3 Research Article 3

Following the findings of RP2 that high process quality and low setup time increase Circular Economy efficiency, RP3 excludes the changes in the circular business models and examines in more detail how product and process changes affect construction companies on a strategic and an operational level. Specifically, the objective of this article was to examine in a construction company with a three-step approach whether value losses in production and environmental impacts correlate with products in the construction industry. First, the statistical results indicated that there is a significant correlation between the time deviation between ideal and actual production time and the measured variable's complexity ($p<0.01$). This indicates that complex products already cause high value losses in the production phase. Considering that those complex products are, further, more complicated to reuse, remanufacture, and recycle at the end of their life, highlights the importance of smart production designs (Hazen et al., 2017). Additionally, the volume of the products also had a highly significant correlation with the time deviation ($p<0.05$). This result also shows that with more voluminous products, value losses in the production occur more often, and probably a smaller or thinner product design can result in fewer value losses. Besides this, the material components steel and concrete had no significant influence on the first results, as is shown in Figure 9:

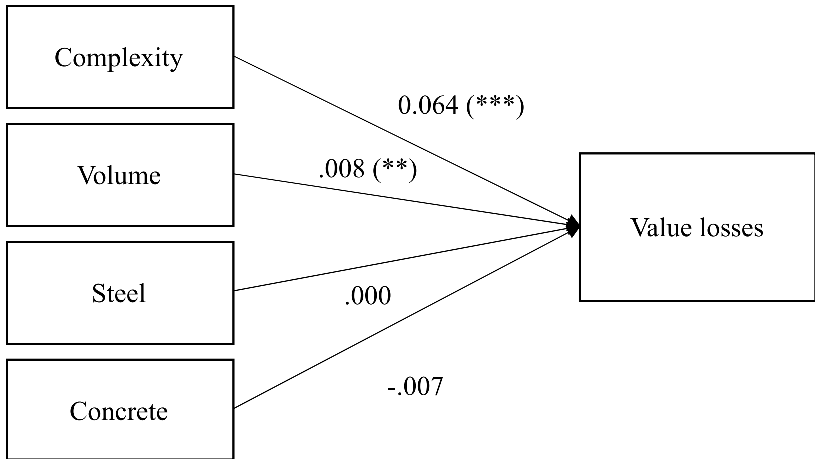

Figure 9: Regression Results (n=379).
** p<.10; ** p <.05; *** p<.01*

In the next step, we used Cost Efficiency Accounting and elaborated that complex products not only cause more value losses but also have a higher environmental impact than less complex products do. Therefore, the complexity was split into the three defined complexity levels, and we found that with each higher complexity level, the cost efficiency decreased by 3.3%. One reason for this could be that complex products require more rework and encounter more unplanned interruptions compared with easier-to-produce products. Furthermore, the examination revealed a potential practical improvement stemming from the fact that the supplying of concrete as material input was mentioned as being the most appropriate reason for a cost increase.

Lastly, we investigated a possible material substitution of steel reinforcement by fiber reinforcement to evaluate how developments towards more environmentally friendly products affect production costs. Fiber-reinforced concrete was chosen because it promises to have better environmental and technical specification compared to conventional concrete

(Ilg et al., 2016). Furthermore, the case company had already experienced working with fiber- reinforced concrete, which means that a transition could be a real application case. Products of all complexity levels could improve their environmental footprint, mainly due to less concrete usage. Especially on complexity level 3, an environmental footprint reduction of 69.4% of the GWP was measured while keeping the production costs ranging from 1312.42 Euro for steel-reinforced products to 1302.68 Euro for fiber reinforcement products equal. These results showed that environmentally friendly products do not necessarily increase the production costs of certain construction products. Moreover, it is possible with suitable instruments, such as Cost Efficiency Accounting, to evaluate whether trade-offs between these decisions are necessary. In our case, with fiber reinforcement it was possible to reduce the amount of required concrete to an extent where it was environmentally as well as economically favorable.

4.4 Research Article 4

In RP3 it was shown that companies have the option to evaluate whether material substitution towards a more environmentally friendly product is also economically feasible. The focus in the final article of this dissertation considers the question of whether construction companies already have environmentally friendly products on the market. Moreover, RP4 examines the question of how companies can measure the circularity of their products on a strategic level and it also evaluates the status quo of new, circular products in the German construction industry. In doing so, RP4 applied an adapted version of the MCI from the Ellen McArthur Foundation to construction products from the OBD in order to measure the circularity on the product level. Based on the objective of evaluating the circularity of the whole life cycle, incomplete data sets, e.g. when relevant life cycle modules were missing, were deleted. 89 products were analyzed and then aggregated into 4 main category levels, i.e. insulation products, plastics, metals, and mineral construction materials. The results answer the research question of how different construction products listed in the OBD perform in terms of circularity. Results revealed that in the German construction industry the circularity of its products is still very low. While the MCI can assume a value of between 0 (no circularity) and 1 (fully circular), the results of product circularity for an average product utility vary between 0.10 and 0.52, with an average circularity of 0.19. Out of 89 analyzed products, 55 only achieved the lowest score of 0.10 which means that a linear material flow with primary materials is still common practice in the German construction industry. An average product utility of a 50-year lifetime was chosen because most construction products are used in buildings which determine the overall lifetime (Bundesministerium des Innern, 2019). Thus, this assumption increases the individual circularity scores. The analysis with individual lifetimes for insulating materials, which are lower than the average lifetime, result in even lower circularity scores. An input–output comparison of recyclable products showed that more products can potentially be recycled which already consist of recycled input materials. This implies that companies which improve their input raw material stream of recycled raw materials also consider the end of life of their products. The metals category achieved the highest circularity score, driven by the steel and iron products, which achieved a score of 0.46 (see Figure 10).

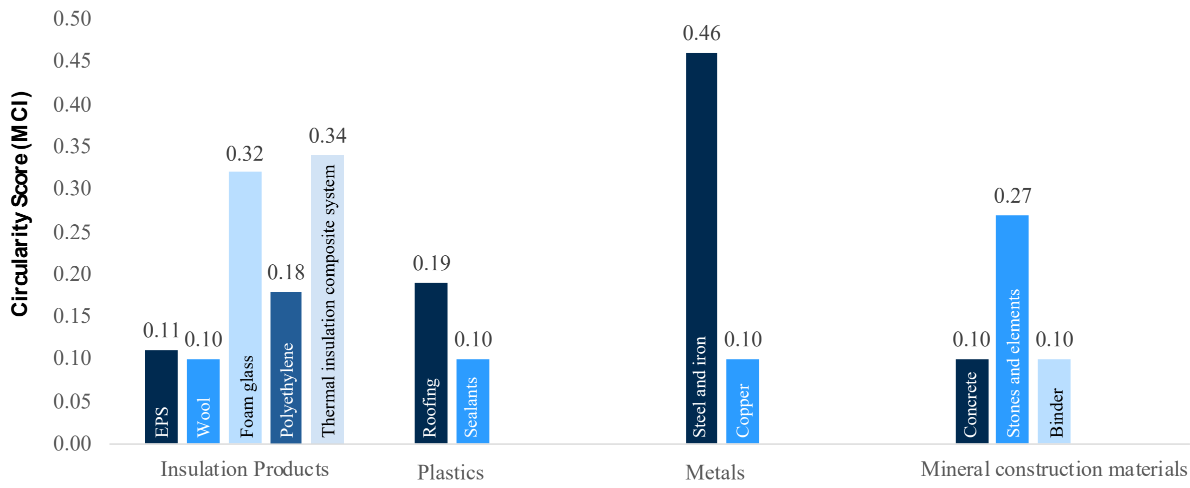

Figure 10: Sub-Category Results of Circularity Indicator.

5 Summary and Conclusion

5.1 Research Implications

The findings of this dissertation are relevant for closing the above-mentioned research gaps regarding whether and how companies in the construction industry can contribute to transforming their industry into a Circular Economy as well as evaluating their specific characteristics with regard to the Circular Economy. On the one hand, the results show that economic and ecological performance are not mutually exclusive. Moreover, it has become clear that both performances are influenced by the same factor in the production environment, namely through the elimination of waste. Since within the Circular Economy as well as in the closing of material loops, the elimination of waste is the key driver (Sassanelli et al., 2019), it can therefore be stated that circular business models can be viable in theory and are not necessarily mutually exclusive due to a lack of economic attractiveness. The empirical results of this dissertation also show that in the example of the willingness of ready-mix concrete producers, that companies are ready to implement circular business models. However, regional conditions and the vertical integration of the companies also make a difference and must be taken into account in such a transition. Especially for a heavy material such as concrete, transportation and logistics needs to be taken into consideration. It also becomes clear that employees remain a driving force for change, especially for Circular Economy efficiency. This does not come as a surprise, since productivity gains in construction are very dependent on employee empowerment (Alazzaz & Whyte, 2015; Holt et al., 2000). The data also demonstrate the importance of employees for Circular Economy efficiency, the latter helping to operationalize and implement a Circular Economy in construction companies. Last but not least, the application of the circularity indicator showed, from a methodological point of view, that already existing indicators can visualize the status quo of the circularity in the construction industry at the product level. Moreover, it also proved that most of the construction products are still considered to be linear, and thus that real circular product solutions are basically non-existent in practice.

5.2 Managerial Implications

Besides the previously described theoretical importance, various implications for practice can be drawn from the results of this dissertation as well. Over the last years, the topic of the Circular Economy has gained a lot of attention in companies (BDI initiativ, 2021). It first started with an organizational transformation due to regulatory requirements from national governments and from the European Union. However, companies also themselves realized that going a step further and not only reacting but also aligning their vision and strategy with a Circular Economy is necessary (Covestro, 2021). This dissertation examines different levels along this transformation process of construction companies. First, construction companies should rethink their supply and value chain activities. This includes on the one hand an improved coordination and communication with old and with new supply chain partners and clients. In particular, a profound knowledge of the material flows over the whole life cycle of products is mandatory for companies for understanding the risks and opportunities involved in a Circular Economy transition. Under the circumstance that companies can oversee their own activities best, this internal perspective needs to be sharpened. The results of this dissertation show that when companies consider increasing their material share of secondary raw materials, they should either invest in this technology themselves or lower their activities in primary input materials. Ready-mix concrete construction companies which understand their internal value proposition and are already operating in recycling activities, are more likely to produce with secondary material than companies who do not. Therefore, the first implication for practice and construction companies can be stated: **Each construction company can contribute to a transition to a Circular Economy by challenging their own as well as other businesses and building up knowledge of material flows.**

This dissertation also shows that companies need efficient steering processes in order to implement their strategy. Often, a potential trade-off between environmentally friendly product solutions and cost-efficient production processes cannot be evaluated due to the absence of suitable data, methodologies, and tools. Cost Efficiency Accounting is such a tool. It was shown in a case study with a construction company (RP3) that it is possible to evaluate potential trade-offs or even correlations between environmentally friendly products and cost efficiency. Besides providing the option to depict a detailed view of value losses in production and potential bottle necks, such as the concrete supply in the examined case company, it also simplifies the evaluation of material substitutions. In RP3 a material substitution of steel-reinforced concrete by fiber-reinforced concrete was analyzed alongside a possible material substitution of conventional concrete by recycled concrete. These results lead to the second implication for practice: **Construction companies should be able to track their value losses in production and to evaluate whether (or which) material substitutions correlate with lower costs and a better environmental performance.**

Furthermore, the operationalization of Circular Economy strategies can only be achieved if employees are involved. Due to the highly manually work tasks in the construction industry, employees can still influence improvements like waste reduction, process changes, and environmentally friendly product development. Yet this operationalization does not need to start from scratch. Often, efficiency programs, such as lean production, are already in place in companies belonging to the construction industry and thus only have to be strengthened by focusing on Circular Economy objectives. Therefore, the third implication can be formulated:

Construction companies depend on their employees when operationalizing Circular Economy strategies and thus should integrate the skills and experience of employees into the transition.

A final implication for the construction industry and for practitioners that can be drawn concerns the actual status of circular products, which is currently at the infancy stage. Since RP4 elaborated that most of the construction products achieved the lowest circularity score, linearity still dominates. These results can have several reasons which have direct relevance for companies. First, it shows that there are still a lot of improvements for circular products industry-wide. Even if some companies, such as Eberhard Bau with its product "zirkulit", are proof that developing circular construction products is possible, it is not yet sufficient. These innovators must prove within the next years that the business model behind them is not only ecologically but also economically feasible. Second, and even more importantly, companies should be able to evaluate their own product portfolio for circularity. Only if they are aware of this portfolio, can they make decisions in order to improve circularity. In this regard, RP4 shows – with its methodological approach of an adapted version of the MCI from the EllenMcArthur Foundation – that measuring circularity on a product level is both possible and important in order to improve the Circular Economy in the construction industry. Hence, the final implication is: **Measuring circularity in construction companies on a product and a company level is mandatory in order to provide a profound basis for decisions on Circular Economy strategy implementation at product level.**

5.3 Limitations and Outlook for Future Research

While this dissertation contributes to the field of quantitative and empirical research for the Circular Economy in the construction industry, there are still some limitations and avenues for future research. With the decision of a multi-methodological approach in this dissertation, it will hardly be possible to replicate results in the same way that the research for this dissertation was carried out. But for such a complex and interdisciplinary research topic, the methodological approach should be chosen to answer the research questions in particular. In RP1, a telephone survey was conducted and was kept short in order to achieve a high respondent rate. While this objective was met, an online questionnaire could also be developed to gain even further and deeper knowledge about the risks and opportunities of ready-mix concrete production companies when transitioning towards a Circular Economy.

Additionally, potential political incentives or regulatory provisions could be considered in order to understand at what point the break-even occurs to change their business model. From a corporate governance point of view, directives such as the Corporate Sustainability Reporting Directive (CSRD), could help to improve circularity in the construction industry and therefore their impacts should be examined in future research. Under the consideration of how new processes affect the strategic and operational implementation, the skills which employees need could be examined in more detail. While RP2 showed that empowerment is one aspect to increase process efficiency and reduce waste, companies should train their employees in skills to enable them. In this vein, topics such as digitization and Industry 4.0 should be considered in order to improve Circular Economy practices. Since RP3 also showed the importance of shop-floor employees together with the methodological advantage of collecting data directly (and manually) in production, an integrated approach with automated data collection could also be examined. Furthermore, even though the case company had a good fit to prove external validity, additional companies could apply the Cost Efficiency Accounting as well to obtain comparable insights and results. It would be also interesting to apply this approach in a decision-making analysis and to analyze whether environmentally friendly product decisions also result in a better overall company performance. Additionally, a quantitative comparison between different circularity indicators for construction products could evaluate further parameters, such as water or energy, which were left out in RP4 due to the methodological limitations of the chosen MCI. Combining these further research avenues with circularity indicators aggregated on company levels, researchers could not only evaluate whether a correlation between an overall environmental and financial performance exists but also extract whether circular products can drive this development. Therefore, a further integration of cost elements is mandatory in addition to a resource-focused view.

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Part 2:
Research Papers of the Dissertation

Research Paper 1: Circular Economy in Construction – An Empirical Evaluation of the Willingness to Produce Recycled Concrete in Germany.

Authors: Dmytro Katerusha, Philipp Dräger

Publication Status: Planned to submit to Journal of Cleaner Production.

Abstract

Within the construction industry, most construction and demolition waste is still downcycled and hinders a transition to a Circular Economy. In the case of concrete, there already exist several technical processes to achieve a circulation of the material. However, the industry is not yet implementing these innovations.

The aim of this study is to identify the economic and geographical determinants of the production readiness of recycled concrete in Germany. For this purpose, a telephone survey of ready-mix concrete producers has been conducted. The resulting data was combined with regional economic and geographical conditions and empirically analyzed. Results indicate that the market concentration, firm size, partially vertical integration, and economic activity of the region have a significant impact on the willingness to produce recycled concrete. With increasing market concentration, company size, and economic activity of the region, the potential willingness to produce recycled concrete increases. It decreases if the concrete manufactures take over the production and procurement of input materials such as sand and gravel in addition to its main activity. The results thus show that companies are willing to minimize downcycling their material and move from a linear to a circular economy, as long as economic factors support it. But for a widespread use, still further external incentives (e.g. from the government) are needed.

Keywords: Circular Economy, sustainable construction, recycled concrete, downcycling, market concentration, vertical integration

JEL Classification: L10, L11, L70, L74, L78

1 Introduction

1.1 Background

In the construction industry, the common perception is that most resources are still used in a linear economy with the take, make, dispose paradigm (Webster, 2015). The amount of waste generated in 2018 was 838.98 million tons and, at 35.9 %, made up the largest share of the total EU waste generation (Eurostat, 2018). One way to counteract the waste of resources is the use of a circular economy. The term Circular Economy is used to summarize strategies for systematic change with the means of recycling, reuse and reduction (Munaro et al., 2020). The Ellen MacArthur Foundation made has largely shifted the focus of its reports to the Circular Economy and contributed to the dissemination of research and practice examples in this field (Ellen MacArthur Foundation, 2013; Webster, 2015). The European Union also recognized the importance of a resource circulation and created a directive to enable the transition to a Circular Economy in Europe (Council of the European Parliament, 2008; European Commission, 2020). Despite this, in Germany, although 89.8% of construction waste (CDW) are already recycled, the recycled CDW is largely used in road and waste facility construction but not in civil engineering. Only 21.6 % of the CDW was recycled for new asphalt and concrete production, which means a lack of exploitation of the full potential of a Circular Economy (Bundesverband Baustoffe – Steine und Erden e.V., 2018).

For this reason, first the waste hierarchy has to be understood and the strategy with the lowest value losses has to be selected to achieve a higher implementation of Circular Economy practices (Council of the European Parliament, 2008; Esa et al., 2017a; Kalmykova et al., 2018). In the example of the construction industry, this means using materials in civil engineering projects again for civil buildings, and not for road construction. In achieving this, companies within the supply chain must meet both the demand and the supply of secondary materials and have to evaluate which strategy they apply (López Ruiz et al., 2020). However, especially in the processing of CDW, the implementation seems to be lacking.

1.2 R-Concrete as a Driver for Circular Economy in Construction

In the construction industry, concrete is commonly used as the foundation for most structures and thus could be especially beneficial for Circular Economy implementation. In a study by Honic et al. (2019), concrete showed even a bigger recycling potential than timber (Honic et al., 2019).

Classic concrete consists of cement, water, aggregates, and additives. The main part are the aggregates (mainly gravel and sand), which make up about 80 % of concretes total weight (Müller, 2018).

However, these aggregates can be replaced to a large extent by secondary aggregates without great loss of quality (Alnahhal et al., 2018; de Brito and Saikia, 2013). The raw materials for this come from CDW, which will be collected after the end of life of buildings, separated, processed, and then re-used in the concrete production (Yu et al., 2021). This so-called r-concrete has no significant worse characteristics than conventional concrete and could therefore be used in the same product applications in building construction (Knappe, 2014; Müller, 2018; Nobis and VollprachtAnya, 2015; Stürmer and Kulle, 2017)

On the other hand, the separation and processing of CDW is still a new and complex process, in which the recycling facility has an important role to deliver the right quality of recycled aggregates (Yu et al., 2021). With poor quality, limited applications are available and most CDW material can only be downcycled (Duan and Li, 2016; Zhao et al., 2010). Also, in developed countries, it is stated that the recycling of concrete is not yet a feasible solution due to high investment costs and the market structure of the CDW industry (Bao and Lu, 2020). But, production costs to produce recycled aggregates seems comparable to conventional one (Wijayasundara et al., 2016). Another barrier mentioned is the lack of appropriately located recycling facilities since the distance makes it uneconomically for concrete producers (Rao et al., 2007). A similar conclusion is made by (Zhao et al., 2010), who see the economy of scale and the location of recycling facilities as the main drivers for economic feasibility.

1.3 Contribution

Literature shows, that the foundation for a functioning r-concrete market - technical prerequisites and political regulation - are given, but there are still further factors missing to establish a circular concrete production.

The decision whether to offer r-concrete is made by the ready-mix concrete producers. It is obvious that if there is no regional supply of recycled concrete, no buildings can be built with r-concrete. Sustainable construction through the use of recycled concrete is highly dependent on the supply of r-concrete and thus on the ready-mix concrete manufacturers as actors in the construction value chain. As the production of recycled concrete requires changes in the existing production processes and infrastructure as well as consideration of specific regulatory requirements, it makes sense to consider the decision situation from the manufacturers' point of view. This study takes the perspective of ready-mix concrete producers and empirically examines the economic and geographical determinants of the willingness to produce recycled concrete. To investigate the willingness to produce recycled concrete, a telephone survey was conducted among ready-mixed concrete producers located in Germany. The data collected in this manner was combined with regional economic and geographical data and applied to an empirical model to test the formulated research hypotheses. The study at hand first derives the research hypotheses on the determinants of willingness to produce r-concrete. Subsequently, the procedure for data collection and the general research design are described in detail. In the following sections, the collected data are descriptively analyzed in the context of established hypotheses. Afterwards, an empirical model is specified with which the hypotheses on the determinants of willingness to produce recycled concrete are investigated. In the last section of this article the central results are discussed and summarized.

2 Theoretical Background and Hypothesis

2.1 Market Concentration and Firm Size

For the production of r-concrete with subsequent use in building construction, large quantities of recycled granulate of adequate, controllable and homogeneous quality are necessary, which requires a cost-intensive selection and control procedure (Gálvez-Martos et al., 2018). In contrast to conventional concrete, whose production is highly technically standardized, the production of r-concrete requires development and adaptation of the special concrete recipe. It depends on the composition of the recycled granulate and the desired concrete properties (Stürmer and Kulle, 2017). Recipe costs incur for each concrete manufacturer involved in the construction project. In order to remain economical as a company it is possible to pass additional production costs on to the client. This can lead to a decrease of the price competitiveness of recycled concrete with the increasing number of concrete suppliers involved. Thus, it can be assumed that recycled concrete is more price-competitive if fewer companies serve the regional demand (Gálvez-Martos et al., 2018; Yu et al., 2021). Since the costs of recipe adjustment are incurred individually for each producer, the price competitiveness of recycled concrete is highest if only one company serves the entire regional demand. Furthermore, it is expected that a decrease in the number of competitors is associated with a decrease in the intensity of competition (Menezes and Quiggin, 2012). Even if the price of recycled concrete is higher than that of conventional concrete in a market where competition is less intense, demand has few or no possibilities to shift to another producers.[2]

Since the usage of recycled concrete impacts the process of value creation and the structure of the value chain, recycled concrete can be considered as an innovation (Yu et al., 2021). If a company decides to produce recycled concrete, it is necessary to develop and adapt the recipe and to change the existing infrastructure. For example, new quality control mechanisms would have to be introduced and additional storage capacity created for the production of recycled concrete. In addition, prototypes must be produced and tested in the earlier phases of innovation (Duranton and Puga, 2001), which requires additional spending on research and development. Due to their increased profits, monopolists can potentially provide more financial resources for research, development, and production than it would be the case in a competitive market (Rosenberg, 1981). However, it can be argued that monopolists have fewer incentives for product innovation since they would replace existing products on which the monopoly position is based (Tirole, 1988). Therefore, they have a strong incentive to maintain the status quo (Arrow, 1962a, 1962b; Usher, 1964). This is in line with literature on the relationship between market concentration and innovation, which suggest that higher market concentration can lead to higher R&D spending and higher innovation (Dasgupta and Stiglitz, 1980; Weiss, 2005). Here, the empirical literature presents twofold results. While F. M. Scherer (1965) and Hamberg (1966) state a positive relationship between market concentration and innovation, Williamson (1965) and Bozeman and Link (1983) identify a negative relationship. These results vary greatly depending on the investigated industry, country and period.

As only the primary aggregate is substituted by secondary aggregate in the production of recycled concrete, no replacement effects as described by Tirole (1988) are expected (Yu

[2] This effect is also reinforced by the fact that concrete is limited transportable. Approximately one hour after production, ready-mixed concrete begins to dry out.

et al., 2021). The change does not directly affect the product, but only the production process as well as supplier relationships. Thus, no negative relationship between then willingness to produce recycled concrete and the market concentration is expected. On the contrary, due to the lower intensity of competition, it can be assumed that the willingness to produce recycled concrete will increase with rising regional market concentration.

Similar argumentation holds for the relationship between the size of the company and the willingness to produce recycled concrete. Larger companies are more capable of investing in the innovation in order to drive research and development of new products (Duranton and Puga, 2001; Schumpeter, 1942), which suggests that there can be a positive relationship between willingness to produce recycled concrete and firm size. Thus, the following hypotheses regarding market concentration and company size can be formulated:

- H1: The willingness to produce recycled concrete increases with rising regional market concentration.
- H2: The willingness to produce recycled concrete increases with rising firm size.

2.2 Vertical Integration

In addition to horizontal integration (market concentration), vertical integration is also considered in the present study. Manufacturers of ready-mix concrete often take on additional activities in the value chain - including production of the primary aggregate, demolition work on the construction site as well as collection and processing of construction waste. For the production of r-concrete, demolition work on the construction site, collection and processing of construction waste are particularly relevant, as the manufacturers of ready-mixed concrete integrated in these areas can use their own recycled aggregates and do not have to purchase them from a third- party companies (Ghisellini et al., 2018). It can therefore be assumed that the manufacturers of ready-mixed concrete are more willing to produce r-concrete if they take on activities, such as demolition work on the construction site, collection and processing of construction waste (Geissdoerfer et al., 2018). On the other hand, if the ready-mixed concrete producer also takes on the production of aggregates in addition to his main activity, a lower willingness to produce r-concrete can be expected. Thus, the following hypotheses regarding vertical integration can be formulated:

- H3: The willingness to produce recycled concrete decreases if the concrete producer additionally manufactures or mines natural stone, sand and gravel.

- H4: The willingness to produce recycled concrete increases if the concrete producer additionally undertakes the demolition work at the construction site.
- H5: The willingness to produce recycled concrete increases if the concrete producer additionally undertakes the waste collection.
- H6: The willingness to produce recycled concrete increases if the concrete producer additionally undertakes the waste recycling.

2.3 Regional Economic Activity

The production of recycled concrete requires raw materials that come from the demolition sites and are processed directly at the construction site or in the concrete plant to a recycled aggregate. For the construction using recycled concrete high amounts of recycled aggregate are required. In order to enable the production of necessary quantities of recycled aggregate, a reasonable amount of demolition sites with a high volume of waste must be available regionally (Bovea and Powell, 2016). Construction and demolition waste occur more likely in regions, which are characterized by a higher economic activity - it is plausible to assume that highly industrialized regions with large population also produce more construction waste. As construction waste is an important determinant of the recycled aggregate availability, it can be assumed that the willingness to produce recycled concrete increases with increasing economic activity of the region. From this follows the hypothesis:

- H7: The willingness to produce recycled concrete increases with rising economic activity of the region.

2.4 Distance to the Primary Input Supplier and Waste Disposal Site

In addition to the vertical and horizontal market concentration, firm size and economic activity of the region, the geographical organization of the value chain can influence the willingness to produce recycled concrete. Transport costs can be considered as an important determinant of the product price (Samuelson, 1954). Most of the concrete mass consists of aggregates and sand, which must be inquired from the supplier and transported to the production site of the concrete. It results in transport costs – which increase with rising distance to the aggregate supplier. Since the increasing distance to the aggregate supplier is accompanied by rising transport costs, it can be assumed that the willingness to produce recycled concrete increases with rising distance from the concrete production site to the sand, gravel and stone supplier.

When deconstructing a building, a decision must be made - to recycle or landfill the demolition waste (Bovea and Powell, 2016). The higher the distance to the landfill, the higher the share of transport costs in the total cost calculation and consequently the higher the likelihood that the waste will be recycled. It is expected that as the proportion of recycled construction waste increases, so will the supply of recycled aggregate, which increases the regional availability of recyclates and thus the potential willingness to produce recycled concrete. Thus, regarding the geographical distances, the following hypotheses can be formulated:

- H8: The willingness to produce recycled concrete increases with rising distance from the supply area of the concrete production plant to the disposal site.
- H9: The willingness to produce recycled concrete increases with rising distance from the concrete production plant to the sand, gravel and stone supplier.

3 Research Design and Data Collection

3.1 Willingness to Produce Recycled Concrete

The willingness to produce recycled concrete is investigated by means of a survey. For this purpose, a telephone survey including all concrete manufacturers in Germany was conducted. The telephone numbers of the companies have been extracted from the database Dafne, which is operated by Bureau Van Dijk - A Moody's Analytics Company and contains the annual reports information of companies located in Germany. 1267 production sites of ready-mix concrete could be identified, which are organized in 412 enterprises. 117 companies took part in the telephone survey - these companies operate a total of 457 concrete production sites. The survey has a response rate of 28.39 % when considering the enterprises and 36 % when considering the production sites. During the telephone survey, a question was asked about the potential willingness to produce recycled concrete in a fictive situation. The questions were based on a 5-point Likert scale to ensure a uniform analysis with a high response rate and decrease the frustration level of answering the questions (Babakus and Mangold, 1992).

In order to avoid an interpretation-related distortion of the answers between the participants, interviewees were pointed out the quantitative significance of the answers - e.g. answer option 2 would mean the likelihood of accepting the order of roughly 25%.

To increase the response rate, the companies that could not be reached were called again two weeks after initial call.

3.2 Distance to the Landfill and Sand, Gravel and Natural Rock Supplier

As the basis for the calculation of geographical distances, the addresses for the following classifications of economic activities have been extracted from the database Dafne:

- Nace Rev. 2. 23.63: Production of transportation concrete (ready-mixed concrete)
- Nace Rev. 2. 08.11: Quarrying of ornamental and building stone, limestone, gypsum, chalk and slate.
- Nace Rev. 2 08.12: Operation of gravel and sand pits; mining of clays and Kaolin

The identification of relevant enterprises was based on the primary and secondary Nace Rev. 2 allocation. The classification 23.63 refers to ready-mixed concrete producers. Classification 08.11 and 08.12 are the companies that produce or sell the aggregates for concrete production. The assignment to the industrial classification has been verified manually - the companies have been removed from the dataset which either have an incorrect classification of the economic activity or are not relevant to the subject of the investigation.

By using open source geoinformation system Quantum GIS (QGIS) version 3.6, geographical coordinates were assigned to the addresses and then transferred to the projecting coordinates reference system (CRS). By using the UTM (Universal Transverse Mercator) Zone 32 N (EPSG:25832), the highest degree of geographical accuracy for Germany could be ensured. Based on the locations of the companies, in the geographic information system used, distances of the ready-mix concrete manufacturer to the nearest supplier of sand, gravel and natural rock were calculated in kilometers. In addition, distances from the ready-mix concrete manufacturers to the next landfill of class 1[3] have been generated. The distances are based on the straight-line and not on the transport route. Since the actual transport route may vary depending on the geographic properties of the area and infrastructure, the calculated distance is only an approximation.

3.3 Economic Activity of the Region

As assumed before, the potential willingness to produce recycled concrete may depend on the economic activity of the region in which the ready-mix concrete production site is located. In order to take into account, the role of economic activity of geographical areas in the analysis, a circle of radius 30 kilometers was drawn around each establishment. The populations of the municipalities located within or intersecting these districts were summed

[3] Landfill class 1 is a standard landfill for moderately contaminated excavated earth and construction waste.

up and acted as a proxy variable for the economic activity of the region in which the ready-mixed concrete site is located. Areas with higher population within the defined supply zone of concrete producer tend to imply higher economic activity and potentially a higher regional supply of recycled aggregates. For this purpose, population data of the Federal Statistical Office of Germany at the district level (Federal Statistical Office of Germany, 2018) used and processed as a shape file at QGIS.

3.4 Firm Size

The regional demographic structure is also considered in the identification of turnover and employees at establishment level. Since the turnover and employment data are not available for individual operating sites, the turnover and the number of employees, which are known at the company level, were distributed among the individual operating sites. For this purpose, circles with a radius of 30 kilometers were drawn around the plants belonging to the same company. Subsequently, the populations of the municipalities located within these supply zones of plants belonging to the same enterprise were added together and thus formed the basis of 100%. Depending on the relative number of inhabitants in the individual supply zones, the population-weighted turnover and employment could be calculated and distributed among the establishments. For example, it is assumed that if 20% of the inhabitants of all zones served by plants of the enterprise are located within the supply zone of a respective establishment, 20% of the turnover of the company is generated as well as 20% of the employees of the entire company are employed there. The calculation of population-weighted turnover of the permanent establishment represents a better alternative than an entry as missing values.

3.5 Horizontal Market Concentration

An appropriate product and geographic market definition is necessary for the analysis of horizontal market concentration and interpretation with regard to the potential willingness to produce recycled concrete. Ready-mixed concrete was defined as a product dimension as it is only substitutable to a limited extent as a building material and can be produced using both primary and recycled aggregates. The geographic dimension of the market in Germany is limited to the 30 km area around the concrete plant, since ready-mixed concrete can only be transported to a limited extent and begins to harden within 60 minutes after the production (Federal Cartel Office, 2017). The Herfindahl- Hirschman Index (HHI), which takes into account both the distribution of turnover and the number of companies, represents an appropriate tool for measuring market concentration. HHI is defined as the sum of the squared market shares of the individual companies in the relevant market and can take the values from 0 to 1 (Herfindahl, 1950; Hirschman, 1964, 1945).[4] In the present study, the Herfindahl-Hirschman Index is calculated as a fixed radius method, similar to the approach used to examine the regional market concentration of hospitals by Gaynor and Vogt (2000) and Wright et al. (2019).[5] It is assumed that if the supply zones of several concrete production sites intersect, the production sites are in direct competition with each other. The Herfindahl-Hirschman Index is based on the turnover of competing plants, as described in the previous subsection. Since a supply area of a company can consist of several competition zones with different *HHI*, the *HHI* of the competition zones was weighted by the respective area. *HHI* is calculated based on the intersections of the individual supply zones and is generalized as:

$$HHI = \sum_{i=1}^{n} s^2 \tag{1}$$

where *s* is the market share of firm *i* and *n* is the number of firms in a respective market. The market share of company *i* is calculated as:

$$s = \frac{x_i}{\sum_{i=1}^{n} x_j} \tag{2}$$

where x_i indicates a turnover of the respective establishment. The denominator represents the total turnover of all operating units within the regional market. As illustrated by the above formulas, the *HHI* was calculated for the supply zones of all ready-mixed concrete plants in Germany.

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[4] *HHI*<0.01 highly competitive industry; 0.01 - 0.15 unconcentrated industry; 0.15 - 0.25 moderate concentrated industry; >0.25 highly concentrated industry.

[5] Both ready-mixed concrete and hospital services can be considered as regionally restricted markets. A production facility for ready-mixed concrete or a hospital in Berlin are not competing with the plants for ready-mixed concrete or hospitals in Hamburg. An exception is highly specialized hospital service - in certain cases the markets may be both national and international.

3.6 Vertical Integration

In the context of the present analysis, the vertical integration of ready-mix concrete producers is also considered as one of the relevant factors which can potentially influence the willingness to produce recycled concrete. Vertical integration can be measured on the basis of whether the ready-mixed concrete producer also undertakes further activities in the upstream and downstream value chain. A total of 4 dummy variables were formed, which show whether the respective activity is being undertaken by the considered ready-mixed concrete manufacturer. From relevant industry classifications (Nace rev. 2), four variables were identified that characterize different stages of the value chain - extraction of natural stones, gravel and sand (08.11 and 08.12), demolition (43.11 and 43.12), collection of waste (38.11) and waste recovery (38.32). The details on the further activities of the ready-mix concrete manufacturer (except the production of ready-mix concrete) have been extracted from the Dafne database and individually verified by internet research. Although the dummy variables provide indications as to whether the specific activity is being undertaken by the company, the relative share of this activity in the total value added is not known, which in principle can reduce the informative value of the dummy variables.

4 Empirical Analysis

4.1 Descriptive Analysis

In the following subsection, the relationships between the economic, geographical and structural factors and the willingness to produce recycled concrete will be examined descriptively in the context of investigated hypotheses. The descriptive statistics for the main variables are summarized in Table 7. If the spatial distribution of ready-mixed concrete producers is considered at the federal state level, it is observable that a large proportion of concrete plants is accounted for the southern federal states Baden-Württemberg (17.52%) and Bavaria (20.68%). The new federal states - Brandenburg, Mecklenburg-Vorpommern, Saxony, Saxony-Anhalt and Thuringia - together account for only 19.42% of the establishments.

Table 7: Descriptive Statistics for the Main Variables.

Variable	Obs.	Mean	Std. dev.	Min.	Max.
Population [in k]	1267	1259	1115	42.808	6821
Turnover [in Euro; k per year]	953	1397	50601	1	549015
Employees	922	11.125	18.213	1	227
HHI (10 km)	1216	0.53	0.372	0	1
HHI (30 km)	1267	0.236	0.195	0	1
HHI (50 km)	1267	0.149	0.140	0.021	0.921
Distance to waste disposal site [in km]	1267	44.505	32.211	0.188	173.11
Distance to sand, stone and gravel supplier [in km]	1267	7.183	6.247	0	62.808

The regional distribution of the concrete production sites is shown in Table 8:

Table 8: Ready-mixed Concrete Plants by Federal States in Germany.

Federal state	Frequency	%
Baden-Würtemberg	222	17.52
Bavaria	262	20.68
Berlin	11	0.87
Brandenburg	57	4.50
Bremen	7	0.55
Hamburg	12	0.95
Hesse	124	9.79
Mecklenburg-Vorpommern	6	0.47
Lower Saxony	118	9.31
North Rhine-Westphalia	139	10.97
Rhineland-Palatinate	78	6.16
Saaarland	4	0.32
Saxony	96	7.58
Saxony-Anhalt	48	3.79
Schleswig-Holstein	44	3.47
Thuringia	39	3.08

The statements made by the ready-mixed concrete manufacturers regarding the potential willingness to produce recycled concrete are shown in Figure 11 - the presentation refers to the concrete production sites. Thus, according to the information provided by the contact persons of the enterprises, 27.35% of the production plants are characterized by the fact that they would definitely or probably accept the order to produce recycled concrete. Low supply has been identified by architects and engineers as well as the contractors as one of the main obstacles to the use of r-concrete in building construction (Katerusha, 2021). However, the descriptive results of this study indicate that the supply of recycled concrete is potentially available. In contrast, 56.24% of the plants would probably or definitely not accept the order to produce recycled concrete.

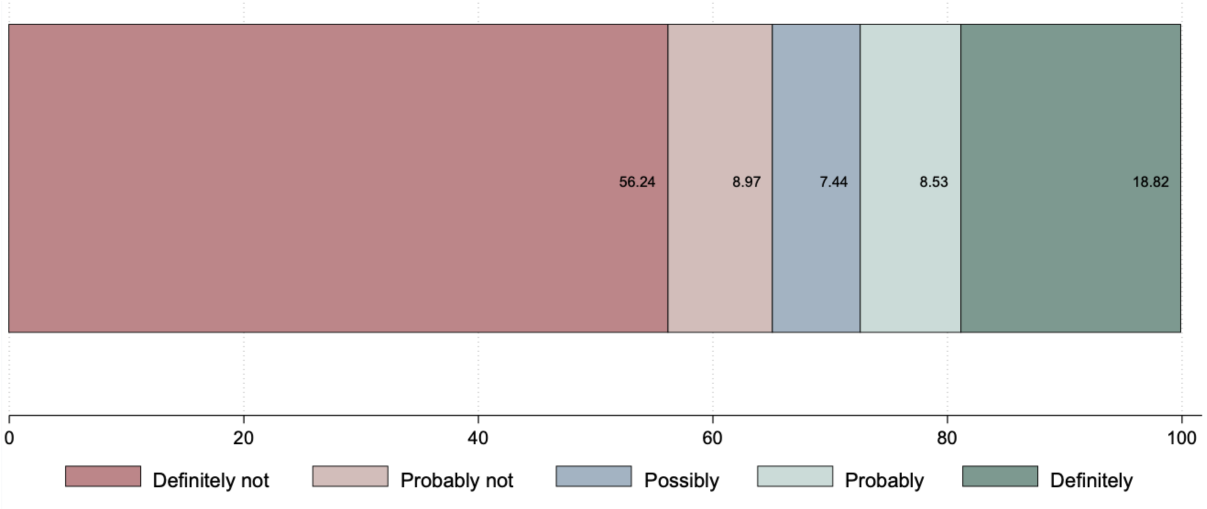

Figure 11: Willingness to Produce Recycled Concrete across Response Categories (%)

Based on numerical values of the responses and the geographical locations of the plants a heat map for willingness to produce recycled concrete can be calculated. In such a map, geographical accumulations of sites with positive answers can be made visible. The higher the number of sites in the certain area and the higher the (numerical) willingness to produce recycled concrete, the ore colorful the area appears. The radius has been defined as 50 km. By extending the perimeter, the outer borders of the colored marking shift and the color intensity decreases - but the locations of the potential hot spots do not change. The site-specific heat map for the potential willingness to produce recycled concrete is shown in Figure 12. The illustration shows the hot spots for high willingness to produce recycled concrete. Hot spots are clearly visible in the west of Germany, namely in the regions of Hamburg, Münsterland, the Rhine-Rhur and Stuttgart region. In the east of Germany, a slight color intensity can still be identified in the Chemnitz region. The highest intensity of the production readiness of recycled concrete is clearly observable in the Stuttgart area.

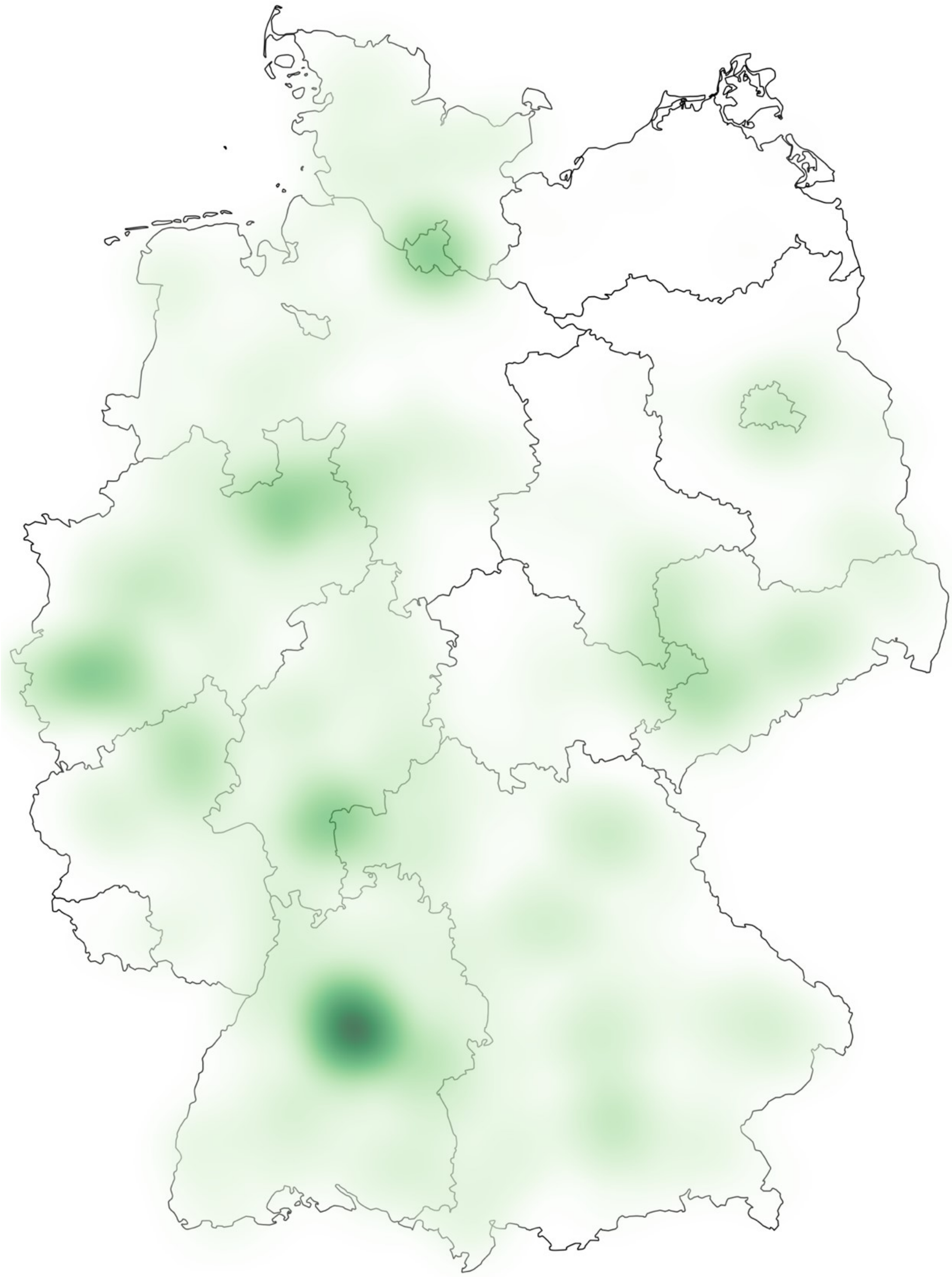

Figure 12: Willingness to Produce Recycled Concrete by Location: Heat Map.

The vertical integration of the companies was measured by whether the company undertakes specific activities at the given stage of the value chain. The absolute and relative distribution of the further activities of ready-mixed concrete producers is shown in Figure 13:

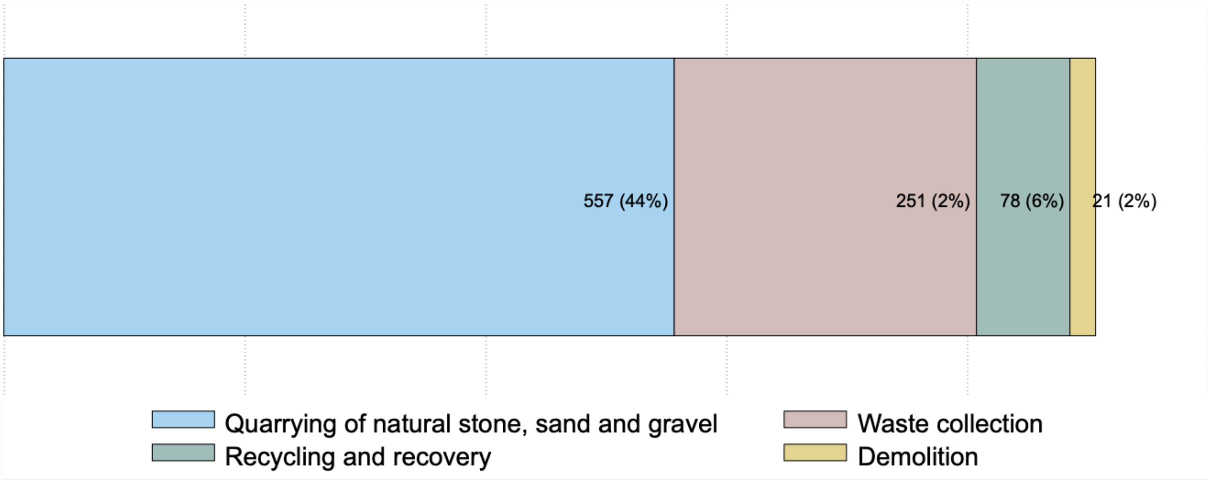

Figure 13: Vertical Integration of Ready-mixed Concrete Production Sites.

Of the 1267 production sites, 44% take over the production of sand, gravel and rock, 20% the collection of waste, 6% the recovery and recycling and 2% the demolition. Most of the ready-mix concrete producers are vertically integrated, but are mostly active in the conventional procurement or production of primary materials. As expected, in the case of high willingness to produce recycled concrete (*probably* or *definitely*), the firms take over activities such as demolition, collection, processing and recycling to a greater extent and are less involved in gravel production. The mean differences were tested with two-sample t-test - for activities such as quarrying of natural stones, sand and gravel ($p = 0.000$) as well as waste collection ($p = 0.0161$) the differences are significant. The equality of median test confirmed the results. The findings indicate that the hypotheses H5 and H3 can be preliminary confirmed. The willingness to produce recycled concrete increases if the production site also undertakes the waste collection (H5) and decreases if it manufactures natural stone, sand and gravel (H3). On the basis of the preliminary descriptive results, the hypotheses H4 and H6 cannot be confirmed, since the two-sample t-tests and equality of medians tests do not indicate significant results.

The distribution of companies' activities by response categories is shown in Figure 14. 57 % of the companies that have indicated that they would probably or definitely not accept the order are involved in the production or distribution sand, gravel and stone. In contrast, 46% of the companies involved in the production or distribution of sand, gravel and stone would probably or definitely accept the order to produce recycled concrete.

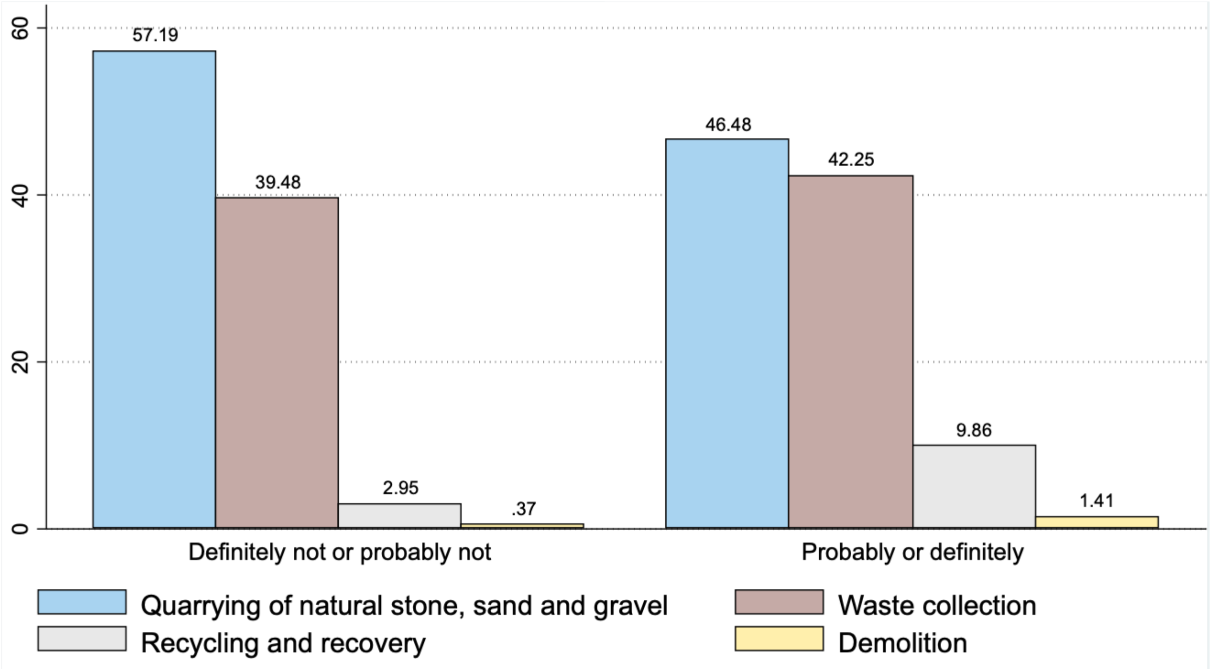

Figure 14: Vertical Integration of Ready-mixed Concrete Production Sites and Willingness to Produce Recycled Concrete.

In the concentration of the ready-mixed concrete market in Germany, monopolies appear to be an exception. Only in a few cases do the permanent establishment operate in a monopolistic market. Most of the markets formed by permanent establishments with an effective radius of 30 kilometers are exposed to a moderate market concentration around the median 0.16. In the context of the present study, the hypothesis has been established that increasing market concentration is positively related to the potential willingness to produce recycled concrete (H1). Two-sample t-test indicates that the hypothesis H1 can be preliminary confirmed - there are significant differences in the means between groups with positive and negative answers (p = 0.064). The hypothesis (H2) that company size (measured as number of employees) can have a positive influence on the potential production readiness of r-concrete can be preliminary confirmed (p = 0.000) as well. The average population in the supply zones of the ready-mix concrete plant is very similar in both the positive and negative answers, corresponding to ≈ 1.4 and ≈ 1.5 million inhabitants - but the differences are not statistically different from zero. Looking at the medians, the differences are highly significant - the median in the group of negative answers is ≈ 0.9 and in the group of positive answers ≈ 1.2 million inhabitants. Thus, the hypothesis (H7) that the production readiness of r-concrete increases with increasing economic activity of the region may be preliminarily confirmed at this stage. The descriptive results can only be interpreted as indications of a possible causal relationship. The final confirmation or rejection of the hypotheses will take place within the framework of a regression model that estimates the causal relationship between the considered covariates and the willingness to produce recycled concrete. Distances between the production sites of the ready-mixed concrete manufacturer and the respective sand, stone and gravel pits or suppliers as well as landfill sites are shown in Figure 15. A large number of gravel suppliers around the ready-mixed concrete sites is observable. A total of 1565 suppliers of sand, stone and gravel have been identified in Germany. Both, the geographic density of ready-mixed concrete producers as well as gravel pit suppliers is considered to be high. The average distance to the landfill in the group of negative answers is 39.58 km and 36.4 km in the group of positive answers. The average distance to the nearest gravel, sand or stone supplier is 7.18 in the group of negative answers and 7.22 in the group of positive answers. In both cases differences are not significantly different from zero. From the descriptive point of view, there is no indication that distances from the concrete site to the landfill and to the gravel supplier may affect the potential willingness to produce recycled concrete.

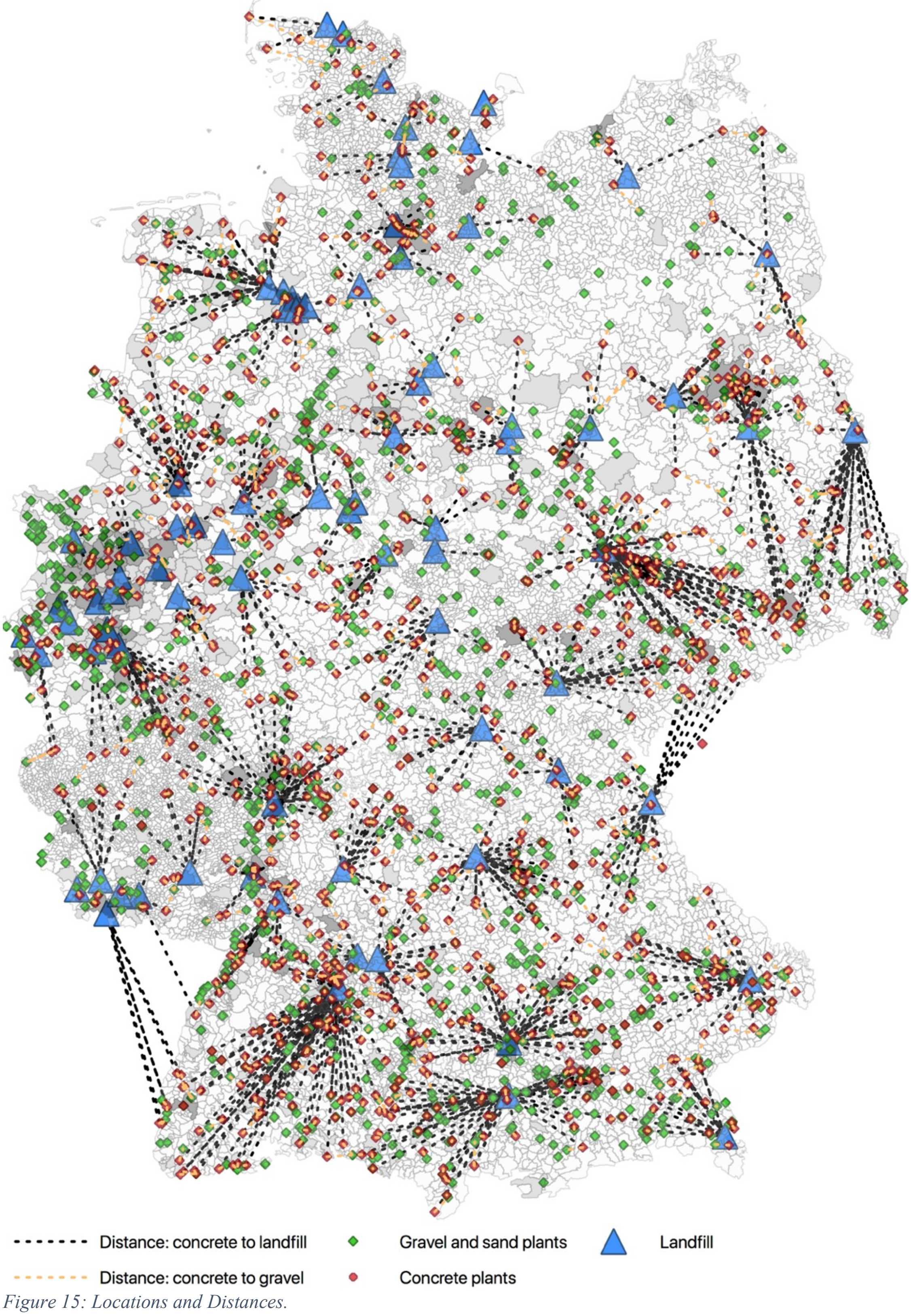

Figure 15: Locations and Distances.

4.2 Empirical Model

As mentioned, ready-mix concrete producers are organized as enterprises and one enterprise may have several production sites. Thus, the variables are structured in two levels - the group specific variables (level 2)[6], which record the characteristics of the companies, and individual specific variables (level 1)[7], which trace the characteristics of the individual production facilities. The multilevel structure of the data can be illustrated by Figure 16:

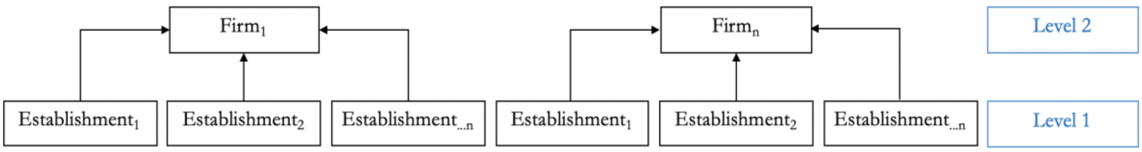

Figure 16: Structure of the Data on Willingness to Produce Recycled Concrete.

In context of the telephone survey, if a concrete manufacturer had several establishments, the call was made to the central office. The contact persons were given the opportunity to state whether the willingness to produce recycled concrete applies to all production sites. Apart from one company[8], all enterprises surveyed stated that the response[9] applies to all sites. The potential willingness to produce recycled concrete is thus a variable of level 2, as it does not or only slightly vary within the company.

The willingness to produce recycled concrete is first analyzed using an ordinal logistic regression. Ordinal logistic regressions describe the causal relationship between the ordinal response variable and one or more independent variables (Fagerland and Hosmer, 2016). Since the permanent establishments are organized in companies, it can be assumed that the permanent establishment belonging to a company has unobserved group-specific "fixed" characteristics, from which the need arises to consider the group-specific fixed effects in logistic regression (Angrist and Pischke, 2009). By introducing a company-specific dummy variable, group-specific differences of the explanatory variables could be controlled. In addition, the corresponding bias in standard errors could be corrected by introducing cluster robust standard errors (Bertrand et al., 2004; Wooldridge, 2010, 2003). Since the willingness to produce recycled concrete is a level 2 (dependent) variable and does not vary (or only slightly) within the companies, the application of an ordinal logistic fixed effects

[6] Vertical integration dummies.
[7] HHI, firm size, economic activity of the region, distances.
[8] Not mentioned for reasons of data protection.
[9] Response to the question "How likely would it be - on a scale of 1, definitely not, to 5, definetely - that you would accept this order?". The question refers to the inquiry concerning the production of recycled concrete.

regression with cluster robust standard errors may be problematic. The dummy variable for the company affiliation as a fixed effect would explain the most of the variation of the independent variable (Baltagi, 2013; Hsiao, 2003; Kim and Frees, 2007).

One way to identify causal effects is to aggregate and specify the ordinal regression model at the second level, which can correct the violation of independence assumption within the response variable. In this case, there is no need to control for unobserved fixed effects at company level. Therefore, for the final model, the data has been aggregated on the (second) company level. For the variables of the second level, no adjustments are necessary; for the variables of the first level, the aggregation was done using medians of the corresponding production plant values. Thus, the basic structural model for ordinal regression at the company level is specified in the linear notation as follows:

$$y_e^* = x'_e\beta + \varepsilon_e \qquad (3)$$

where y_e^* indicates the latent continuous variable underlying the willingness to produce recycled concrete of the enterprise e = 1..., C as a function of the vector of the independent variables x_e and the logistically distributed error term ε_e. The full structural model for ordinal logistic regression can be presented as follows:

$$\begin{aligned} y_e^* = \; & \beta_0 + \beta_1 \times market\ concentration \\ & + \beta_2 \times quarrying\ of\ natural\ stone, sand\ and\ gravel \\ & + \beta_3 \times waste\ collection + \beta_4 \times recycling\ and\ recovery \\ & + \beta_5 \times demolition + \beta_6 \times firm\ size \\ & + \beta_7 \times regional\ economic\ activity \\ & + \beta_8 \times distance\ to\ input\ supplier \\ & + \beta_9 \times distance\ to\ waste\ disposal + \varepsilon_e \end{aligned} \qquad (4)$$

The market concentration is the area-weighted Herfindahl-Hirschman Index calculated as fixed radius method with a radius of 30 km. As a proxy for the economic activity of the region, the number of inhabitants within a radius of 30 km from the site location was used. To avoid possible interdependencies with market concentration, the number of employees was used as a proxy for the firm size.

4.3 Results

The regression results are shown in Table 9[10]. One of the important assumptions of ordered logistic regression is the proportional odds assumption or parallel regression assumption (McCullagh, 1980). This implies that β -coefficient is same for all equations of the logits of different categories, regardless of which categories are tested. In other words, it is assumed that the slope of the coefficients of the dependent variable is the same for each response category. Violating the assumption can lead to bias in the estimation results - it may happen that the effect of an independent variable is not statistically different from zero, as it has a negative impact on one category, but at the same time a positive impact on another category (Fullerton, 2009). If one would consider the influence of the variable separately on the respective category, in both cases a non-zero result could be present. However, Peterson and Harrell (1990) point out that the parallel regression assumption can be liberally applied if the sample size is small. It means that the p-value for the small-sample parallel regression assumption test could be artificially too small leading to an inappropriate refusal to accept the proportional odds assumption.

The likelihood-ratio test of proportionality of odds across response categories is used to check the parallel regression assumption (Wolfe, 1997). For the regression model (1), the significant test coefficient indicates that the proportional odds assumption may be violated. In such a case, different options are available. The causal effects of the covariate on the ordinal dependent variable can be also modelled by partial proportional odds regression (Peterson and Harrell, 1990). The response variable is still treated as an ordinal variable, but allows the selective assumption of proportional odds for certain variables. In this case, a separate odds ratio coefficient is generated for each category of the dependent variable. As this generates separate regression equations for each category, the data need increase. Due to the relatively low number of observations at the second level, this method is out of the question. Another possibility would be to specify the model as a multinomial regression model. The major drawback is the fact that the response variable is treated as a categorical variable without a natural order, which is associated with a considerable loss of information with regard to the research question. A minimally invasive option is to transform the 5-level response variable into a 3-level response variable.

[10] In contrast to the empirical models analyzed in the previous course of the work, higher significance thresholds have been used here. This is due to the fact that empirical models in the previous chapters are based on data from the factorial survey and discrete choice experiments. The respondents were exposed to an experimental situation - under such conditions higher p-values can usually be realised than in the empirical models, which are not based on a theoretical or experimental considerations.

Table 9: Ordinal Logistic Regression Model on Potential Willingness to Produce Recycled Concrete.

Variables	Odds ratios	
	(1) 5-level response	(2) 3-level response
Employees	1.061** (0.030)	1.081** (0.036)
Population (30km)	1.061** (0.026)	1.064** (0.030)
HHI (30km)	1.037*** (0.014)	1.042*** (0.017)
Quarrying of stone	0.331** (0.179)	0.201** (0.136)
Waste collection	3.934** (2.283)	2.361 (1.845)
Recycling	0.564 (0.533)	0.436 (0.511)
Demolition work	1.367 (1.998)	2.427 (5.064)
Distance to supplier	1.031 (0.045)	1.054 (0.056)
Distance to disposal	1.007 (0.008)	1.008 (0.010)
Obs.	101	101
Pseudo-R^2	0.100	0.191
Goodness of fit	P-values	
Likelihood-ratio test of proportionality of odds	0.0072	0.1633
Pregibon-Tukey	0.202	0.215
Ordinal Hosmer-Lemeshow	0.6135	0.3663
Pulkstenis-Robinson	0.6723	0.8813
Lipsitz	0.3350	0.1972

*Standard errors in parentheses; *p<0.1, **p<0.05, ***p<0.01.*

To improve interpretability HHI was multiplied by 100 and population was divided by 100000.

The response categories *definitely not* and *probably not* are grouped under category 1; the answers *definitely* and *probably* under category 3; *possible* is coded as the category 2. Thus, ordinal logistic regressions have been specified as a 5-level response in (1) and as a 3-level response model in (2).

The likelihood-ratio test of proportionality of odds across response categories for the 3-level response model (2) is not significant. Therefore, the parallel regression assumption is fulfilled. One disadvantage of this method is that the decoding from a 5-level-response to 3-level-response is accompanied by the loss of information. Also, the information is unevenly condensed - category 1 and 3 of model (2) each contain two categories of the model (1). However, category 2 of the model (2) contains only one category of the model (1). The advantage of 3-level response specification, is the fact that the parallel regression assumption is satisfied.

The advantage of the 5-level-response model specification is that the information content of all variables is fully preserved with respect to the dependent variable. The disadvantage is the possible violation of the proportional odds assumption, which can bias the estimation results. However, as mentioned before, the likelihood-ratio test of proportionality of odds can be applied liberally when the sample size is small. When comparing models (1) and

(2), there are no indications on false non-significant effects due to violated parallel regression assumption.

The ordinal version of the Hosmer-Lemeshow test (Fagerland and Hosmer, 2016, 2013), Lipsitz test (Lipsitz et al., 1996) and Pulkstenis-Robinson test (Pulkstenis and Robinson, 2004) were used to measure the goodness of fit. The test results presented in Table 9 give no indication that the models (1) and (2) are misspecified. The specification link test for single equation models (Pregibon, 1980) is not significant, indicating an appropriate model specification for (1) and (2). Table 9 also presents pseudo-R^2 (McFadden, 1974), which is intended to estimate the proportion of the criterion variance explained by the model. In comparable models, the pseudo-R^2 measures are usually smaller than the determination coefficient of the linear regression models (Norusis, 2005), so that pseudo-R^2 values between 0.2 and 0.4 are regarded as very successful (Tabachnick and Fidell, 2007). The pseudo-R^2 values for model specifications (1) and (2) are 0.10 and 0.19, indicating meaningful choice of predictors and appropriate predictive power. The present results indicate that the considered models are adequately specified, fit well into the data and can therefore be examined in more detail in the further analysis. Based on available results, the following hypotheses can be confirmed:

- H1: The willingness to produce recycled concrete increases with rising regional market concentration.
- H2: The willingness to produce recycled concrete increases with rising firm size.
- H3: The willingness to produce recycled concrete decreases if the concrete producer also manufactures or mines natural stone, sand and gravel.
- H5: The willingness to produce recycled concrete increases if the concrete producer also undertakes the waste collection.
- H7: The willingness to produce recycled concrete increases with rising economic activity of the region.

However, the following hypotheses cannot be confirmed:

- H4: The willingness to produce recycled concrete increases if the concrete producer also undertakes the demolition work at the construction site.
- H6: The willingness to produce recycled concrete increases if the concrete producer also undertakes the waste recycling.
- H8: The willingness to produce recycled concrete increases with rising distance from the supply area of the concrete production plant to the disposal site.

- H9: The willingness to produce recycled concrete increases with rising distance from the concrete production plant to the sand, gravel and stone supplier.

When interpreting the results, it is important to bear in mind that in the context of the present analysis the hypotheses have been examined with regard to the median values of all permanent establishments of a company, as the data have been aggregated to the company level using medians. From the odds ratios, predicted probabilities across response categories can be calculated and presented in Figure 17. To ensure interpretability, the predictive margins were calculated from the 3-level-response model. To illustrate the differences between possible parameter specifications, the estimated probabilities for categories 1 (definitely not or probably not) and 2 (probably or definitely) were calculated for three possible scenarios. The status quo scenario corresponds to the model specification in which all dependent variables have been set to their mean values. In the negative scenario it was assumed that, the production plants take over the production of sand and gravel but not the collection of waste; consist in median of 5 employees and operate in a relatively small town with a low market concentration. In the positive scenario, the ready-mixed concrete plants collect waste but do not produce sand and gravel; consist in median of 20 employees and operate in a large city with a high market concentration. In Figure 17, substantial differences in the willingness to produce recycled concrete become clear - in a positive scenario, the probability of the second category is almost 100%; in the negative scenario, however, it is almost zero.

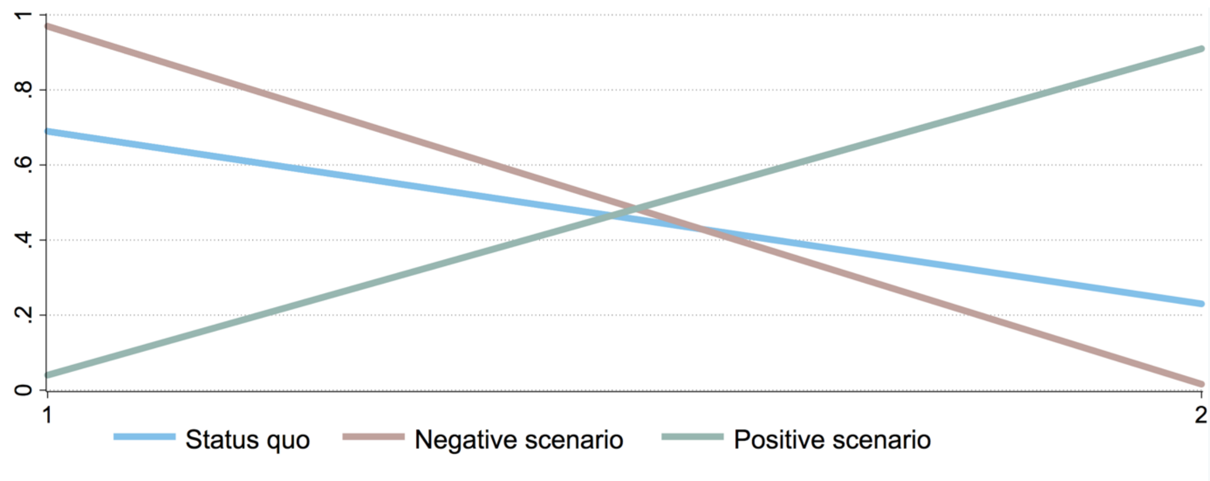

Figure 17: Predicted Probabilities across Response Categories.

To improve interpretability HHI was multiplied by 100 and population was divided by 100000.

Status quo: all parameters set to mean values.

Negative scenario: HHI=10, population=100000, production of gravel=1, waste collection=0, employees=5. Positive scenario: HHI=70, population=1000000, production of gravel=0, waste collection=1, employees=20. Category 1: definitely not or probably not; category 2= probably or definitely.

Interesting insights result from the dynamic consideration of the predicted probabilities of different answer categories (Figure 18). The figure shows how the probabilities of the response categories change when the covariates change. The intersection of the red and green curves marks the point of the considered variable at which the likelihood is higher that recycled concrete will be produced than that it will be not. At the market concentration, this point is reached at a value of about 50 (HHI=0.5). By market concentration of 100 (HHI=1), the probability of the positive response is nearly 100%. Overall, it can be stated that recycled concrete is more likely to be produced than it will be not if the supply area of the plant has more than 3.7 million inhabitants, the market concentration exceeds 50 (HHI=0,5) and more than 25 employees are employed in the plant.

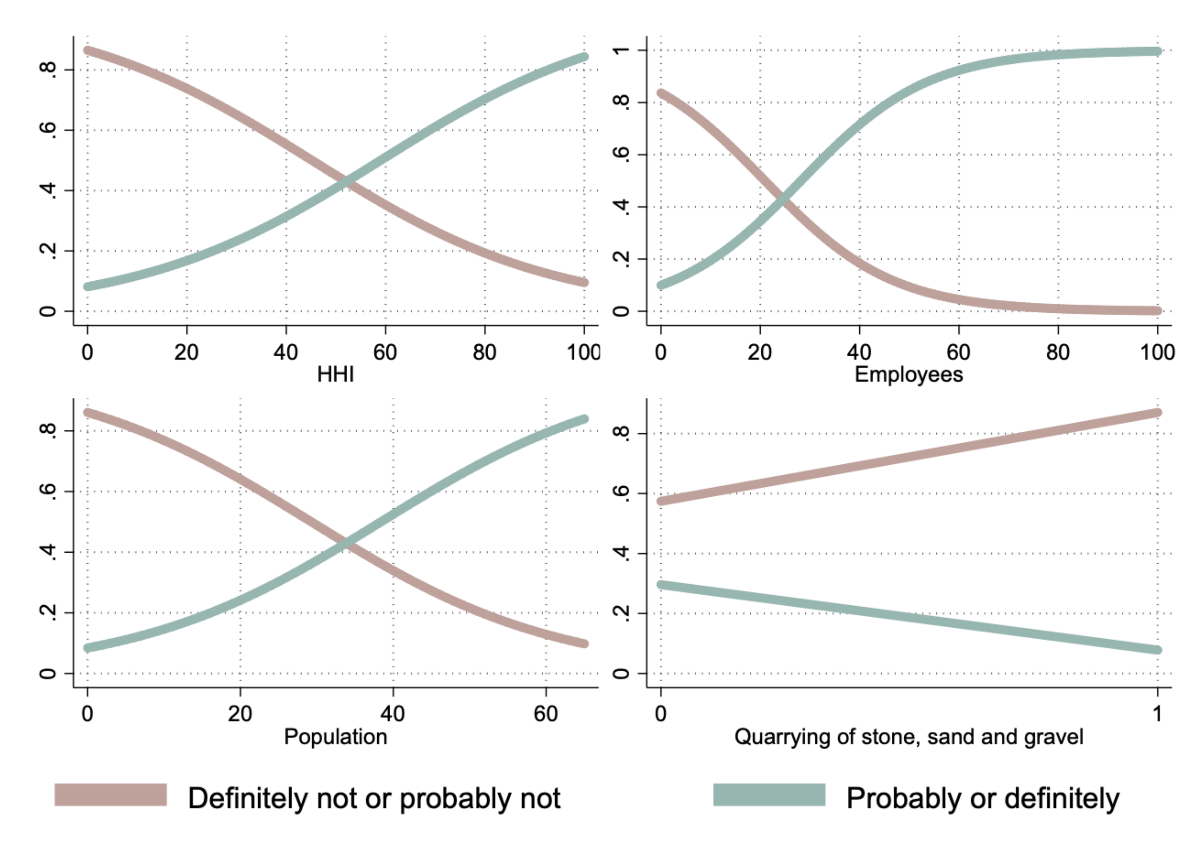

Figure 18: Predictive Margins across Response Categories.

HHI multiplied by 100; population in 100000; middle category is not illustrated.

4.4 Robustness

In order to check the robustness, the models have been estimated using different methods. The regression results are shown in Table 10. In the models (1) and (2), the dependent variable was transformed into a metric variable and estimated as a linear regression model (OLS) - the response category 5 was recoded to 1, category 4 to 0.75, etc.. In a 3-level response model the response categories were transformed to 0, 0.5 and 1 respectively. The main effects such as company size, market concentration, population and production of gravel, sand and rock prove to be robust and are also significant if the model specification is changed. The effect of waste collection is less robust and loses significance in all model specifications. With regard to the main effects of the individual covariates, it can be stated that the preferred ordinal logistic regression is largely robust against changes in the model specification.

Table 10: Robustness Check: Willingness to Produce Recycled Concrete.

Variables	Coefficients	
	(1) OLS (5-lvl.-reponse)	(2) OLS (3-lvl.-reponse)
Employees	0.012** (0.005)	0.016** (0.006)
Population	0.008* (0.004)	0.008** (0.005)
HHI	0.006*** (0.002)	0.007*** (0.003)
Quarrying of stone	-0.193** (0.087)	-0.232** (0.098)
Waste collection	0.142 (0.100)	0.040 (0.116)
Recycling	-0.106 (0.151)	-0.093 (0.169)
Demolition work	0.106 (0.304)	0.180 (0.340)
Distance to supplier	0.008 (0.008)	0.012 (0.009)
Distance to disposal	0.001 (0.001)	0.001 (0.002)
Obs.	95	101
Adj. R^2	0.151	0.21

*Standard errors in parentheses; *p<0.1, **p<0.05, ***p<0.01.*

To improve interpretability HHI was multiplied by 100 and population was divided by 100000.

5 Discussion

The results have shown that the market concentration, firm size, partially vertical integration, and economic activity of the region have a significant impact on the willingness to produce recycled concrete. With increasing market concentration, company size and economic activity of the region, the potential willingness to produce recycled concrete increases. It decreases if the concrete manufactures take over the production and procurement of primary input materials such as sand and gravel in addition to its main activity.

Explanations for those results can be the following: in a competitive environment with a high market concentration firms can only survive long term, if they are willing to change their strategy to ensure their market share. Refusing this, will increase their risk to fail on the market. Although, it could be possible that the results would vary, if we would not ask for the “potential willingness”, but moreover the companies’ actual strategical plans. In high market concentration environments, companies who answered to produce CDW with a high likelihood, have nothing to lose when they stay flexible.

The high likelihood of the willingness to produce r-concrete for larger firms is on the one hand also plausible. Larger firms are usually more aware of the overall sustainability issues and know that this an upcoming topic in their industry. The question if it does pay off to be green (with producing r-concrete) is still yet not answered, but larger firms can usually afford it more easily (Bao and Lu, 2020). Additionally, smaller firms are often more dependent on a single customer and don't have the power to force them into buying r-concrete. On the contrary, smaller firms are often more innovative and can move faster in new fields. Since the results do not support this statement, it would be an interesting further research topic to examine, if innovative firms are more willing to produce recycled concrete.

The positive relationship between the region's economic activity and the potential production readiness of recycled concrete can be attributed to the fact that there is a higher intensity in construction and demolition, especially in the agglomerations, and thus a supply of recycled aggregates. The production of recycled concrete in urban agglomerations has logistical advantages, above all, because large quantities of mineral construction waste are generated in these areas and the distances between the individual construction sites are shorter (Rao et al., 2007). Since the mining of primary aggregates is associated with considerable interventions in the natural and water balance as well as in the landscape, the use of recycled concrete can create considerable ecological added value and prevent the mining of additional primary resources.

In case of the vertical integration of primary resources, it also makes sense that firms don't want to cannibalize their own business areas. This can have several reasons the most appealing is that their internal value chain is more efficient than co-operating with other companies, which results in lower internal transfer prices (Zhao et al., 2010).

6 Conclusion

The objective of this article was to examine how to take the circular economy in the construction industry to a higher level and to reduce value losses of CDW. The most important strategy for this is closing the material loop (Bao and Lu, 2020; Geissdoerfer et al., 2018).

Further research could be done in the already mentioned examination of the innovativeness of the firms since this could indicate which companies invest in new technologies or future developments. Additionally, a comparative price assessment of r-concrete should be made to ensure, that r-concrete is from a cost perspective equal to conventional concrete. Lastly, there needs to be a customer-oriented increase of r-concrete as well as a bigger awareness of future employees in the construction supply chain (Katerusha, 2021). One of the options for the federal states and the municipalities is to take recycled concrete into account when awarding public building tenders. In this way, previously non-existent government demand for recycled concrete can be created, which would stimulate the development of the market for recycled concrete from the customer side. Another way to increase the production of r-concrete could be to award it by the government. Even though the vertical integration of recycling and demolition activities seemed to not be significant, the government could force construction companies to take back a certain amount of material. Then construction companies would have an incentive to think about or already use their backflow materials. Another idea could be introducing a financial certificate, which construction companies can use as a "buy-out" and give specialized recycling companies the right to produce recycled aggregates. Financial certificates can have several advantages compared to a government driven approach. First, the market would be able to calculate the real value of recycled products, taking into account demolition costs, processing costs, and transportation costs. Second, those certificates could be traded on a stock exchange, which decouples the long lifecycle of a construction product with its financial value. By doing this, investors do not need to wait for the product's end of life but can be rewarded beforehand. Lastly, with a financial certificate, many more stakeholders such as financial institutes and private investors, can participate in shaping the construction industry into a Circular Economy.

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Research Paper 2: Who Drives Circularity?—The Role of Construction Company Employees in Achieving High Circular Economy Efficiency

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Abstract

The Circular Economy in the construction industry is still in its infancy. It seems particularly difficult for companies in this sector to make strategic decisions that enable sustainable operations and that ensure long-term business success. This article investigates factors, such as Employee Involvement at the operational level, that facilitate Circular Economy practices for companies in the construction industry. For this purpose, we conducted a company survey and analyzed it using a structural equation model. The results show that it is worthwhile for companies to empower their manufacturing employees to take actions by themselves in order to increase process quality and to reduce setup time, which together lead to a better Circular Economy efficiency.

Keywords: Circular Economy, Circular Economy efficiency, Employee Involvement, Process Quality, Setup Time Reduction, Construction Industry

1 Introduction

1.1 Background

The construction and building industry, with its vast impact on society and on the environment, is one of the top priorities of the European Union (EU) for achieving a cleaner and more competitive Europe (European Commission, 2020). The amount of construction waste generated in 2018 was 935 million tons and it was responsible for 35.90% of the total EU waste generation. Over their entire lifecycle, the generated greenhouse gas (GHG) emissions constitute up to 40% of all such emissions in the EU (European Union, 2019; Eurostat, 2018). The most prominent concept for solving this major environmental problem is the transition towards a Circular Economy, which has the potential to reduce GHG emissions by up to 80% due to a greater material efficiency and to reuse the material (Hertwich et al., 2020; Gallego-Schmid et al., 2020).

The term “Circular Economy” is used to summarize strategies for systematic change that aim at a reduction of primary resource input, and at increases of reuse and recycling. One basic objective of the Circular Economy is to avoid wasting raw materials and to close material cycles (Kirchherr et al., 2017). This objective includes minimizing resource input, waste, and energy consumption (European Commission, 2020a; Evans et al., 2009; Keijer et al., 2019; Webster, 2015).

The EU’s action plan for the Circular Economy in the construction industry aims to address this objective and sets requirements for the durability and all forms of recyclability of construction products (European Commission, 2020a). By fostering the use of material passports as well as environmental product declarations, the action plan will directly affect how construction companies operate (European Commission, 2020b).

Circular Economy action plans can be implemented on various aggregation levels: First – on the macro level – nations, regions, and cities can take actions. On the second level – the meso level -, industrial parks or supply chains in a specific industry can implement circular strategies. And third, on a micro level, single companies can change their business practices (products, processes) in order to improve their circularity (Elia et al., 2017).

Especially on the last level – the company level – many implementation issues continue to exist and the levels of circularity of construction products are still low, while the principle of the “linear economy” dominates (Dräger et al., 2022; Heisel et al., 2019). Reasons for this are mainly the low proportion of recyclable materials used and the very costly separation of construction waste (Eisele et al., 2020; Katerusha, 2021). From the perspective of a construction company, the question arises as to what extent these Circular Economy practices are economically feasible. Hence, it must be ensured that the objectives of a Circular Economy are in line with corporate incentives and goals and that companies adopt the necessary operational competencies. Particularly when considering pathways of the transition from traditional linear practices towards more circularity, research on the Circular Economy's operational implementation is still scarce. For this reason, this article aims to shed light on this transition.

1.2 Literature

On a strategic level, circular business models for companies are already being increasingly discussed in both research and practice (Geissdoerfer et al., 2018). In particular, the research literature emphasizes potential complementarities between the reduction of resource consumption due to Circular Economy practices, and economic profitability. Prominent examples of these Circular Economy practices are Product Service Systems (PSS), where manufacturing companies no longer sell the products themselves, but instead rent out the product utilities with the objective of reducing resource consumption while still remaining profitable (Leising et al., 2018; Swift et al., 2017). Other examples are designs for recycling, for disassembly, or for reuse, where building components still have a value after their first life (Ünal et al., 2019). All of these described approaches are potentially effective Circular Economy practices. However, such approaches are often lacking an explanation and fail to provide sufficient evidence for how more circular business models can be operationalized. We understand such increased operationalization as Circular Economy efficiency. Higher Circular Economy efficiency goes along with the use of fewer resources per product, an increase of the product's useful lifetime, and less material waste in all stages of production, product use, and product recycling. Circular business models that are also economically feasible have so far been the exception due to their challenges to operationalize them, and quantitative studies are rarely available. Other research streams have moreover examined the interconnections between manufacturing efficiency and environmental efficiency, often referring to Hart's Natural Resource-Based view, where the competitiveness of a firm depends on how it manages its natural resources (Hart, 1995). Even though many of these articles are not focusing on a specific industry such as the construction industry, their results are nevertheless important for increasing the construction industry's transition towards a Circular Economy due to its similar objective of reducing waste (King and Lenox, 2009; Letmathe, 2002; Rothenberg et al., 2009). Up to now, the pronounced short-term focus on environmental considerations within the construction industry has mostly been set on reducing energy consumption as well as greenhouse gases (Pomponi and Moncaster, 2017). However, efforts have recently been made to additionally focus on the overall lifecycle, including material efficiencies. This is, for example, demonstrated by the actual implementation of lifecycle assessments of buildings in the European Union's framework for sustainable buildings, which considers environmental impacts during their lifecycle, ideally from cradle to cradle (European Union, 2019). More specifically, several researchers see potential for further reducing the construction industry's environmental impact when companies invest in Circular Economy approaches, e.g., in product design for achieving a longer durability (Bakker et al., 2014; Bocken et al., 2016; Geissdoerfer et al., 2017). For the implementation of a Circular Economy, the focus must be placed on efficient resource management and the associated material flows (Geng and Doberstein, 2008; Pomponi and Moncaster, 2017). Recently, Dräger and Letmathe (2022) focused on this topic within the construction industry by examining how the manufacturing efficiency correlates with environmental improvements. The construction industry, with its mostly project-based value creation architectures and lower standardization compared with other industries, offers a particularly good opportunity to achieve such a transformational change (Chui and Mischke, 2019).

The extensive literature review by Benachio et al. (2020), in which the authors examined factors that can facilitate Circular Economy practices in the construction industry, shows that there is still a lack of research in the fields of manufacturing and operations. In particular, two influencing factors are of high relevance: (1) Employees and (2) Processes. In the construction industry, as in most industries, the optimal utilization of processes and people is considered to be an essential economic advantage (Love et al., 2000).

(1) Employees: Considering employees, their empowerment is particularly relevant, i.e. increasing the degree of autonomy and self-determination of employees in production. Hence, it is remarkable that the empowerment of employees in the construction industry is particularly low, as the Rethinking Construction report emphasizes (Egan, 1998). Managers have often been criticized in this regard for their withholding of employee empowerment because they perceive it as a form of power ceding (Denham et al., 1997). That employees are essential for the construction performance is further shown in a study by Marin-Garcia and Bonavia (2015), who drew their results from an empirical case of ceramic tiles in Spain. Alazzaz and Whyte (2015) have shown in their study that there is a positive linear

relationship between employee involvement and productivity. The same conclusion was arrived at by Price et al. (2004), who showed that empowerment strategies are a big driver for construction performance. In construction companies, empowered employees could improve Circular Economy practices, e.g., through reducing and sorting different types of construction waste when it occurs on site, which would save time as well as costs and would enable a better recycling cycle of these resources (Wang et al., 2010).

(2) Processes: Besides the factor "employees", the construction industry should maintain a high level of process quality, which could also lead to improvements in Circular Economy efficiency. This context has been discussed mostly in the literature on lean production, a process through which environmental efficiency, often driven by economic considerations, can be improved. Kurdve and Bellgran (2021) propose that Circular Economy efficiency, specifically prolonging the life of the materials as well as reducing waste and improving the product system, can be achieved by lean improvements. In their examined cases, improvement potential came from ensuring a high process quality, i.e. implementing with six sigma an optimized change interval of tools, which resulted in less waste generation during production (Kurdve and Wiktorsson, 2013). In the construction industry, the lean concept has gained increasing importance through lean construction. Lean construction is a philosophy based on lean manufacturing concepts (Diekmann et al., 2005; Jørgensen and Emmitt, 2008; Koskela, 1992). Francis and Thomas (2020) showed that on the one hand many conceptual studies and individual case studies have been conducted to analyze the linkage between lean construction and environmental improvements. But on the other hand, a quantification and an empirical comparison between various construction companies is still needed (Francis and Thomas, 2020, Dräger and Letmathe, 2022).

Holt et al. (2000) argue that poor performances of employees or of processes are mutually dependent and should therefore be considered in conjunction. However, related to the construction industry, both factors have been insufficiently explored, as research has not adequately studied the extent to which employee empowerment and manufacturing process efficiency affect Circular Economy efficiency. Table 11 summarizes the results of this literature overview and shows that there is a research gap regarding the interdependencies between Circular Economy practices and manufacturing processes as well as employee-orientation in the construction industry.

Table 11: Literature Review of Specific Areas.

#	References	Circular Economy	Process Orientation	Employee Orientation	Construc-tion Industry
1	Koskela (1992)	-	X	-	X
2	Porter and Linde (1995)	-	X	-	-
3	Denham et al. (1997)	-	-	X	X
4	Egan (1998)	-	-	X	X
5	Bon and Hutchinson (2000)	X	-	-	X
6	Love et al. (2000)	-	X	X	X
7	Holt et al. (2000)	-	X	X	X
8	Letmathe (2002)	-	X	X	-
9	Price et al. (2004)	-	-	X	X
10	Diekmann et al. (2005)	-	X	X	X
11	Jørgensen and Emmitt (2008)	-	X	-	X
12	Geng and Doberstein (2008)	-	X	-	X
13	King and Lenox (2009)	X	X	-	-
14	Rothenberg et al. (2009)	X	X	-	-
15	Wang et al. (2010)	X	-	X	X
16	Kurdve and Wiktorsson (2013)	X	X		
17	Bakker et al. (2014)	X	-	-	-
18	Marin-Garcia and Bonavia (2015)	-	X	X	-
19	Alazzaz and Whyte (2015)	-	X	X	X
20	Bocken et al., (2016)	X	-	-	-
21	Cherrafi et al. (2016)	X	X	X	-
22	Pomponi and Moncaster (2017)	X	-	-	X
23	Geissdoerfer et al. (2017)	X	-	-	-
24	Swift et al. (2017)	X	-	-	X

25	Geissdoerfer et al. (2018)	X	-	-	X
26	Leising et al. (2018)	X	-	-	X
27	Ünal et al. (2019)	X			X
28	Benachio et al. (2020)	X	-	-	X
29	Francis and Thomas (2020)	X	X	-	X
30	Kurdve and Bellgran (2021)	X	X	X	-
31	Dräger and Letmathe (2022)	X	X	-	X

1.3 Contribution

To the best of our knowledge, there is no relevant research combining all four aspects, specifically the role of employees in operationalizing the Circular Economy practices through process orientation, and how this relationship influences corporate Circular Economy efficiency in the construction industry. The contribution of this research paper is, therefore, to empirically investigate relationships between employee involvement, process improvements, and the efficiency of Circular Economy practices in the construction industry. In this vein, this research paper is not aiming at examining new, potentially effective Circular Economy practices, but moreover provides empirical insights how construction companies can transform their manufacturing processes in order to operationalize Circular Economy practices and to improve their Circular Economy efficiency. For this purpose, the research question resulting from the before mentioned research gap is:

How do employee empowerment and process-orientation affect the efficiency of the Circular Economy in the construction industry?

The remainder of this article is structured as follows: Section 2 outlines the theoretical background of our study, including the defined hypotheses and the research model. In section 3, the methodology is presented. Section 4 outlines the results of the survey and provides a discussion of the key findings, followed by the final section, which focuses on limitations and potential avenues for further research.

2 Theory and Hypothesis Development

2.1 Lean Management Theory

The principle of lean management originated in Japan after the Second World War and gained worldwide recognition and imitation through its consistent implementation by Toyota in the 1970s until today (Womack et al., 1990). During this period, the supply of raw materials and the build-up of inventories were critical bottlenecks that made it necessary to increase production performance (Diekmann et al., 2005). These bottlenecks gave rise to various approaches in companies, such as just-in-time production, total quality management (TQM), continuous improvement, and zero inventories. Womack et al. (1990) describe the principles involved, i.e. specification of value, identification of the value stream, product flow, customer pull, and managing towards perfection as follows:

- Specify value: For the specification of value, it is at first important to focus on the customer’s view. By doing this, a company should identify the needs of a customer and assess what that customer is willing to pay for a product or a service. This is particularly important for new circular business models, where PSS is being used more often. One prominent example is that of the airport in Amsterdam, to which the Philips company rents out the lighting rather than selling the airport its light bulbs. This circular business model helps the airport with its strategy to produce zero waste by 2030 and to reduce the electricity consumption by 50% by using efficient LED lamps (Circular Economy Institute (CEI), 2015). Similar circular business models have been researched for specific construction components. In the Netherlands, for instance, an EIT Climate KIC project examined a leasing concept for facades at the university TU Delft (ClimateKIC, 2015). The examined values for customers allow consistent cash flows over time, reduce non-core processes (e.g., maintenance), and improve the flexibility of the facades with regard to design and technology (Azcarate-Aguerre et al., 2018).
- Identify the value stream: With this principle, the company must identify all those activities which create value for its customers. Any activities which do not create any additional value, should be eliminated. Such activities are considered to be waste and not to contribute to the value that the customer demands. In the Circular Economy, waste is mainly considered to be resource waste, and thus Circular Economy practices in the manufacturing industry focus on avoiding waste or substituting it through continuous improvement (Kurdve and Bellgran, 2021).

Additionally, identifying the remaining waste and considering all relevant value streams are crucial for transitioning to a Circular Economy (Perey et al., 2018).

- Make the product flow: By doing so, a company makes sure that it acts and produces products in a process-oriented way and that it does not rely on slow department decisions. Furthermore, by aligning the steps of all processes, waiting times for both machines and employees are reduced, which also minimizes the value losses. This principle is also very relevant for the Circular Economy, where products and resources can only circulate if all process steps are known and aligned. This view might even include reverse product flow after a product's useful lifetime.
- Pull of the customer: This principle emphasizes once again the focus on the customer. However, in this case, it is not so much the defining of the value but rather the delivering of the value at the right time, which means then when the customer wants it. Therefore, principles such as just-in-time production and delivery should be applied. While these are not necessarily only relevant for Circular Economy practices, they should be considered in this field of research. For example, a Circular Economy practice –like take-back mechanisms for used products – requires a high level of process efficiency because the customers decide when and to where they will bring the products back (Hazen et al., 2017). Particularly Circular Economy supply chains rely on product and resource deliveries at the right time to ensure economic efficiency. Ciliberto et al. (2021) also argue that such a customer focus correlates positively to Circular Economy practices, and especially improves economic efficiency. In particular, a customer focus can reduce the volatility of prices, because a company is able to produce exactly what the customer wants and reduce.
- Manage toward perfection: The last principle emphasizes continuous improvement and increases the transparency of products and processes, so that waste is shown on the surface. This principle is particularly important in a Circular Economy where, through continuous improvement, better and more efficient ways need to be found in order to keep the resources in a loop.

For implementing these principles, the focus has often been set on reducing waste, ensuring continuous improvement, and reducing cycle times. Prior studies have shown a positive correlation between lean manufacturing and environmental performance (King and Lenox, 2009; Yang et al., 2011). Porter and Linde (1995) emphasized the similarities between Environmental Management (EM) and TQM. Similarly to quality defects, pollution and waste are signs of poor resource efficiency. Rothenberg et al. (2009) and King and Lenox (2009) concluded that continuous improvement which is focused on lean plants leads to more awareness and further suggestions for reducing waste. In the same vein, Kurdve and Bellgran (2021) examined eight different case studies, in which such continuous improvements led to Circular Economy contributions by avoiding waste or keeping the resources in a loop due to better recycling processes.

However, because the lean management philosophy was developed within the manufacturing industry, the lean principles have also been adapted to fit the construction industry, as the two industries have different characteristics (Diekmann et al., 2005). For example, the construction of a building is often project-oriented instead of flow-oriented and thus often cannot be fully standardized. However, recent innovations, such as Building Information Modeling (BIM) and the increased usage of off-site production, support a flow orientation. Nonetheless, buildings are still seen as immobile rather than mobile products, and thus building construction takes place at an individual location. In a fully implemented Circular Economy, this assumption can be suspended and buildings can be seen as dynamic layers of different building parts (Durmisevic, 2018). However, in the current industry structure not all work can be undertaken in a controlled environment such as a manufacturing plant and on-site construction workers are still very important for maintaining high productivity levels (Dixit et al., 2017). Furthermore, many different companies have to work concurrently on a project, which often results in increased coordination efforts. In order to accommodate these special characteristics, two aspects for lean construction approaches need to be reconsidered (Diekmann et al., 2005). First, even greater emphasis has been placed on involving employees, who are to receive further training at every level of the hierarchy and are encouraged to become proactively involved (Lapré et al., 2000). By doing so, Circular Economy practices, such as reducing waste during production and sorting waste on construction sites, can be achieved more efficiently (Wang et al., 2010). Second, repetitive work processes in construction companies need to be defined to ensure higher levels of standardization. This could be achieved with a high level of prefabrication, where the quality of delivery and processes is controlled and can remain constant. Errors and value losses can then be detected more easily and solved, whereby Circular Economy efficiency can be improved (Minunno et al., 2018). Moreover, parts and components can be constructed and standardized in a way that the materials included can be more easily separated and the recyclability of these construction materials can be improved.

2.2 Natural Resourced-Based View

As the second part of our theoretical foundation, we draw from the Natural Resource-Based View of Hart (1995). His theory is an extension of the Resource-Based View and argues that companies depend on their entire ecosystem and that their competitive advantage depends on that environment. In addition to company-related resources, resources that are removed from the natural environment play a major role. To ensure their long-term economic competitiveness, companies must focus on three strategic objectives. First, environmental pollution should be reduced by recording and reducing emissions and waste in companies. In a narrow definition of Circular Economy practices, reducing waste at all stages of a product's lifecycle and keeping the product in a loop, is literally in line with objectives related to Circular Economy practices. Second, product responsibility should be assumed for the entire lifecycle of a product. This means that environmental sustainability factors, such as recyclability, should be taken into account as early as at the product development stage. In a Circular Economy, such factors can be affected through new business models, such as product service systems (PSS), which ensure responsibility over the entire product lifecycle. Finally, both of the above strategies - reducing environmental pollution and taking greater product responsibility - should be integrated into a corporate vision so that they are ensured at all levels. Company examples, such as Moringa in Germany, incorporate these views by building only cradle to cradle (Moringa, n.d.) Their main project in Hamburg HafenCity aims to build a sustainable residential multi-purpose building which contains a high share of recycled materials without any pollutants. The building includes apartments, co-working spaces, restaurants, a kindergarten, and green facades. Additionally, the company works in close cooperation with the research to ensure an incentive-based end-of-life treatment of construction products and materials through material recovery rights (ZukunftBau, 2022).

2.3 Hypothesis Development

Our study is designed to investigate the impact of the role of employee involvement on Circular Economy efficiency in the construction industry. That proactive involvement of employees has a positive influence on production efficiency has often been demonstrated, especially in the operations management literature (Dhingra et al., 2014; King and Lenox, 2009; Rothenberg et al., 2009). In this context, the principles of lean production are often used, but not with a focus on a specific industry (King and Lenox, 2009; Yang et al., 2010).

Most of the literature refers to the above-mentioned principles, such as product flow and just-in-time production, which are all linked to reliable and high levels of process quality in production. Although lean production is not as widespread in the construction industry as, for example, in the automotive industry, a similar relationship between employee involvement and lean production can nevertheless be assumed (Diekmann et al., 2005; Francis and Thomas, 2020; Jørgensen and Emmitt, 2008). One specific characteristic of the construction industry which is most prominent, is the immobility of a product's use phase (Nam and Tatum, 1988). This means that a final product like a building is in the end assembled on-site, and, often, preliminary products (e.g., walls) are, too. In these on-site production processes, a high proportion of manual labor is required, and the building projects often need to meet special and unique requirements. Moreover, employees are still essential in construction projects and have a high influence on process quality. For these reasons, hypothesis H1a is assumed:

H1a: Employee involvement in construction companies increases the process quality of manufacturing processes.

Another important factor discussed in the lean production literature is the reduction of non-value-adding activities (Han et al., 2007), Since the batch size is typically rather small in the construction industry, preparatory work which of includes non-value-adding activities such as tool changes, machine setups, and the preparation of input materials occur more often (Wu et al., 2023). Alazzaz and Whyte (2015) have already showed this linkage for off-site production, but for on-site production the role of employees in reducing setup times is also relevant because of less standardization and automation, and more individual orders (Melenbrink et al., 2020). This means, that employees have to decide in many individual cases about how to configurate their preparatory work in the most efficient way. In order to achieve this efficiency in construction companies, employees need to be empowered able to decide how the preparatory work can be done best. Therefore, hypothesis H1b assumes that:

H1b: Employee involvement in construction companies reduces setup times during manufacturing processes.

High process quality does not only reduce resource waste, and ceteris paribus cost, but also waste, because the natural environment often serves as a sink for emissions, waste water, or solid waste (Dhingra et al., 2014; King and Lenox, 2009; Rothenberg et al., 2009). This aspect is particularly important when considering the Circular Economy, as the aim here is to achieve a high level of efficiency, especially for materials and resources. Circular

Economy practices which have been used with regard to manufacturing involve the reduction of waste (Adams et al., 2017; Esa et al., 2017a), the usage of secondary raw materials (Nußholz et al., 2019), or the usage of environmental-friendly designs already in the early stages of a production planning process (Akanbi et al., 2019). Accordingly, if high process quality is maintained, it is possible to generate lower amounts of waste during production (Kurdve and Bellgran, 2021). However, the usage of secondary raw materials can also increase due to a higher process quality, either achieved through the reuse of waste and scrap (Kurdve and Bellgran, 2021) or through material substitution offering a better visibility of value losses and bottlenecks (Dräger and Letmathe, 2022). Last but not least, a higher process quality ensured, for instance, through BIM-systems, enables construction companies to design environmental-friendly products efficiently already from the beginning onwards (Xue et al., 2021). Thus, we formulate hypothesis H2a:

H2a: A high process quality in manufacturing processes increases Circular Economy efficiency.

In addition to that, a reduction of recuperative maintenance with preventive maintenance reduces unnecessary repairing times, reworking, and waste generation, e.g., of auxiliary material as well (Adams et al., 2017). Lastly, it can also be assumed that by reducing setup times, companies are able to use materials with a lower environmental impact in a standardized manner because they can better adapt to production changes. If lean production already enables companies to manufacture environmentally friendly products, this will have an impact on Circular Economy efficiency. Therefore, hypothesis H2b is:

H2b: A low setup time during manufacturing processes increases Circular Economy efficiency.

Based on the hypotheses developed, the underlying research model can be visualized as follows:

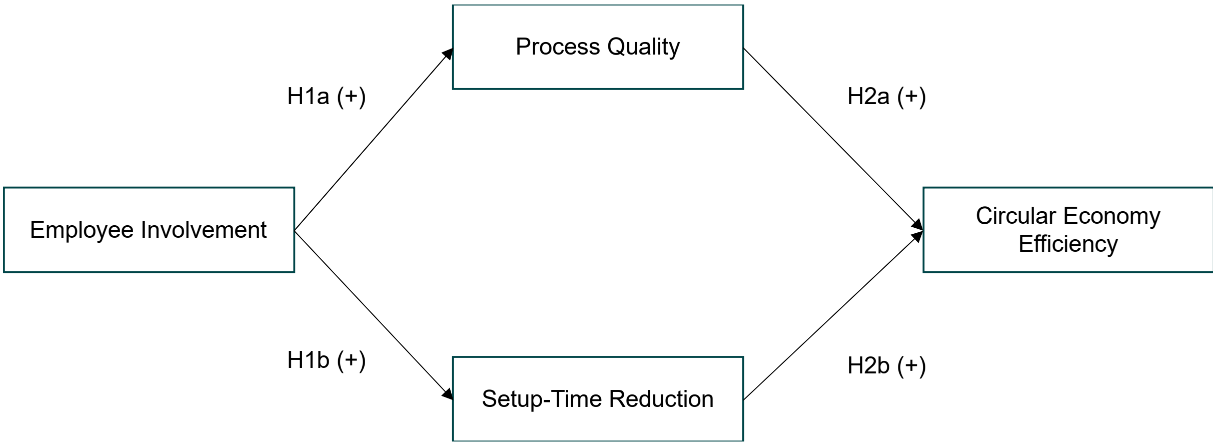

Figure 19: Research Model with Expected Hypothesis Outcomes.

3 Methodology

3.1 Data Collection

The data for answering the research question were collected by a survey, which was created for German-speaking (Germany, Austria, Switzerland) companies from the construction industry. For this purpose, the questionnaire was first translated into German, then implemented in soscisurvey (https://www.soscisurvey.de) and sent out via e-mail in August 2020. Beforehand, the questionnaire was validated by various academic and industry experts with vast experience in the construction industry; the translation was edited by native speakers, doublechecked, and back-translated to ensure the best understanding of the survey questions.

To obtain the survey participants, the Nace Rev. 2 listing was used to check whether the companies were active in one of the following areas (Eurostat, 2008):

- 233 - Manufacture of ceramic building materials,
- 235 - Manufacture of cement, lime, and gypsum,
- 236 - Manufacture of products from concrete, cement, and plaster,
- 237 - Cutting, shaping, and finishing of stone,
- 239 - Manufacture of grinding tools, abrasives products, and other products made from non-metallic minerals,
- 381 - Collection of waste,
- 382 - Waste treatment and repair,
- 383 - Recovery,
- 41 - Building construction,
- 42 - Civil engineering,

- 43 - Preparatory construction site work, construction installation, and other finishing trades.

All Nace Rev. 2 companies produce and transport parts or products which are directly related to the construction industry. In addition to these companies, we included companies who treat or recycle end-of-life construction products or buildings (Nace Rev. 2 codes 38.1, 38.2, and 38.3). Overall, the surveyed companies take different positions in the value chain and thus have different relevance for forming a Circular Economy in the construction industry, as Figure 20 shows:

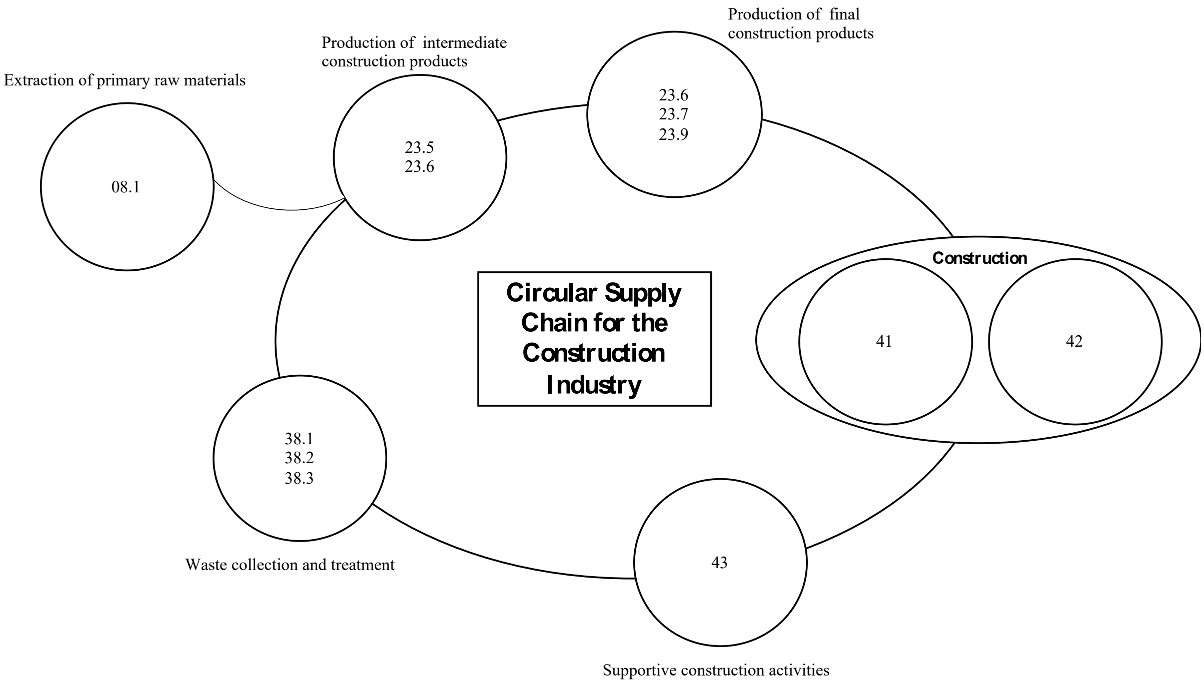

Figure 20: Circular Supply Chain for the Construction Industry, based on Nace Rev. 2.

The questionnaire was sent to the CEO's e-mail address, where available, otherwise to the company's information e-mail address. The questions were based on 5-point Likert scales to ensure a valid analysis and a high response rate, and also to reduce the questionnaire's complexity (Babakus and Mangold, 1992).

Construct Measurement

To measure the constructs, the survey was recorded and evaluated using a 5-point Likert scale. In total, the following 4 constructs were surveyed: Employee Involvement (EI), Setup Time Reduction (SR), Process Quality (PQ) and Circular Economy efficiency (CEE).

Employee Involvement

Employee Involvement was measured by the construct of Shah and Ward (2007) due to this construct's high relevance in the lean management literature, its sound theoretical foundation, and its proven validity (Marodin et al., 2018). It includes 4 items, which target different types of active employee participation in the production process. In each case, the degree of implementation was asked for:

EI1: Shop-floor employees are key to problem-solving teams.

EI2: Shop-floor employees drive suggestion programs.

EI3: Shop-floor employees lead product/process improvement efforts.

EI4: Shop-floor employees undergo cross-functional training.

Setup Time Reduction

The construct Setup Time Reduction was also adopted from Shah and Ward (2007) for the same reasons. It collects information about the degree of implementation of different practices:

SR1: Redesigns equipment to shorten setup time.

SR2: Uses special tools to shorten setup time.

SR3: Trains employees to reduce setup time.

SR4: Redesigns jigs or fixtures to shorten setup time.

Process Quality

For the construct Process Quality, items from the well-developed construct of Fullerton and Wempe (2009) were adopted. We chose the non-financial performance and efficiency measurements attributes because they focused on the most relevant process quality items:

PQ1: Scrap.

PQ2: Rework.

PQ3: On-time delivery.

PQ4: Process time interruptions.

Circular Economy efficiency

For the construct Circular Economy efficiency, we adapted the construct of Montabon et al. (2007) for measuring Environmental Efficiency. Ensuring a better fit to the Circular Economy objectives, we focused on the areas of waste prevention (Adams et al., 2017; Esa et al., 2017b), reuse of secondary materials (Nußholz et al., 2019), and the application of environmentally-friendly designs (Akanbi et al., 2019). Again, we measured the degree of implementation through 5-point Likert scales for the following items:

CEE1: Use of recycled material in the production process.

CEE2: Proactive waste reduction in terms of pollution prevention / waste elimination.

CEE3: Reprocessing of used components in relation to products, where some of the parts or components are recovered or replaced.

CEE4: Use of environmentally oriented design processes to design products eco-efficiently.

CEE5: Quantifiable environmental targets are used in product development.

CEE6: Environmentally friendly alternatives are specifically sought in product development.

3.2 Data Analysis

The hypotheses and the research model developed were tested using a covariance based structural equation model (SEM). A SEM is particularly suitable when various relationships of latent variables, which are not directly observable, are to be empirically investigated. By applying a factor analysis and a structural path analysis, a simultaneous assessment of the measurement model and the structural model is possible (Lee et al., 2011). Compared with other empirical analysis methods, SEMs allow a high validity and reliability of the construct measures (outer model) and of the structural model relationships (inner model) to be achieved (Bollen, 1989; Hair, 2009). For computing the SEM, Stata version 14.1 was used.

4 Results

After cleansing, 78 companies which had answered all the questions were considered for our analysis. The questionnaire was mainly answered by the CEOs or business owners (72%), followed by financial managers (e.g., management accounting, bookkeeping) with 12%, and others, i.e. project leaders. The average company size was 47 employees, which is above the average of the construction industry. The average company age was almost 39 years, indicating a high level of experience of most companies in the construction sector.

The dimensionality of the constructs for the outer model was evaluated by factor analysis (FA). Therefore, all factor loadings were measured and factor loadings below 0.70 were removed. This was the case for CEE_1, CEE_2, CEE_3, PQ_1, PQ4, and EI_4. The reliability of the remaining constructs was measured with Cronbach's alpha. Here, all constructs exceeded the recommended value of 0.70 (Fornell and Larcker, 1981; Hair, 2009; Hair et al., 2017). The results of the FA are provided in the Appendix. Additionally, the correlations between the different constructs were measured. They exhibit significant correlations between all constructs, especially between the hypothesized constructs. Considering these aspects, we conclude that the measurement model has a good overall fit. The results of the main SEM model are shown in Figure 3. The χ^2 statistic was not significant, which indicates a first good fit. Other indices were the root mean square of approximation (RMSEA) of 0.000, the standardized root mean square residual (SRMR) of 0.029 (cut-off value 0.08), the comparative fit index (CFI) of 1.000, as well as the Tucker-Lewis index (TLI) of 1.044. Following the goodness of fit, no re-specification of the model was necessary, because CFI and TLI were above the recommended value of 0.90 (Hu and Bentler, 1999).

Hypothesis 1a is highly significant with a coefficient of 0.30 ($p<0.01$) which means that Employee Involvement positively influences the Process Quality in construction companies. Also, the correlation between Employee Involvement and Setup Time Reduction is highly significant with a coefficient of 0.56 ($p<0.01$) Thus, hypothesis 1b, which states a positive relationship between those two factors, is supported as well. Hypothesis 2a, suggesting a positive relationship between Process Quality and Circular Economy efficiency, is also supported with a coefficient of 0.26 ($p<0.01$). Lastly, hypothesis 2b is also significant with a coefficient of 0.38 ($p<0.01$). The overall explained variance of the model is relatively high with R^2=0.35305; the lowest value is related to Process Quality (R^2=0.0929), followed by Circular Economy efficiency (R^2=0.2429), and Setup Time Reduction (R^2=0.3083).

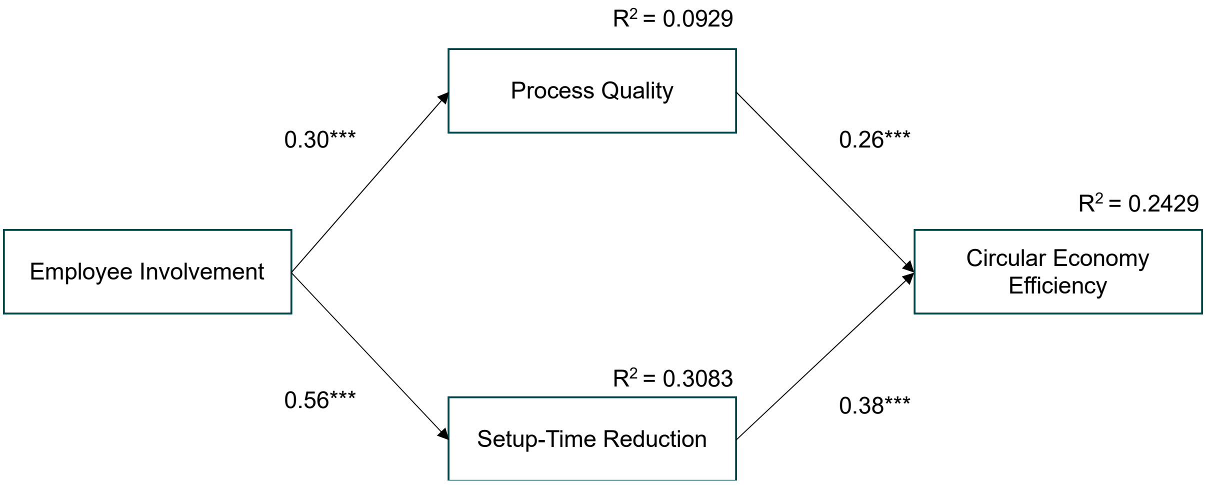

Figure 21: Structural Equation Modeling (SEM) Parameter Estimates (standardized solution).

**Coefficient statistically significant at p < .10 (two-tailed); **coefficient statistically significant at p < .05 (two-tailed); ***coefficient statistically significant at p < .01 (two-tailed)*

For the robustness of the proposed model shown in Figure 21 (model 1), we additionally tested two scenarios (model 2 and model 3), which are presented in Table 12:

Table 12: Different Tested Models.

	Model 1	**Model 2**	**Model 3**
PQ → CEE	.2595437**	.355743***	.2624001**
SR → CEE	.3773866***	.3648605***	.3859567***
EI → CEE			-.0165585
EI → PQ	.3048599***	.5350242***	.3048599***
EI → SR	.5552202***	.6408256***	.5552202***

**Coefficient statistically significant at $p < .10$ (two-tailed); **coefficient statistically significant at $p < .05$ (two-tailed); ***coefficient statistically significant at $p < .01$ (two-tailed)*

First, model 2 was tested with all variables included from the measurement model (see Table 13). This model still showed significant results, although the goodness of fit indicators showed lower values (RMSEA = 0.103; SRMR = 0.092; CFI = 0.852; TFI = 0.827). Additionally, we evaluated one model (model 3) with an additional direct connection between Employee Involvement and Circular Economy efficiency. Interestingly, this relationship was not statistically significant and provides a hint on that Employee Involvement only indirectly contributes to Circular Economy efficiency. An explanation could be that Circular Economy efficiency needs to be operationalized in production through more specific tools and procedures that simultaneously improve setup times and process quality as well as Circular Economy efficiency.

5 Conclusion

In this article, we have investigated the question of whether strong employee involvement has an impact on an improved Circular Economy efficiency in construction companies. For this purpose, a questionnaire was sent to construction companies in Germany, Austria, and Switzerland. The 78 completely answered questionnaires were tested using a structural equation model.

First, the results indicate that in the construction industry, employee involvement has a strong impact on process quality, which is answered in hypothesis 1a. This finding shows that especially in areas where automation is not on the same level as in other industries, employees play an important role in maintaining high standards. Second, the answer to hypothesis 1b shows that preparatory activities such as setup times, which account for a large proportion of non-value-added activities in the construction industry, can be significantly reduced if employees are given more responsibilities.

These two factors, high process quality and low setup time, are essential for influencing Circular Economy efficiency, which leads to our third contribution, supported by the results of hypothesis 2a and 2b. This makes sense under the aspect that the Circular Economy efficiency in the construction industry depends in particular on avoiding waste in production as well as reusing or recycling process waste. The major implication of the article is, that especially in the construction industry, one success factor for operationalizing Circular Economy strategies is if manufacturing employees are provided with the freedom to implement related practices of their own accord, since they are the people who can detect unnecessary waste in production processes. This act of detection can then lead to a direct reuse of the resources and thus improve the Circular Economy efficiency. Additionally, employees can positively influence a Setup Time Reduction in production, which helps to adapt the production processes faster for transitioning to Circular Economy-efficient products. On the one hand, efficient setups times reduce waste, i.e. inefficient energy usage or wrongly used tools. On the other hand, these efficiency gains can only be detected by employees who are encouraged to think “outside the box”. This is particularly important for Circular Economy-efficient products, because they require an innovative mindset in the design phase as well as in the production phase. This contribution also underlines the theoretical foundation of lean construction, which implies that special attention must be paid to an employee-centered approach in order to transfer the lean philosophy to the construction industry (Diekmann et al., 2005).

This suggests that a transformation to a Circular Economy will work if employees are involved and empowered. Hence, companies should implement practices that involve their employees as promotors of improving the environmental efficiency and Circular Economy efficiency of their employers. The operational implementation of these strategies, measurable in terms of efficiency, materializes mostly in the form of an increased resource efficiency, which can, however, include several factors.

Material savings in product design, but also less waste in the form of scrap, can increase this form of resource efficiency. In both scenarios, people are still the driving factors that are influencing resource efficiency, even though digital performance measurement systems are increasingly present in the construction industry (Jang and Lee, 2018; Xue et al., 2021). However, resource efficiency leading to better capacity utilization and lower costs still plays a crucial role. With regard to capacity utilization, efforts should be made to reduce those time portions that do not add value, i.e., waiting times (idle times) and setup times. These value-added losses can include substantial cost efficiency losses in construction companies, as already shown by Dräger and Letmathe (2022). However, cost efficiency can be misunderstood, as it can suffer due to new process chains and ramp-up costs in the beginning, but it can also perform better than conventional processes in the long run. All three factors should be designed to be as efficient as possible, since they are mutually dependent and consequently influence the overall efficiency.

6 Discussion

In summary, our results show that employee involvement can be an important facilitator of establishing Circular Economy practices in the construction industry. However, in the context of this work, the focus was mainly on Circular Economy efficiency, but without consideration of the cost and revenue perspective. Further research should therefore look more closely at the extent to which Circular Economy efficiency has a financial impact on companies. For example, it could be investigated as to what extent investments in employees – but also modern facilities – have an impact on Circular Economy efficiency. Investments in employees should include training sessions that build an awareness for the fact that actions in production processes affect Circular Economy efficiency, e.g., waste reduction of tools. It can be expected that the results could even be strengthened if training sessions went beyond established lean practices and focused more on specific characteristics of circularity. This can either include the handling of new or alternative raw materials, or the more frequent reuse of tools. While this is not adding an additional layer in an effective Circular Economy, it shows rather that already known circular concepts have to be implemented more efficiently. Kurdve and Bellgran (2021) already showed that in such cases an overuse of tools could be reduced by up to 50% and a recycling rate of 75% was possible. Additionally, further automation and digitization investments in the production process will affect Circular Economy efficiency. BIM, as a flexible digital solution to store and manage construction data, enables companies to evaluate their products' environmental footprints through Lifecycle Assessments (LCA) and can enable companies to evaluate circular products on a detailed level (Xue et al., 2021). Furthermore, it would be interesting to see how Circular Economy strategies are implemented operationally in manufacturing. The financial competitiveness with consideration of market mechanisms under which such strategies emerge would also be of interest. Especially in the construction industry, any procurement that is aimed at purchasing primary materials at the lowest possible cost can obstruct the reusing of secondary materials. Hence, Circular Economy strategies should be implemented with a long-term view in mind. Another point that should be investigated in more detail in this context is whether the results differ when other areas of the construction value chain, e.g., recycling and processing companies, are included in the evaluation. This could lead to holistic strategies that are applicable for an entire and more sustainable value chain architecture and not just for individual companies. While this study depicts only specific parts of an effective Circular Economy, future research could investigate if employee involvement and lean practices also support further Circular Economy strategies. Additionally, future research should evaluate in more detail, if a ‘one fits all approach’ holds true for different types of construction companies, e.g. through multiple case studies. Ultimately, a circular way of thinking and operating can only be implemented in the construction industry if the chosen approach takes all actors (including the customers) into account.

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Appendix

Table 13: Constructs and Indicators.

Variable	**Factor Loadings**	
Circular Economy Efficiency	**Cronbach's Alpha: 0.8836**	
CEE_1		0.5294
CEE_2		0.5452
CEE_3		0.5091
CEE_4	0.7519	
CEE_5	0.8419	
CEE_6	0.8978	
Process Quality	**Cronbach's Alpha: 0.7591**	
PQ_1		0.5408
PQ_2	0.7045	
PQ_3		0.5872
PQ_4	0.7045	
Setup Time Reduction	**Cronbach's Alpha: 0.8949**	
ST_1	0.7126	
ST_2	0.8052	
ST_3	0.9178	
ST_4	0.8410	
Employee Involvement	**Cronbach's Alpha: 0.8687**	
EI_1	0.8291	
EI_2	0.7964	
EI_3	0.7958	
EI_4		0.5954

Variables < 0.7 were excluded and are not contributing to Cronbach' Alpha.

Table 14: Correlation Matrix.

	CEE	**PQ**	**ST**	**EI**
CEE	1			
PQ	0.3363***	1		
ST	0.4543***	0.2842***	1	
EI	0.2637**	0.3142***	0.5544***	1

**Coefficient statistically significant at p < .10 (two-tailed); **coefficient statistically significant at p < .05 (two-tailed); ***coefficient statistically significant at p < .01 (two-tailed).*

Research Paper 3: Value Losses and Environmental Impacts in the Construction Industry – Tradeoffs or Correlates?

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Abstract

Construction activities have significant adverse impacts on the environment which typically include dust and gas emissions, noise pollution, waste generation, water consumption, and air pollution. One step towards a more sustainable construction industry during the production stage is producing precast construction components in manufacturing facilities. However, most precast facilities are not yet able to track value losses such as waste from time and scrap. The main objective of this article is to examine the correlation between those value losses and the environmental impact with Cost Efficiency Accounting - a new measurement method applied to the best of our knowledge for the first time in the construction industry. We collected data on 460 products within a precast production facility and analyzed how the material used (steel, concrete, etc.) correlates with the production times and the complexity of the products. On the basis of these results, we found that high costs are related to negative environmental impacts, but we also discuss implications of the results for improving the environmental and economic performance of the construction industry simultaneously.

Keywords: Cost Efficiency Accounting, value losses, sustainable material substitution, sustainability, construction industry

1 Introduction

Climate change is one of the most challenging issues for our society. At a political level, many efforts tackle climate change. For instance, as part of the European Climate Change Programme (ECCP)[11] the European Union has set targets for reducing Greenhouse Gas (GHG) emissions in the EU progressively up to 2050 (European Comission, 2008). These targets were most recently revised and now aiming to cut GHG emissions by 55% by 2030, while achieving climate neutrality by 2050 (European Commission, 2020). One sector with significant adverse impacts on the environment is the construction industry (Ding et al., 2018). The products of this industry are still responsible for 36% of the energy-related GHG in Europe (European Commission, 2021). Besides the very prominent GHG emissions, other adverse impacts include dust and gas emissions, noise pollution, waste generation, water consumption, and air pollution (Chuai et al., 2021). For achieving the European targets, changes at the corporate level in the construction industry are required. For the concerned companies, different opportunities exist for them to become more "green": (1) innovative and environmentally friendly products and (2) organizational improvements.

The first perspective - (1) innovative and environmentally friendly products – incurs some challenges. Concrete, as one of the most used materials in the world, is responsible for approximately 8% of global CO_2 emissions (Miller & Moore, 2020), most of it still from the production of its major component, i.e. Portland cement clinker (Costa & Ribeiro, 2020). The main reason is that vast quantities - e.g. for walls, ceilings, bridges - of concrete are used in many construction applications (Crow, 2008). Concrete as a material can technically be recycled and reused with recycled aggregates, but concrete also consists of other components (Tošić et al., 2015). Reinforced concrete is a common composite for improving the technical characteristics of concrete applications, for instance the material's tensile strength. Steel is the most used material for those composites, because it has a lot of advantages, for instance ease of usage, and high availability. However, disadvantages of steel include a substantial environmental footprint, a high weight, and corrodibility (Brameshuber et al., 2006). Even though developments in the steel industry have been made to improve their products, especially through innovations in the production process (Muslemani et al., 2021), there are other product developments as well, which are trying to replace steel with fibers to reinforce concrete. These substitutes promise to have technical advantages such as light weight, ease of installation, corrosion resistance (Brameshuber,

[11] All abbreviations are summarized in the Appendix (list of abbreviations).

2016) as well as environmental advantages (Conroy et al., 2006). However, fibers and other reinforcement materials are substantially more expensive and can only compete against steel if they are produced offsite with efficient and highly productive processes that avoid waste production (KPMG, 2016).

This leads to the other perspective - (2) organizational improvements. When considering their organizational structure, construction companies still underperform in strategically important areas such as productivity, delivery performance, skill shortages, and data transparency (KPMG, 2016). Low productivity as well as waiting times can also be a n important driver for extensive energy use (Francis & Thomas, 2020). These relative weaknesses of the construction industry can be explained by a variety of factors: less sophisticated supply chains compared to other sectors, many decentralized small and medium-sized enterprises, and still dominant individual onsite production (Wu et al., 2019). Those factors do not foster environmentally friendly developments. One solution can be implementing approaches that foster Corporate Social Responsibility in construction companies (Barthorpe, 2010). Another one can be offsite production, which means prefabricated, process-oriented, and standardized production in a more controlled environment than onsite production. Nevertheless, the offsite market in Europe is, with a share of revenues of 7%, still rather small compared to the onsite construction (KPMG, 2016). Other countries, such as China, have a much higher share of prefabricated products and measure their environmental impacts in more detail (Gao & Tian, 2020). In Hong Kong, the government promotes prefabrication since 2002, which has resulted in a broader adoption of prefabrication techniques (Tam et al., 2015).

For the construction sector, studies that investigate the interplay of the environmentally friendly product perspective and the organizational improvement perspective are basically non-existent. Due to the tremendous importance of the construction industry with regard to its GHG emissions, more research that disentangles the relationship between manufacturing and environmental performance in the construction industry is a promising avenue. Therefore, we aim to first look at tools that can be used to measure both the manufacturing and the environmental performance. Then, by employing a hand-collected data set, we analyze the specific case of the offsite production of a construction firm and provide some evidence of the tool's validity and the statistical interdependence of production inefficiencies and environmental performance.

The remainder of the paper is organized as follows: Section 2 discusses the relationships between the environmentally friendly product perspective and the organizational perspective with regard to their impact on the firm's environmental and financial performance and derives the relevant research questions. Section 3 introduces the theory of the measurement of cost and environmental inefficiencies. Section 4 describes the applied methodology. Section 5 reports the empirical results of the case company and provides answers to the research questions. Section 6 discusses limitations and gives an outlook for further research.

2 Literature Review

The perspectives described in the introduction – (1) the environmentally friendly product perspective and (2) the organizational perspective – should not be considered separately, because there are many connections between them. It is also necessary to add to these perspectives an economic and an industry perspective, since viable approaches to increase the industry's sustainability have to take the economic situation and the specific contextual factors of the construction industry into account. Hence, it is worthwhile analyzing the product and the organizational perspectives in more depth with regard to the relationship between economic and industry-specific aspects of the construction industry:

(1) Environmentally friendly product perspective. Ilg et al. (2016) discussed high performance materials in the construction industry as a solution to reduce CO_2 emissions. A potential material innovation to lessen the industry's environmental impact are fiber-reinforced polymers that can be produced with lower CO_2 emissions and also have potential cost advantages. The overall environmental impact of those new products and materials is often examined either with Life Cycle Assessment (LCA) tools (Ortiz et al., 2009), certification assessments such as BREAAM (Ding, 2008) or from an economic market perspective (Tam et al., 2006). The extensive literature review by Ortiz et al. (2009) has revealed that most studies use the Global Warming Potential (GWP) as an indicator to measure the environmental impact of inputs and products from the construction sector. Especially, concrete and reinforced steel cause a high negative environmental impact. Dimoudi & Tompa (2008) investigated different materials and conclude that concrete and reinforced steel alone cause 59.6% to 66.7% of the energy consumption of buildings during their construction phase. The same conclusion has been reached by Bribián et al. (2011), who conducted a LCA analysis and state that steel is the most impactful material on the environment with 25.5% primary energy usage, followed by cement, which contributes 11.7% to the energy consumption. Furthermore, steel is responsible for 18.7% and cement

even causes 30.3% of the CO_2 emissions. Recent studies showed that cement (Costa & Ribeiro, 2020) as well as aggregates for concrete (Honic et al., 2019) can be at least partially produced with construction and demolition waste and because of this big recycling potential can lower the environmental impact of concrete. Although this can be done without a substantial loss of quality (Alnahhal et al., 2018), the separation process when demolishing buildings, especially with reinforced concrete, is still expensive. Guggemos & Horvath (2005) compared the environmental impact of steel framed buildings with concrete framed buildings during the construction phase and do not find major differences in energy usage. Mao et al. (2013) provided a comparison between different manufacturing methods in the construction sector (offsite vs onsite manufacturing) and their ecological impact with regard to GHG emissions. They find that prefabricated building elements produce significantly fewer GHG emissions than conventional ones do (Mao et al., 2013). Reasons such as more standardized production processes and less waste as a consequence already point towards the organizational perspective.

(2) Organizational perspective. This perspective focusses on organizational improvements, mainly on the manufacturing level. Although manufacturing philosophies, like Lean Management with its many tools, are often considered, Jørgensen & Emmitt (2008) pointed out that in the construction industry no common understanding of Lean exists and thus only a few companies are using such an approach. For companies, using Building Information Modeling (BIM) approaches could be a way to facilitate and integrate Lean Management approaches (Francis & Thomas, 2020). Furthermore, studies focussing on the organizational perspective often fail to consider environmental implications (Diekmann et al., 2005). Other studies also showed that construction waste (Formoso et al., 1999) and the monitoring of waste flows (Vrijhoef & Koskela, 2000) is a major issue in construction supply chains and affects the environment the most. Pekuri et al. (2011) revealed that measurement systems in construction companies are not easy to implement but performance measurements that cover costs and environmental aspects are nonetheless necessary. Bon & Hutchinson (2000) came to the same conclusion and stated that especially on the plant and process levels the construction industry lacks solutions. Again, the most promising approaches are a greater use of BIM to manage the planning process (Lu et al., 2021). Nevertheless, the relationship and interdependencies between ecological and manufacturing constraints are a well-known topic, which can be examined in many different ways. Among others, King & Lenox (2001) showed that investing in lean practices can improve companies' environmental performance as well. Overall, empirical studies

indicate a positive relationship between lean management practices and environmental as well as economic impacts. For example, Rothenberg et al. (2001) found that lean management practices reduce a firm's emissions as well as its water and energy usage. Yang et al. (2011) added the financial and economic performance to their studies and found a positive relationship as well. While the environmental impact is mostly associated with emissions and waste, only Dües et al. (2013) considered also the linkage between production times and environmental impacts. The research of Hajmohammad et al. (2013) examined empirically the theory of the Natural Resourced-Based View with a focus on how environmental performance can be improved through manufacturing efficiency. As all these studies point towards a complementary relationship between economic and environmental objectives, there might be tradeoffs as well. Specifically, strict regulatory regimes, such as limit values for emissions or product requirements, e.g. ensuring the energy efficiency of buildings, might lead to higher costs, as the paper by Letmathe & Wagner (2018) shows. However, within a given regulatory regime, manufacturing approaches that aim to reduce costs of waste during production and to increase productivity seem to have positive consequences for improving a firm's and an industry's environmental performance as well. For the construction industry, this might be particularly true, as formal environmental management systems are implemented to a far lesser degree than in other industry sectors. In this vein, Tam et al. (2006) discussed regulatory compliance, auditing activities, and resource consumption as main indicators for assessing companies of the construction industry. Chan & Chan (2004) also suggested that for succesful construction projects inefficiencies from time and quality should be tracked. Arbulu et al. (2003) have found substantial inefficiencies of onsite construction processes, especially when batch sizes are low. However, even though prefabricated products can potentially reduce these inefficiencies due to better managed and more standardized processes, research on prefabricated (offsite) construction as a more sustainable production method in the construction sector is relatively scarce (Li et al., 2014).

Table 15 shows the results of the literature review and the respective contribution of the articles to the four selected areas. Even though literature which discusses the interplay between environmental and organizational performance in general is plentiful, we are not aware of any works which consider the product and the organizational perspectives as well as economic and industry-specific aspects of onsite production in the construction industry simultaneously. Our research focuses on that research gap and combines all four perspectives. The results allow us to provide insights on how an important industry such as the construction industry can measure and improve manufacturing performance and the environmental performance of products. It further sheds light on the controversially discussed relationship between environmental and economic performance in a specific sector.

Table 15: Literature Review of Selected Areas

#	References	Environmentally friendly products	Organization	Economy	Construction Industry
1	Formoso et al. (1999)	-	-	-	X
2	Bon & Hutchinson (2000)	X	-	X	X
3	Vrijhoef and Koskela (2000)	-	-	-	X
4	Arbulu et al. (2003)	-	X	-	X
5	Chan & Chan (2004)	-	X	-	X
6	Diekmann et al. (2005)	-	X	-	X
7	Guggemos & Horvath (2005)	X	-	-	X
8	Tam et al. (2006)	X	-	-	X
9	Dimoudi & Tompa (2008)	X	-	-	X
10	Ding (2008)	X	-	X	X
11	Jørgensen & Emmitt (2008)	-	X	-	X
12	Rothenberg et al. (2009)	X	X	-	-
13	King & Lenox (2009)	X	X	-	-
14	Ortiz et al. (2009)	X	-	-	X
15	Bribián et al. (2011)	X	-	-	X
16	Yang et al. (2011)	X	X	X	-
17	Dües et al. (2013)	X	X	-	-
18	Mao et al. (2013)	X	X	-	X
19	Hajmohammad et al. (2013)	X	X	-	-
20	Li et al. (2014)	-	X	-	X
21	Kim et al. (2016)	-	X	X	X

22	Ilg et al. (2016)	X	-	-	X
23	Martínez León & Calvo-Amodio (2017)	X	X	-	-
24	Alnahhal et al. (2018)	X	-	-	X
25	Honic et al. (2019)	X	-	-	X
26	Costa & Ribeiro (2020)	X	-	-	X
27	Francis & Thomas (2020)	X	X	-	X
28	Lu et al. (2021)	X	-	X	X

As elaborated in the literature review, research often examines ways how an industry can improve its environmental performance by introducing high-level systems, such as environmental management systems. However, in every industry specific instruments are required that allow the identification and exploitation of potentials for improvement. Lean Management is one [strategic] approach to support companies in doing so, but it has to be combined with specific instruments and methodologies. Our contribution has both a high scientific and a high practical relevance to promote sustainability in the construction industry. On the one hand, we show quantitatively that environmental and economic aspects are not mutually exclusive, but can complement each other. In particular, material substitution can foster the circularity of the construction industry and lower its environmental impact simultaneously. On the other hand, the article also has a high practical relevance as we were the first ones – to the best of our knowledge - who applied the cost efficiency accounting method in the construction industry. This novel method allows construction companies to evaluate if and to what degree environmentally-friendly material substitution pays off economically due to efficiency gains. Since this method was developed especially for SMEs, it is particularly suitable for the construction industry and can help individual companies to act more efficiently and sustainably. Hence, this paper aims to answer the following research questions:

RQ1: How can Cost Efficiency Accounting help to identify products that allow companies to reduce their environmental impact?

RQ2: To which degree do value losses during the production stage correlate with their environmental impact in the construction industry?

We show that not only value losses from material but also from production time deviations have a substantial impact on the production's environmental impact. We also present a differentiated analysis of in which cases improving environmental performance will incur higher costs and in which cases it can reduce the costs to help companies to choose an optimal product mix in order to achieve both goals, a better environmental performance and a higher manufacturing efficiency. For answering the research questions, a German manufacturer of precast components for the construction industry was selected in order for us to apply the methodology and to answer the research questions at hand.

3 Theoretical Background

The theoretical foundation of this article mainly focuses on the concepts of Cost Efficiency Accounting (Letmathe, 2002) and the Natural Resourced-Based View (Hart, 1995). Cost Efficiency Accounting is a concept with the objective to measure and reduce value losses during the production processes. As it measures different types of waste, it is suitable for addressing the main research questions of this article. Cost Efficiency Accounting emphasizes a single performance indicator, the cost efficiency, that is defined as the ratio of ideal and actual costs of a reference object, e.g. a process, a product, or an organizational unit:

$$CW_s = \frac{C_s^{ideal}}{C_s^{actual}} \tag{1}$$

with: CW_s Cost Efficiency of a reference object s

C_s^{ideal} Ideal costs of a reference object s

C_s^{actual} Actual costs of a reference object s

Note that Cost Efficiency has no unit as it reflects the ratio of two cost units. Ideal costs define an "artificial" construct that characterizes an ideal production in which no value losses exist, i.e. the consumptions of all inputs (materials and capacities) equal their optimal levels. Simply speaking, all materials will be part of the final products, machines run at their optimal speed, and humans work at the (long-term) cost-optimal productivity levels. Ideal costs are calculated by multiplying ideal consumptions by their planned cost rates. The ideal consumption can be defined individually but should mostly contain the areas "time" (capacity consumption of machines and human labor) and "material". Any deviations from the ideal costs can be traced back to inefficiencies (waste) in certain areas. Those areas include (for the following Letmathe, 2002):

- No waste of material: All material used in the productions areas goes entirely into the products, which means that no cuttings, shrinkage, theft, or any other type of material waste occur.
- No solid waste, sewage, and emissions: The production process will not yield any undesired by-products. This property excludes all outputs which are not value-adding.
- No scrap or rework: The entire output conforms to all relevant quality specifications, which will lead to a zero-defect production (Halpin, 1966). If this property is given, the gross output quantity (actual output quantity) will equal the net output quantity (useful output quantity).
- No quality inspection, checking, and supervising: Since no waste of material and no scrap occur, quality inspections and further checking and supervising are not necessary.
- No setup times: Setups do not reduce productivity. This means that changeovers from one product to another will not lead to any interruption to the production process.
- No waste of processing time: Breakdowns of machines or reduced performance of employees do not happen. A specific output can always be produced within the cost-optimal processing time.
- No inventory: Raw materials, parts, and semi-finished products are supplied just-in-time before they are used. This means they do not have to be stored. The same logic holds for finished products which are completed exactly when they are due for delivery.
- No time losses during production: Unplanned interruptions to machines and shop-floor workers are excluded, and time fluctuations are not considered.

These attributes define ideal standards which cannot be accomplished in practice. For example, in most cases it is impossible to eliminate setup times entirely or to install a just-in-time system with no inventory. Hence, a Cost Efficiency of "1" cannot be achieved in practice as the laws of thermodynamics here also apply. Corresponding targets must take this into account and either aim for an increase or a specific target level. Cost efficiency is thus comparable to the indicator "Energy Efficiency", which is widely used in various industries. Again, an efficiency level of "1" cannot be achieved, yet this indicator is very popular and is used to compare machines, industry processed, heating systems, etc. Cost efficiency losses result from any deviation from the ideal production. By aiming at the elimination of all non-value adding activities and resources, there is an unambiguous direction for improvement. Since cost efficiency is a dimensionless indicator, the cost efficiencies for each of those areas can be aggregated. Hence, they can be compared within a single process or production of a product and show directly in which area the highest improvements can be achieved. Another advantage of this universal indicator is that it does not have to deal with the underlying cost data, which lowers the complexity of its interpretation and facilitates direct improvements on the shop floor.

This study also relies on argumentation of the Natural Resource-Based View (Hart, 1995) that companies are dependent on their ecosystems and that their competitive advantage relies upon these. Therefore, companies should focus on three strategic capabilities. First, pollution prevention, which means tracking and reducing emissions, wastes, and effluents. Studies have shown that companies can realize significant savings by doing so through production improvements, following legal requirements and obtaining a better image (Gimenez et al., 2012). Second, product stewardship, which focuses on product development and integrates environmental requirements throughout the entire product life cycle. A common feature for realizing product stewardship is the use of LCAs, in which the environmental impact of products is analyzed from "cradle to grave" (Wenzel et al., 2000). Another approach is that of developing products for a circular economy, which means looking at environmental impacts from "cradle to cradle" (McDonough & Braungart, 2002). Through product stewardship, companies can develop new products which have lower life cycle costs. Third, sustainable development, which combines pollution prevention and product stewardship and builds a common strategy with a shared vision.

In summary, our research is based upon the before mentioned theories, as we want to show how improving its manufacturing efficiency can contribute to improving a company's environmental performance.

4 Methodology

The research methodology is based on the case study method (Yin, 2014). We used a single-case design to answer our research questions. Our focus lies on precast (offsite) production of construction companies to examine how especially these can contribute to reducing the environmental impact of the construction industry. Therefore, we applied the following criteria in order to comply with the research design suggested by Yin (2014):

Case selection. For the application of the theoretical framework, we have chosen a precast construction company located in Germany. The company is medium sized and family owned and therefore typical of the German construction industry. The company employs almost 600 employees, which are working in five facilities, of which two are specialized in producing precast building elements. The examined production facility was worked in two shifts with modern equipment. The reinforcement as well as the shells were mostly produced inhouse. The company does not have a formal environmental management system implemented and relies mostly on project-based performance measures. Since these characteristics apply to many other construction companies as well, the findings should reflect options to reduce their environmental impact as well as options for the further dissemination of the results in other precast production in other companies. The examination took place in the main precast facility in the case company, where precast building structures are produced in production cells in single and small batches. On the shop-floor, seven different product types are produced: stairs, walls, curtain walls, attics, ceilings, roof trusses, and stilts.

Those products contain steel and concrete as their main material input, and additionally different installation parts such as insulations, plastics, and spacers, based on customer demands which define the products' complexity, i.e. the complexity of products mainly refer to their geometric characteristics (e.g. angles which are needed for specialized walls, insulation materials spacers). The more complex a product was planned, the more frequently the process steps "other preparation" or "multi-layer-concreting" had to be run through, as shown in Figure 22. We focused on the direct production process, depicted in Figure 22, in which we tracked direct value losses during the production within a period of three months. Preceding processes, such as production of the shell, were not considered because the main environmental impact and the efficiency of material consumption (steel and concrete) are determined in the core production steps 3 and 4 (see Figure 22) in the respective production cells.

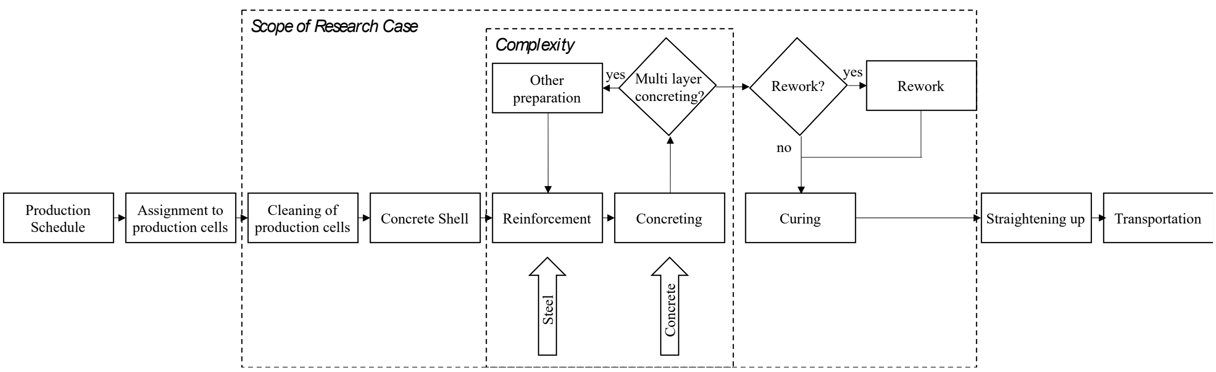

Figure 22: Scope of Research.

Case validity. In the case study, we used multiple sources of evidence by collecting data from production documents filled out on the shop floor, internal company data figures from Enterprise Resource Planning (ERP)-Systems, direct observation and measurement, as well as interviews. First, we evaluated with the plant manager which production process we wanted to examine. For this purpose, we analyzed two different production facilities, where different production processes were used. After that examination, we chose the production process which is described above (see Figure 22). The reason for this was that the production program is representative of the case company as well as of many other construction companies in Germany with the productivity level being rather low compared to other industries. Then, we prepared the production documents with the production planning team and explained them to the shop floor in the form of a workshop. The production documents included the actual production times, rework, waiting times, and also value losses in the case of complexity, quality, or interruptions. After the workshop, the production documents formed the basis and the instruction for the data collection to measure the production progress, the productivity, and the efficiency losses for a variety of products and orders. The data collection by the employees took place over three consecutive months. After each workday, the newly collected data were transferred to a database and synchronized with data from the ERP-System. The different sources of data are stated in Table 16.

Table 16: Sources of Collected Data, which was Needed for the Analysis.

Data	On the shop floor	ERP-System	Interviews
Time	Actual production times; rework; waiting times	Planned production times	Processes
Material	-	Concrete; steel; geometrics	-
Value losses	Complexity; quality; interruptions	-	Areas of value losses; interruptions

We measured the environmental performance of the products through their GWP (measured in CO_2-equivalents), as it is the most common indicator for comparing different products with regard to their environmental impact (Ortiz et al., 2009). For this purpose, we used Environmental Product Declaration (EPD), which is a standardized methodology for quantifying the environmental impact of a product (according to DIN EN 15804:2014-07; DIN EN ISO 14025:2011-10). The data are provided by the “Institut für Bauen und

Umwelt (IBU)", which focuses on construction and environment and is the official provider of EPDs in Germany (Del Borghi, 2013). We took the mean value of all registered glass fiber products for the main input materials consumed during the production process. Manufacturing efficiency was measured through the cost efficiency as described in the theoretical background. The ideal amounts of material were collected from the production planning system and were based on the technical drawings. The ideal production times were calculated as an improvement from the planned production times, which were based on the working steps necessary to yield a given output of a specific product. We measured the production costs of the products as the sum of personnel costs and material costs. Based on these data, we built a structured database which included datasets of 460 production orders in total.

Quantitative Analysis. We used multiple regression analyses to investigate the associations between production inefficiencies and environmental performance because it is one of the most used methods to investigate the relationship between one dependent variable Y and multiple independent variables X_j ($\forall$ j $\in$ J) (Backhaus et al., 2011). Y is in our case the relative time deviation measured as the percentage of the deviation between the actual production time[12] and the ideal production time divided by the ideal production time. We used the relative time deviations to be able to compare different orders in terms of production times and volume. β_0 is the unknown (_cons) Y-intercept, β_j ($\forall$ j $\in$ J) are the unknown population parameters to be estimated in the form of a J x 1 vector, and X_j ($\forall$ j $\in$ J) denote the independent variables in the form of a J x K matrix, with J being the total number of independent variables and K denotes the total number of observations (Cook & Weisberg, 1983). Our model includes J=5 independent variables, which reflect material measurements such as the consumed concrete (conc), reinforced steel (steel), and other steel components (steeloth) plus volume (volume) and complexity (compl) of different products.

In summary, the variables lead to the following regression model:

$$Idtimedev = \_cons + \beta 1 * conc + \beta 2 * volume + \beta 3 * steel + \beta 4 * steeloth + \beta 5 * compl$$

[12] The actual production time also includes the waiting times.

The definition of all variables is provided in Table 17:

Table 17: Definition of Selected Variables.

Variables	Regression Code	Values	Definition
Volume	volume	In m^3	Length x width x height of the product is calculated through the ERP-System.
Complexity	compl	1: easy; 2: medium; 3: hard	Indicator which measures how difficult a product is to produce, e.g. if a wall has windows, inclined walls. The evaluation is based on the experience of the shop floor workers.
Production Time (Actual)		In h	Real production time measured on the shop floor.
Production Time (Planned)		In h	Production time calculated by the ERP-System, based on incremental working steps needed to produce the product.
Production Time (Ideal)		In h	Production time which is required if no value losses occur.
Production Time Deviation	Idtimedev	In h	Time deviation between actual production time and ideal production time.
Waiting Time		In h	Time reflecting delayed material supply, shop floor workers working on other products, or technical issues.
Concrete	conc	In m^3	Amount of concrete which is needed to build the product.
Steel (reinforced)	steel	In kg	Amount of reinforced steel which is included in the final product and calculated by the ERP-System.
Steel (others)	steeloth	In kg	Prestressed steel or bar steel which is in the final product and calculated by the ERP-System.

5 Results

5.1 Descriptive Results

The data collection contains data about 460 production orders which were produced during the time of our data collection. These 460 production orders cover seven different product types (from walls over tiles to stairs). First, we cleared incorrectly filled out data, which included missing production times and missing material data (mainly steel). We also eliminated the product type "Stairs" (n=34) because their dimensions were calculated in a different way and the results were therefore not comparable with orders covering the other product types. For 9 orders, we calculated the complexity as 2.5, since the responsible product managers stated the complexity as being between 2 and 3. In total, 422 production orders remained which form the dataset used in our analyses.

The mean complexity of the products was stated to be 2.3 with a standard deviation of 0.5. While the products needed on average 10.0 hours to be produced, the mean waiting time was 0.2 hours. Compared to the planned production times it can already be noticed that time deviations were very low on average (9.992 hours – 9.868 hours = 0.124 hours). However, the standard deviation was 4.186 hours indicating that productions times varied substantially and were often much higher or lower than the average time. Compared to the ideal production times deviations amounted to approximately 21 percent of actual production time ((9.992 hours – 7.894 hours)/9.992 hours = 21.00%). The average amount of concrete used was 4.3 m^3 per product and the products had a mean volume of 6.8 m^3. Besides the concrete, the products mainly required steel with a consumption of reinforced steel of 134.8 kg and a mean consumption of other steel of 309.5 kg. All descriptive data are summarized in Table 18:

Table 18: Results from Data Collection - Product Profile (n=422).

Variables	Values	Mean	Std. Dev.	Min	Max
Volume	In m^3	6.779	7.196	.109	33.758
Complexity	1: easy; 2: medium; 3: hard to produce	2.264	.519	1	3
Production Time (Actual)	In h	9.992	4.186	1.500	23.000
Production Time (Planned)	In h	9.868	3.653	2.620	23.100
Production Time (Ideal)	In h	7.894	2.922	2.096	18.480
Waiting Time	In h	.189	.399	0	4
Concrete	In m^3	4.298	2.760	.120	14.620
Steel (reinforced)	In kg	134.779	119.216	0	462.190
Steel (others)	In kg	309.459	325.683	2.176	1840.16

5.2 Regression Results

First, we ran a logistic regression with the whole sample size to test the time deviation to planned production times. We implemented a dummy variable to evaluate whether there are general relationships between the variables. The dummy variable takes the value of 0 if a negative time deviation between actual and planned production time exists and the value of 1 if the deviation between actual and planned production time is positive. The results show that there is a positive and highly significant ($p<0.001$) correlation between complexity and the time deviation, as shown in Table 19. This already indicates that an introduction of ideal times can be useful. Additionally, the volume has a positive impact on time deviations at the 0.05 significance level.

Table 19: Logistic Regression Results for Dependent Variable "time deviation" (n=422).

Independent Variables	Coefficient	Std. Err.	P> |z|
Concrete	-.1512746	.0887974	0.088
Volume	.055755*	.0227538	0.014
Steel (others)	.000861	.0006054	0.155
Steel (reinforced)	.0036786	.0016716	0.028
Complexity	1.133712***	.2270329	0.000
_cons	-3.167614***	.5229227	0.000

* p<.10; ** p <.05; *** p<.01

After the logistic regression, we eliminated all production orders with negative time deviations, which was the case for 43 products. This is necessary because in Cost Efficiency Accounting an actual production time lower than an ideal production time is not possible, since an overall efficiency higher than "1" can never be achieved (no value losses at all, see theoretical background)[13]. Hence, these cases are likely to represent measurement errors. After that, 379 production orders remained in the linear regression. The applicability of the regression model was tested with common tests for linearity, completeness, collinearity, homoscedasticity, and the normal distribution of the error terms (Gordon, 2010). The regression results in Table 20 show that complexity still has a significantly positive influence on the production time deviation ($p < 0.05$). This means that it is more likely that more non-planned problems occur when complex products are produced compared to less complex products. Furthermore, there is also a highly significantly positive coefficient for volume ($p < 0.01$), which can be explained by longer waiting times for concrete to be supplied. Hence, complexity can be seen as a driver to separate products with high value losses from products which can be produced relatively efficiently. This result is straightforward to interpret, as a non-complex construction part, such as a wall with no windows and no gradients produced in a high volume, is less prone to time losses during the production process.

[13] In single areas this is possible, but at the expense of other areas, e.g. a faster than the ideal production time can cause value losses in quality.

Table 20: Regression Results with Dependent Variable "time deviation" (n=379).

Independent Variables	Coefficient	Std. Err.	P> |t|
Concrete	-.0071276	.00826	0.389
Volume	.0085684***	.001967	0.000
Steel (others)	-3.87e-06	.0000567	0.946
Steel (reinforced)	.000028	.0001511	0.853
Complexity	.0647982**	.0210215	0.002
_cons	.1184941	.0484906	0.015
Prob > F	0.00000		
R-squared	0.1032		

* p<.10; ** p <.05; *** p<.01

5.3 Cost Efficiency and Environmental Performance

Considering the previous results, we performed a cost efficiency analysis split by the different complexity levels. The results support our statement that the cost efficiency decreases with higher complexity by about 3.3%, only based on value losses due to efficiency losses of production times. One possible reason for that could be that highly complex products require more rework or that process steps are performed which are not documented in the ideal production time and therefore cause more interruptions and higher value losses. For 63 of the products, concrete supply was mentioned as one possible reason for those value losses. These results indicate that complex products tend to have special requirements for concrete (e.g. a special type of mixture) or different layers of concrete, which need more batches of concrete to be supplied in the production process. Also, complex products have a higher environmental impact than less complex products. The calculation shows that products with the highest complexity 3 pollute the environment with a mean of 1699.83 CO_2-equivalents while products with the complexity levels 2 or 1 only with means of 1555.41 CO_2-equivalents and 738.41 CO_2-equivalents respectively[14].

5.4 Decision Analysis

Lastly, we investigated a possible sustainable material substitution to lower the environmental impact of the products that we investigated. We chose to substitute steel as the reinforcement material by fiber, since fiber is known to have technically and logistically favorable characteristics (Ilg et al., 2016). Recent studies have shown that fiber-reinforced concrete only needs a third of the amount of concrete and only needs ten per cent of

[14] CO_2-equivalent for complexity level 2: 1431.44 (conc) + 33.82 (steel) + 90.16 (steeloth) = 1555.41
CO_2-equivalent for complexity level 1: 523.39 (conc) + 186.31 (steel) + 28.71 (steeloth) = 738.41

reinforcement material compared to steel reinforcement in order to achieve the same tensile strength (Ortlepp et al., 2018). For the case company, fiber reinforcements also fit into the production scheme because the production facility had already produced fiber-reinforced walls in the past. Because there are still very little data about the environmental footprint of these new products, we calculated a mean value of the GWP with data taken from existing LCAs, which used glass fiber as the main reinforcement material (Del Borghi, 2013).

Material substitution allows an improved environmental performance over all complexity levels. Especially products with the highest complexity level 3 improved their environmental performance from a CO_2-equivalent of 1699.83 with conventional steel to 520.83 with fiber reinforcement, which equals a reduction of 69.4 percent (see Table 21). This means that there is a high potential for improving the environmental performance of precasted products even when production complexity is high. When comparing both alternatives economically, costs of both material choices are nearly equal (1312.42 Euro for steel-reinforced products compared to 1302.68 Euro with fiber reinforcement). That is mainly because of the reduced material consumption needed for fiber-reinforced products.

Table 21: Material Substitution for Complexity Level = 3

Area	**Consumption**		**Costs [€]**		**Environmental impact [CO_2-equivalent]**	
	/w steel	**/w fiber reinforce-ment**	**/w steel**	**/w fiber reinforce-ment**	**/w steel**	**/w fiber reinforce-ment**
Concrete	4.73 [m^3]	1.58 [m^3]	236.55	78.85	1561.73	520.58
Material substitution (reinforced)	0.19 [t]	0.02 [t]	37.46	93.65	52.44	0.10
Material substitution (others)	0.31 [t]	0.03 [t]	61.18	152.96	85.66	0.16
Production time	12.99 [h]	12.99 [h]	977.23	977.23		
Total			1312.42	1302.68	1699.83	520.83

6 Conclusion, Limitation, and Outlook

In this article, we showed how a precast construction company could adopt two distinct perspectives – the organizational perspective and the product perspective – to reduce efficiency losses in order to lower the products' and the productions' environmental impact. Our respective empirical analyses show that Cost Efficiency Accounting is a suitable tool to measure product and production efficiency and its application led to the following findings relevant for the entire construction industry:

First, we have shown that ideal production times indicate a better direction to improve the processes and product decisions than planned production times because they do not provide information on the potential productivity gains. Because offsite construction companies are still missing competitive productivity rates, the advantages of ideal production times are distinct. In our case, we revealed a bottleneck situation in the supply of concrete. This bottleneck was especially relevant when it came to complex products, because they often needed specialized concrete. That resulted in an even bigger time losses and therefore, in higher value losses.

Second, we analyzed the correlations between production times and the material used and showed that not the amount of material but rather the complexity of a product is the main driver of production time deviation and, therefore, that complexity is a more important indicator of value losses than indicators of material consumption (e.g. concrete, steel). That means that a complex product tends to cause more value losses than less complex products do. This suggests that companies should categorize their products into different complexity levels for production and focus their analyses on the value losses of their more complex products. For these products, rigorously applied production standards and efficiency measurements provide a promising avenue to improve the products' economic and environmental performance simultaneously. Another avenue could be to standardize even more (modularize) and to simplify complex product designs.

Third, we analyzed the cost and environmental efficiency for the different complexity levels. The cost efficiency decreases with higher complexity. In addition to that, we integrated an environmental perspective into the measurement, based on the CO_2-equivalents of the materials used. As a result, we have shown that complex products also have had a higher environmental impact than products with a lower complexity. Interestingly, the environmental impact has increased even more with higher complexity than the value losses. Under these circumstances, companies are able to track their value losses in production as well as their environmental performance when introducing systems such as Cost Efficiency Accounting.

Last, we evaluated a possible material change from steel reinforcement to fiber reinforcement under cost and environmental aspects. For all complexity levels we found a better environmental performance, whereas cost levels do not substantially change. Even when considering recent price developments in the steel market, the results stay do not vary that much. With an increase of the steel price by a factor of five, the actual costs would increase by around 30% (from 1312.42 EUR to 1709.99 EUR for complexity level 3), which makes the switch to a more circular material solutions even more economically beneficial. While companies tend to improve their cost efficiency first, this example shows that focusing on environmental performance alone can have substantial positive effects but does not necessarily translate into cost savings. However, when focusing on material substitution, other phases of the product life cycles should be taken into account, most importantly and foremost, the potential to reuse or recycle materials after the products' useful lifetimes. Additionally, it has to be considered whether the technical specifications such as durability in the entire building remain unchanged as a result, or whether the ecological advantages remain stable over the entire life cycle. Hence, other attributes should be considered in more detail as well. In line with the Natural Resource-Based View of the firm, the study shows that producing environmentally friendly products can also lead to cost savings.

As our main insights are driven by the in-depth analysis of the production of data of a single case company by using data often not available to researchers, limitations of this study lie in the fact that we cannot claim that our results hold generally true. But since Cost Efficiency Accounting is a relatively new concept, there are not many comparable studies. While this concern occurs in other research methods such as single experiments as well, we propose the same approaches for facing it. Further research should build a multiple set of cases to replicate the same phenomenon, but under different conditions. Additionally, our study mainly focused on efficiency losses of production time deviations. One big advantage of Cost Efficiency Accounting is that other efficiency losses can be compared with efficiency losses of other areas, e.g. material losses. Future research could consider this in more detail. It would be also interesting to investigate bottleneck situations on the shop floor in particular and look at how those can be addressed better to lower efficiency losses in particularly critical products stages or links of the supply chain. Lastly, other substitutions could be considered as well; especially materials such as concrete could easily be substituted by recycled concrete. This approach would be an important step toward moving the construction industry in the direction of a circular economy.

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Research Paper 4: Measuring Circularity: Evaluation of the Circularity of Construction Products using the ÖKOBAUDAT Database

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Abstract

Background: Owing to the large amounts of energy, greenhouse gases, and waste that it generates, the construction industry is fundamental to the transition towards a circular economy. Indicators which show the circularity of products –and thus make them comparable with each other – can be used to support the implementation of such an economy. In this article, we have adapted the Material Circularity Indicator of the Ellen MacArthur Foundation in order to analyze the circularity of construction products available in the German environmental database ÖKOBAUDAT.

Results: The adapted indicator is applied to 89 building products from the categories of insulation materials, plastics, metals, and mineral building materials. More than half of the products receive the lowest score of 0.10, indicating poor implementation of circular strategies in the German construction industry to date.

Conclusion: Circular material flows are most likely to be employed for metals. However, the overall low circularity scores indicate a big need for better implementing circularity strategies.

Keywords

circular economy, circularity indicator, circularity measurement, construction industry, material circularity indicator

1 Background

Buildings are responsible for 50% of energy consumption, 40% of greenhouse gases, 50% of raw material extraction, and a third of water consumption in the European Union over their entire lifecycle (European Commission, 2019). In addition to the high consumption of primary materials, the construction industry is also the largest waste polluter accounting for 35.7% of the total waste generated in the EU in 2018 (Eurostat, 2020). At country level, the share of construction waste in total waste generation is even higher amounting e.g. to 87.9% in Liechtenstein, 70.2 % in France or 53.7 % in Germany (Eurostat, 2020). Only 50% of construction and demolition wastes in Europe was estimated to be recycled in total in 2018 (European Commission, 2018) and downcycling is commonly considered as an important problem in the construction industry (Hossain et al., 2020). In contrast to the linear model, circular economy models decouple the economic growth from the consumption of primary raw materials. The main objective of the circular economy is to avoid wasting raw materials and to close material loops by adopting circular strategies, such as reuse, repair, remanufacturing, and recycling of products and their materials (Munaro et al., 2020). A circular economy in the construction industry is still in its infancy and there is consequently a very high potential for an increased use of recycled materials, increased reuse of resources, and more sustainability (Eisele et al., 2020). For the transition towards a circular economy, both scale and quality of construction and demolition waste recycling need to be increased in the near future (Ghaffar et al., 2020). Even though the topic of circular economy in the construction industry has been increasingly addressed in the scientific literature in recent years, there are still research gaps here, especially with regard to the measurability of circularity in the form of indicators and the applicability of these indicators in practice (Hossain et al., 2020).

On the way to success with any of the circularity strategies, the measuring of the circularity of products and product categories plays an important role. Currently, indicators – particularly those at the product level – are not well developed and none of the existing approaches has established itself as a standard (Elia et al., 2017; Ellen MacArthur Foundation & Granta Design, 2015; Geng et al., 2012; Linder et al., 2017). Data availability for specific products the misalignment of existing indicators represent further major problems in the circularity evaluation of specific construction products. Therefore, this article aims to answer the following research question: How do different construction product (groups) listed in OBD perform in terms of circularity measured with a circularity indicator?

As part of this work, the Ellen MacArthur Foundation's (EMF) *Material Circularity Indicator* (MCI) for measuring the circularity of products and product categories is adapted and applied to the data on construction products available in ÖKOBAUDAT (OBD), an online database hosted by the German Federal Ministry of the Interior, Building and Community (Bundesministerium des Innern, für Bau und Heimat, 2020).

The article's remaining sections are organized as follows: section 2 reviews the related literature and compares approaches for measuring circularity. Section 3 introduces the methodology applied for evaluating products listed in the OBD database and calculates their current circularity in the construction industry. In section 4, evaluation results for different construction products are presented and analyzed. Section 5 shows the discussion and limitations of this study. Finally, a conclusion of the analysis is drawn and avenues for further research are outlined in section 6.

2 Existing Indicators for Measuring Circularity

On the product level, approaches for measuring circularity are still underdeveloped. This research gap has been identified by several authors, and the need for a circularity indicator at product level has been highlighted (Elia et al., 2017; Ellen MacArthur Foundation & Granta Design, 2015; Janik & Ryszko, 2019; Linder et al., 2017; Saidani et al., 2019). In the following, existing circularity indicators at product level are compared, based on their circularity objectives according to the literature review by Elia et al. (2017). These objectives were selected from those of the European Environment Agency and contain (a) reducing input and use of natural resources, (b) increasing the value preservation of products, (c) reducing emission levels, (d) reducing valuable material losses, and (e) increasing the share of renewable and recyclable resources (EEA, 2016; Elia et al., 2017). Analogously to Elia et al. (2017), the analysis focuses on the key characteristics of a circular economy without considering economic aspects which are classified as enabling factors in the EEA (2016) framework.

The *Circular Economy Index* of Di Maio & Rem (2015) calculates the ratio of the recycled material value of a product compared to the material value required for this product. Similarly, the *circularity* approach introduced by Linder et al. (2017) expresses recyclability as the ratio of the value of recycled materials and the value of all materials used in the product. The *Reuse Potential Indicator* according to Park & Chertow (2014) evaluates a product with regard to its reusability and serves as a decision-making basis for avoiding waste. The approach of the *Remanufacturing Product Profiles* by Gehin et al. (2008) evaluates products with regard to their ability to be reprocessed, but neglects recycling and reuse.

A very frequently cited concept is the Ellen MacArthur Foundation's (EMF) *Material Circularity Indicator* (MCI). This indicator compares the material flows from sustainable and primary sources of a product with each other (Ellen MacArthur Foundation & Granta Design, 2019). The weighted sum of the circularity values of all products in a company can also be used to evaluate the company's entire product portfolio and can indicate a company's overall circularity (Ellen MacArthur Foundation & Granta Design, 2019). Due to the rather complex calculation, consistent data could be hard to assess for a uniform comparison, e.g. to evaluate the recycling efficiencies (Gonçalves et al., 2021).

The different measurement and circularity objectives according to Elia et al. (2017) are reflected in different ways by the indicators mentioned. The *Circular Economy Index* (Di Maio & Rem, 2015), the *circularity* (Linder et al., 2017) as well as the *Reuse Potential Indicator* (Park & Chertow, 2014) are limited to the objective of increasing renewable and recyclable resources. The *Remanufacturing Product Profiles* only consider one of the five objectives and are furthermore insufficiently developed, because it only considers remanufacturing and excludes reuse as well as recycling (Linder et al., 2017). The *MCI* and hence also the *Circularity Indicator* not only assess resource-saving objectives but also the reduction of material losses and the durability of products. Table 22 shows the circularity objectives that are taken into account by the indicators mentioned.

Table 22: Comparison of Different Circularity Indicators and their Objectives based on the Criteria Elaborated by Elia et al. (2017).

Approach	**Considered Circularity Objectives**				
	Reducing input and use of natural resources	Increasing share of renewable and recyclable resources	Reducing emissions	Reducing valuable material losses	Increasing the products' durability
Circular Economy Index (Di Maio & Rem, 2015)		X			
Circularity (Linder et al., 2017)		X			
Reuse Potential Indicator (Park & Chertow, 2014)		X			
Remanufacturing Product Profiles (Gehin et al., 2008)	X				
Material Circularity Indicator (Ellen MacArthur Foundation, 2019)	X	X		X	X
Circularity Indicator (Madaster Services B.V., 2018)	X	X		X	X

As shown in Table 22, EMF's MCI meets several of the objectives considered and is also frequently discussed in the literature. Saidani et al. (2019) confirm that the MCI provides robust values across different circularity settings (Saidani et al., 2019). According to Janik & Ryzsko (2019), MCI is suitable as a circularity indicator at the product level due to its broad calculation basis. As a result of this comparison, the study at hand chooses the MCI, adapting it to meet the specific characteristics and requirements in the construction industry and to measure the circularity of construction products accordingly.

3 Methodology

This section provides an overview of the data and methods used and their underlying assumptions. The online open-source environmental database OBD, published by the German Federal Ministry of the Interior, Building and Community, contains environment- and climate-related data of construction products for lifecycle assessment of buildings. High data quality is guaranteed through external audits, data input based on expertise, and DIN EN 15804 conformity (Bundesministerium des Innern, für Bau und Heimat, 2019; Figl et al., 2019).

The lifecycle of construction products in OBD follows DIN EN 15804 and consists of the manufacturing (A1-A3), construction (A4-A5), use (B), and disposal phases (C) (see Appendix I). Modules A1-A3 describe all processes associated with manufacturing, including the manufacture of the product itself. A4 and A5 refer to the construction of buildings and the installation of products. The usage phase is indicated by the letter B. B is divided into seven individual modules, which also take maintenance and repair into account. B6 and B7 relate to the use of energy and water while the building is in operation. Modules C1-C4 describe the end of life including the waste treatment required for recycling (DIN EN 15804:2020-03, 2020). The database classifies datasets on different aggregation levels: products are classified into fixed product categories which can be further summarized into sub-categories. The latter are grouped into main categories (Figl et al., 2019). For each product and its stages in the product life cycle, the database collects the respective relevant environmental data. Additional information outside the product lifecycle such as reuse, recycling or recovery potential is presented in a separate module D (Figl et al., 2019). The OBD data consist of 24 standardized indicators on environmental impact, resource input, wastes generated, as well as material and energy flows (DIN EN 15804:2020-03, 2020; Figl et al., 2019). Information is always based on a reference unit, e.g. square meters (DIN EN 15804:2020-03, 2020).

The indicator chosen for this study, MCI, measures the circularity of material flows on a scale from 0 to 1, with 1 indicating a product which is entirely produced out of recycled materials and can – by definition - also be entirely reused or recycled (without recycling losses) at the end of its lifetime (Ellen MacArthur Foundation & Granta Design, 2019). Three components, namely product linearity (see formula (3)), i.e. the mass of primary raw materials used and wastes produced, as well as the duration and intensity of product use as compared to the industry average ($F(X)$, see also formulas (9) and (10)), form the basis for the final MCI formula (see formula (1)) which will be explained in detail in the following sub-sections (Ellen MacArthur Foundation & Granta Design, 2019).

3.1 Identification of Relevant Database Parameters

The MCI formula conducts a pure material flow analysis without considering energy consumption (Ellen MacArthur Foundation & Granta Design, 2019). In order to apply the MCI formula to OBD data, indicators on resource input, wastes generated, and material flows based on a reference mass can be considered. The following seven indicators fulfilling these criteria are listed in Table 23 below[15]:

Table 23: Relevant Indicators from OBD (own Compilation based on OBD).

Character	Name	Input/Output	Unit
CRU	Components for reuse	Output	Kg
HWD	Hazardous landfill waste	Output	Kg
MER	Substances for energy recovery	Output	Kg
MFR	Substances for recycling	Output	Kg
NHWD	Non-hazardous disposed waste	Output	Kg
RWD	Radioactive disposed waste	Output	Kg
SM	Use of secondary materials	Input	Kg

For the comparison of different products, the respective reference values in OBD are highly important as the actual product mass is not given in the database (DIN EN 15804:2020-03, 2020). In the following, index B depicts the relation to a reference unit, with M_B indicating the product mass based on the product reference unit.

3.2 MCI Calculation

The application of the MCI formula for OBD data requires minor adaptions to match OBD data content. The MCI is defined as follows:

$$MCI^* = 1 - LFI * F(X) \tag{1}$$

$$MCI = \max(0, MCI^*) \tag{2}$$

MCI: Material Circularity Indicator
$F(X)$: Utility factor built as a function of the utility X of a product
LFI: Linear Flow Index

The latter formula aims at eliminating potential negative values in order to ensure an MCI scale from 0 to 1 (Ellen MacArthur Foundation & Granta Design, 2019).

The Linear Flow Index (LFI) exposes the share of product material that is subject to a linear material flow. Products with an LFI of 100% contain primary raw materials only without any recycled or reused material, whereas an LFI of 0% indicates a fully circular product without using a virgin feedstock and unrecoverable waste production (Ellen MacArthur Foundation & Granta Design, 2019):

$$LFI = \frac{V_B + W_B}{2M_B + \frac{W_{F_B} - W_{C_B}}{2}} \tag{3}$$

V_B: Mass of virgin feedstock used in a product based on the product's reference unit

[15] A list with all symbols used for the calculation can be found in Abbreviation list.

W_B: Mass of unrecoverable waste associated with a product
M_B: Mass of a product based on the product's reference unit
W_{F_B}: Mass of unrecoverable waste generated when producing recycled feedstock for a product
W_{C_B}: Mass of unrecoverable waste generated in the process of recycling parts of a product

As OBD contains an indicator for secondary materials (SM), the quantity of virgin raw materials (V_B) used for a product can be calculated as follows based on the product reference size:

$$V_B = M_B - SM \quad (4)$$

SM: Use of secondary materials

In OBD biological feedstock cannot be identified and thus is not separable from SM.
The original formula for quantifying non-recyclable wastes (W_B) was adapted for the reference size basis with the index B by adjusting the included parameters accordingly and supplemented by a control value (K_0), which will be further explained in the following section:

$$W_B = W_{0_B} + \frac{W_{F_B} + W_{C_B}}{2} + K_0(-1) \quad (5)$$

W_{0_B}: Mass of unrecoverable waste through a product's material going into landfill, waste to energy, and any other type of process where the materials are no longer recoverable
K_0: Control variable

Furthermore, adaption of the MCI scale was required for the different input variables in the above-mentioned formula. Unrecoverable waste (W_{0_B}), formerly defined as total product mass less quantities being recycled or reused, is now calculated with the sum of all unrecoverable (non-circular) waste outputs, namely all outputs except MFR and CRU:

$$W_{0_B} = HWD + NHWD + RWD + MER \quad (6)$$

HWD: Hazardous landfill waste
$NHWD$: Non-hazardous disposed waste
RWD: Radioactive disposed waste
MER: Substances for energy recovery

Since no distinction can be made between biological feedstock, energy recovery is not subtracted from unrecoverable waste (Ellen MacArthur Foundation & Granta Design, 2019).
The MCI formula assumes quantities entering into the recycling process to be given as a share of total product mass (W_{C_B}). Instead, OBD directly provides an absolute quantity of materials entering into the recycling process (MFR), which simplifies the formula for

calculating the amount of waste generated during the recycling process at the end-of-product life:

$$W_{C_B} = (1 - E_C)MFR \quad (7)$$

E_C: Efficiency of the recycling process used for the portion of a product collected for recycling
MFR: Substances for recycling

For quantifying material losses during loop closure processes, MCI considers non-recoverable waste generated during the production of recycled product raw materials. However, OBD does not distinguish between reused and recycled materials used for the product. The OBD indicator SM thus corresponds to the fractions of mass of a product's feedstock from recycled or reused sources, i.e. the sum of the MCI components F_R and F_U, multiplied with the product mass M_B. The absence of any distinction between recycled materials or reused components entering into a product in OBD requires the integration of SM in the formula for calculating waste generated during the production of recycling material:

$$W_{F_B} = \frac{(1-E_F)SM}{E_F} \quad (8)$$

E_F: Efficiency of the recycling process used to produce recycled feedstock for a product

As SM includes not only recycled but also reused product materials, the amount of unrecoverable waste calculated in formula (8) might be slightly too high. However, since material reuse represents a strategy being relatively new and thus not widely applied in the construction sector, it is assumed that the share of F_R - and consequently the deviation of the result calculated with formula (8) from reality - is in practice very low (Kristensen & Mosgaard, 2020). Nevertheless, this assumption will be further addressed in the discussion section.

For the utility factor F(X), either lifetime or functional units may be considered for measuring product utility (Ellen MacArthur Foundation & Granta Design, 2019). In order to establish a broad comparison between different product types (Linder et al., 2017), the calculation of X is not based on the definition of functional units but on the product lifetime compared to industry average. Detailed insights in the respective calculations are provided in sections 3.3 as well as 4.3 and 4.4. Product utility is thus calculated with:

$$X = \left(\frac{L}{L_{av}}\right)\left(\frac{U}{U_{av}}\right) \quad (9)$$

$$F(X) = \frac{0{,}9}{X} \quad (10)$$

X: Utility of a product
L: Actual average lifetime of a product
L_{av}: Actual average lifetime of an industry-average product of the same type
$F(X)$: Utility factor built as a function of the utility X of a product

An overview of the adapted formulas is given in the following Table 24:

Table 24: Comparison of Formulas for MCI Calculation.

EMF formula	**Adapted formula**
$V = M(1 - F_R - F_U - F_S)$	$V_B = M_B - SM$
$W = W_0 + \frac{W_F + W_C}{2}$	$W_B = W_{0_B} + \frac{W_{F_B} + W_{C_B}}{2} + K_0(-1)$
$W_0 = M(1 - C_R - C_U - C_C - C_E)$	$W_{0_B} = HWD + NHWD + RWD + MER$
$W_C = M(1 - E_C)C_R$	$W_{C_B} = (1 - E_C)MFR$
$W_F = M\frac{(1 - E_F)F_R}{E_F}$	$W_{F_B} = \frac{(1 - E_F)SM}{E_F}$
$LFI = \frac{V + W}{2M + \frac{W_F - W_C}{2}}$	$LFI = \frac{V_B + W_B}{2M_B + \frac{W_{F_B} - W_{C_B}}{2}}$
$F(X) = \frac{0{,}9}{X}$	$F(X) = \frac{0{,}9}{X}$
$X = \left(\frac{L}{L_{av}}\right)\left(\frac{U}{U_{av}}\right)$	$X = \left(\frac{L}{L_{av}}\right)\left(\frac{U}{U_{av}}\right)$
$MCI^* = 1 - LFI * F(X)$	$MCI^* = 1 - LFI * F(X)$
$MCI = max\,(0, MCI^*)$	$MCI = max\,(0, MCI^*)$

For the circularity assessment on category level, several products having the same intended use are grouped into categories (DIN EN 15804:2020-03, 2020). For every category, a circularity index employing average product circularity is calculated in order to enable comparison amongst categories.

The categories to be calculated are fixed by the OBD database structure, namely main categories (MC), sub-categories (SC), and product categories (PC) with their corresponding formula characters MCI_{MC}, MCI_{SC} and MCI_{PC}. Within each category, the different circularity indicators are equally taken into account using the arithmetic mean:

$$MCI_{PC} = \frac{1}{n}\sum_{i=1}^{n} MCI_{P_i} \quad (11)$$

The calculation on higher aggregation levels follows the same formula structure analogously. The category evaluation thus represents a weighting of the contained circularity indicators, which may lead to distortions in case of outliers in categories with few sub-elements.

3.3 Assumptions

On the product level, a circularity index will be calculated for each product, with material flows being calculated as relative shares. Consequently, different products may be compared to each other even if they are based on different reference values. Ensuring product comparability requires controlling that the sum of all inputs equals the output sum. The sum of outputs can be calculated using the following OBD indicators:

$$R = HWD + NHWD + RWD + MER + MFR + CRU \qquad (12)$$

R: Sum of outputs
CRU: Components for reuse

The input sum equals primary plus secondary materials. In order to control the above-mentioned condition, the control value (K_0) compares outputs to the reference weight M_B (Inputs) of the reference unit of the product:

$$K_0 = R - M_B \qquad (13)$$

If the sum of outputs equals the sum of inputs, K_0 is zero. K_0 reaches negative values if the sum of all outputs is smaller than the sum of the input weights. Positive values for K_0 cannot occur since the sum of all outputs cannot exceed the sum of all inputs. The control value is thus only considered if the sum of inputs exceeds the output sum. If occurring, the difference value is added to the waste flow in formula (5), as recycled and reused materials are already considered in MFR and CRU. Hence, the control variable prevents missing data from decreasing the LFI.

On the input level, modules A1, A2, and A3 – in OBD aggregated as a combined module A1-A3 - are taken into consideration assuming that A1 is most relevant for the material flow analysis (DIN EN 15804:2020-03, 2020). Due to the OBD aggregation, losses during the production process cannot be considered (Ellen MacArthur Foundation & Granta Design, 2019). As the MCI analysis focuses on raw material flows, transportation which primarily consumes energy is also excluded in the analysis even though it may have an important environmental impact especially for heavy construction products. Modules A4 and A5 do not significantly contribute to resource requirements, virgin raw materials are calculated for modules A1-A3 only (see Appendix I). However, since data for these modules are often missing in OBD (DIN EN 15804:2020-03, 2020), the modules were excluded for the MCI calculation in order to compare a larger number of products based on a homogenous database.

On the output level, modules C1, C3, and C4 are considered in a sum of all modules per indicator in the OBD dataset for all output indicators (DIN EN ISO 14040:2009-11, 2009). Analogous to the input level, transportation, i.e. C2, is not taken into account.

Since product lifetime is already included in the analysis of the product utility and OBD provides only few datasets for the usage period, it was decided to adhere to common practice and only refer to the production and disposal phases while omitting the usage period (B1-B7) (DIN EN 15804:2020-03, 2020). Module D, which is also commonly considered for material flow analysis (DIN EN 15804:2020-03, 2020), indicates recycling potentials but is not considered in order to avoid double-counting of recycling potentials, which are already reflected in C4 with MFR and CRU (DIN EN 15804:2020-03, 2020).

Product utility calculation requires a product lifetime analysis. OBD does not contain any data on product lifetime. For the industry, the average lifetime of construction materials is based on the average usage time of buildings, which varies between 30 and 80 years depending on the respective building type (Bundesministerium für Verkehr, Bau und Stadtentwicklung, 2012). As it is impossible to predict in advance in which building type a certain construction material will be used, we assume an average lifetime of 50 years in accordance with the German Federal Ministry of the Interior, Building and Community (Bundesministerium des Innern, für Bau und Heimat, 2019). The individual product lifetime also has to be deducted from external sources, i.e. official data on product lifetimes of construction materials (Bundesinstitut für Bau-, Stadt- und Raumforschung, 2017), or product declarations in OBD (DIN EN 15804:2020-03, 2020). However, such data are not available for all products so that the analysis will first assume a utility factor of 1 (see assumption (2)). In practice, any value higher than 1 is impossible, as the demolition of a building terminates the useful life of construction material products. Thus, product utility may take a value of 1 at a maximum, indicating $L \leq L_{av}$ (see assumption (4)).

Recycling efficiencies E_F and E_C vary for different products and detailed information are given neither in OBD nor in literature (Eisele et al., 2020; Heisel et al., 2019). Thus, instead of using exact individual efficiencies, the standard value of 75% indicated by Madaster Services B.V. (2018) is applied for E_F and E_C.

The following Table 25 provides a summary of all assumptions made:

Table 25: Assumptions.

	Assumptions made
(1)	$SM = F_R M_B$
(2)	$\frac{U}{U_{av}} = 1$
(3)	$K_0 = 0$
(4)	$L \leq L_{av};\ L_{av} = 50\ years$
(5)	$E_F = E_C = 0.75$

4 Results

4.1 Descriptive Data Analysis

The following results are based on OBD version 2020-II (Bundesministerium des Innern, für Bau und Heimat, 2020). The database contains 920 datasets at the time of the evaluation, which are conform to DIN EN 15804+A1 (4130 data points in total).

Since end-of-life data are already included in modules C1-C4, separate end-of-life datasets based on generic data without external verification were eliminated (Figl et al., 2019). Furthermore, the main category "Other" was eliminated because due to lacking relevant data. Due to the study's focus on materials which are well suitable for recycling (Eisele et al., 2020), less relevant categories, such as building technology, components of windows, and curtain walls and coatings, were not considered. The analysis thus focuses on the main categories mineral construction materials, metals, plastics and insulation products. As previously explained, modules A4, A5, B1-B7, C2, and D were not included in the analysis and thus also removed from the dataset.

The analysis aims at performing a circularity evaluation for the entire product lifecycle, which requires products with incomplete datasets to be deleted. In order to ensure a broad comparison between different (sub-) categories, categories containing only a single product were removed. In a last step, double entries for products, especially from the sub-category of copper, were deleted. After data cleansing, the dataset contains 89 datasets (products) in 21 product- and 12 sub-categories belonging to the four main categories of mineral building materials, insulation materials, plastics, and metals. Even though all OBD data comply with high quality standards (Bundesministerium des Innern, für Bau und Heimat, 2019; Figl et al., 2019), one may distinguish between the following three types of datasets:

Table 26: Types of Datasets in ÖKOBAUDAT (in accordance with Figl et al., 2019).

Dataset type	Characteristics	Conformity assessment
Specific dataset	Producer data for specific products	Independent verification
Average dataset	Data based on multiple companies or industry associations	Independent verification
Generic dataset	Data based on expertise and literature	no

As generic data are not subject to external assessment, a mark-up of between 10% and 30% is added to the datasets before publication in OBD (Figl et al. 2019).

4.2 Product Comparison

A first evaluation of the product circularity can be made by comparing the input materials with the output materials. The recycling-content, i.e. the proportion of secondary materials used as input (I_R), can serve as a reference, similarly to the definition of Linder et al. (2017):

$$I_R = \frac{SM}{M_B} \tag{14}$$

On the output level, it is useful to compare the sum of outputs being recycled or reused (i.e. MFR and CRU) with total inputs (M_B). Thus, O_R expresses the proportion of a product recycled or reused at the end of its product life:

$$O_R = \frac{MFR+CRU}{M_B} \tag{15}$$

Inputs consider aggregated modules A1 to A3, whereas outputs consider modules C1, C3, and C4. All products show a value of 0 for CRU i.e. they do not contain any components which can be reused. This corresponds to assumption 1 shown in Table 5.

Most products have a value of zero for I_R (65 products) and O_R (74 products). Out of the 89 products, 24 are partially produced from secondary materials ($I_R > 0$). For 15 products, O_R is greater than zero, i.e. these products' portions are returned to the material cycle at the end of a product's life. In total, only 5 products – 3 brick products as well as 2 products belonging to the product group tiles and panels - are combining recycling for their inputs and outputs ($I_R > 0$ and $O_R > 0$).

Different values for I_R and O_R – with values of O_R exceeding those of I_R in most cases - indicate that material cycles are not completely closed. However, EMF's MCI explicitly states that its methodology is not limited to closed loops (Ellen MacArthur Foundation & Granta Design, 2019). Overall, the analysis of I_R and O_R shows significant improvement potentials in terms of circularity.

4.3 Product Circularity based on Average Product Utility

As formerly described, MCI is calculated based on the assumption of a usage period equal to industry average in a first step. Considering that the end-of-life of a building also represents the end-of-life for construction materials, assuming average product utility maximizes product circularity indexes.

The product circularity values (MCI_P) vary between 0.10 and 0.52 with an average of 0.19 and a median of 0.10. Based on the EMF definition in equation (10), 0.10 represents a completely linear product utility corresponding to the industry average and is calculated for 55 out of 89 products. Only 14 products obtain values of above 0.40. The top five products obtaining the highest MCI values are shown in Table 27. All these top five products show relatively small correction values K_0, with deviations between outputs and inputs ranging from 0.84% to -2.89%.

Table 27: Top-five Products Obtaining the Highest Scores for X=1.

Product	$\frac{K_O}{M_B}$	LFI	MCI_P
Masonry brick	-2.89 %	0.53	0.52
Masonry brick (insulation filled)	-2.89 %	0.53	0.52
Facing brick, paving brick and brick slips	0.00 %	0.59	0.47
Sikaplan G	0.84 %	0.60	0.46
Ceramic tiles and panels	0.00 %	0.60	0.46

Table 28 summarizes data for eight products chosen for comparison. Besides data on material circularity and linear flows, the table contains information derived from the product comparison based on OBD parameters and information on the deviation of product outputs expressed as shares of total product mass.

Table 28: Product Comparison based on MCI for X=1.

Product	$\frac{K_O}{M_B}$	LFI	MCI_P	I_R	O_R
(1) FOAMGLAS T4+	0.00 %	0.76	0.31	0.49	0.00
(2) ROCKWOOL Rock wool insulation material in medium bulk density range	0.00 %	0.88	0.21	0.24	0.00
(3) Sikaplan G	0.84 %	0.60	0.46	0.00	1.00
(4) Bitumen membranes PYE-PV 200 S5 ns (slated) (Thickness 0,004 m)	20.00 %	1.00	0.10	0.00	0.00
(5) Profil - König GmbH & Co. KG – Galvanized ceiling profile CD60/27	-2.00 %	0.61	0.45	0.00	0.98
(6) Blank copper domestic installation pipes	-93.00 %	1.00	0.10	0.00	0.00
(7) Masonry brick(insulation filled)	-2.89 %	0.53	0.52	0.20	0.93
(8) Masonry mortar -Light masonry mortar	17.00 %	0.94	0.16	0.13	0.00

Data calculated for material circularity corresponds to input and output recycling shares. Products having high recycling shares show high material circularity indicators (product 7), whereas the opposite applies for products with low recycling shares, such as products 4 and 6. The product comparison reveals important differences for the deviation of outputs. For product 4, the high value for output deviation may be explained by the fact that the product relies on generic data being subject to a security surcharge of 10 – 30% (Figl et al., 2019). A small deviation between inputs and outputs may serve as an indicator of high reliability of the calculated values. 64% of the products analyzed have an input/output deviation between -15% and 15% (see Appendix II).

4.4 Product Circularity based on Individual Product Lifetimes

As an example, the product circularity of insulating materials is now calculated based on their specific lifetime. The industry average still corresponds to the reference lifetime for buildings of 50 years. Specific lifetimes of different insulation materials are derived from the literature (Bundesinstitut für Bau-, Stadt- und Raumforschung, 2017).

The Federal Office for Building and Regional Planning indicates specific lifetimes of 40 years for polyethylene products as well as for thermal insulation composite systems (Bundesinstitut für Bau-, Stadt- und Raumforschung, 2017). Including specific lifetimes for both product groups reduces their product utility to 0.8 and consequently also leads to a decrease in product circularity (see Table 29).

Table 29: Material Circularity Indicators for Polyethylene Products Considering Individual Lifetimes.

Product	LFI	$F(X)$, $X = 1$	$F(X)$, $X = 0.80$	MCI_P, $X = 1$	MCI_P, $X = 0.80$
CLIMAFLEX SPIRAL made of NMC NATUREFOAM	0.68	0.90	1.13	0.39	0.24
CLIMAFLEX made of NMC NATUREFOAM	0.83	0.90	1.13	0.26	0.07
CLIMAFLEX STABIL / EXENTROFLEX COMPACT made of NMC NATUREFOAM	0.70	0.90	1.13	0.37	0.22

Table 30: Material Circularity Indicators for Thermal Insulation Composite Systems Considering Individual Lifetimes.

Product	LFI	$F(X)$, $X=1$	$F(X)$, $X=0.80$	MCI_P, $X=1$	MCI_P, $X=0.80$
Thermal insulation composite system with glued EPS insulation panel	1.00	0.90	1.13	0.10	0.00
Thermal insulation composite system with glued and dowelled EPS	1.00	0.90	1.13	0.10	0.00
Thermal insulation composite system with glued and dowelled mineral fiber insulation panel	0.92	0.90	1.13	0.17	0.00
Thermal insulation composite system with glued mineral fiber lamella insulation panel	0.92	0.90	1.13	0.17	0.00
Thermal insulation composite system with rail fastening	1.00	0.90	1.13	0.10	0.00
Thermal insulation composite system adhesion and coating mineral scratch plaster	1.00	0.90	1.13	0.10	0.00
Thermal insulation composite system adhesion and coating synthetic resin plaster	1.00	0.90	1.13	0.10	0.00
Thermal insulation composite system adhesion and coating mineral lightweight plaster	1.00	0.90	1.13	0.10	0.00
Thermal insulation composite system adhesion and coating mineral decorative plaster	1.00	0.90	1.13	0.10	0.00
Thermal insulation composite system adhesion and coating silicone resin plaster	1.00	0.90	1.13	0.10	0.00

In accordance with Heller et al. (2019), Table 30 reveals that thermal insulation composite systems show high linear flows and a lack of recycling at the end-of-product life. For all other thermal insulation products, specific lifetimes correspond to the industry average of 50 years (Bundesinstitut für Bau-, Stadt- und Raumforschung, 2017). Consequently, the inclusion of specific lifetimes does not change their product circularity values.

4.5 Category Circularity based on Average Product Utility

Aggregating product circularity values to average values per product group, as categorized in OBD, provides circularity values of between 0.1 and 0.51. Brick products – out of which two have been under the top five circular products in former sections – show the highest product category circularity value followed by steel profiles. Aggregation to sub-categories leads to a circularity range of between 0.1 and 0.46; main categories' circularity scores vary between 0.15 and 0.28 respectively. Metals represent the main category with the highest main group circularity scores (see Table 31).

Table 31: Material Circularity Indicators for all OBD-Categories Analyzed for X=1.

<table>
<tr><th>Main category (MCI_{MC})</th><th>Sub-category</th><th>MCI_{SC}</th><th>Product category</th><th>MCI_{PC}</th></tr>
<tr><td rowspan="8">Insulation products (0.21)</td><td>Thermal insulation composite system</td><td>0.11</td><td>Thermal insulation composite system</td><td>0.11</td></tr>
<tr><td rowspan="2">Polystyrol expanders (EPS)</td><td rowspan="2">0.10</td><td>EPS gray</td><td>0.10</td></tr>
<tr><td>EPS white</td><td>0.10</td></tr>
<tr><td>Foam glass</td><td>0.32</td><td>Panels</td><td>0.32</td></tr>
<tr><td rowspan="2">Mineral wool</td><td rowspan="2">0.18</td><td>Mineral wool</td><td>0.16</td></tr>
<tr><td>Rock wool</td><td>0.21</td></tr>
<tr><td>Polyethylene</td><td>0.34</td><td>Foam</td><td>0.34</td></tr>
<tr><td rowspan="3">Plastics (0.15)</td><td rowspan="2">Roofing membranes</td><td rowspan="2">0.19</td><td>Bitumen roofing membranes</td><td>0.10</td></tr>
<tr><td>PVC roofing membranes</td><td>0.28</td></tr>
<tr><td>Sealants</td><td>0.10</td><td>Bitumen</td><td>0.10</td></tr>
<tr><td rowspan="2">Metals (0.28)</td><td>Steel and iron</td><td>0.46</td><td>Steel profiles</td><td>0.46</td></tr>
<tr><td>Copper</td><td>0.10</td><td>Copper pipes</td><td>0.10</td></tr>
<tr><td rowspan="9">Mineral construction materials (0.16)</td><td rowspan="4">Mortar and concrete</td><td rowspan="4">0.10</td><td>Screed dry</td><td>0.10</td></tr>
<tr><td>Aghesive and adhesive mortar</td><td>0.10</td></tr>
<tr><td>Masonry mortar</td><td>0.12</td></tr>
<tr><td>Plaster and plaster mortar</td><td>0.10</td></tr>
<tr><td rowspan="4">Stones and elements</td><td rowspan="4">0.27</td><td>Tiles and panels</td><td>0.35</td></tr>
<tr><td>Gypsum panels</td><td>0.11</td></tr>
<tr><td>Dry screed</td><td>0.12</td></tr>
<tr><td>Brick</td><td>0.51</td></tr>
<tr><td>Binder</td><td>0.10</td><td>Gypsum</td><td>0.10</td></tr>
</table>

If the product circularity scores based on individual lifetimes are taken into account for category aggregation, the decreasing circularity scores for thermal insulation composite products and polyethylene products affect category scores as well. When considering specific product lifetimes, the circularity score for the main category insulation materials thus decreases from formerly 0.21 (Table 31) to 0.16, as Table 32 indicates. Since the utility factors and thus the ratings of the products decrease due to lower lifetimes, the ratings of the categories also decrease.

Table 32: Circularity Indicators in the Insulation Products Category for Individual Product Utility.

Main category (MCI_{MC})	Sub-category	MCI_{SC}	Product category	MCI_{PC}
Insulation products (0.16)	Thermal insulation composite systems	0.00	Thermal insulation composite systems	0.00
	Polystyrol expanders (EPS)	0.10	EPS gray	0.10
			EPS white	0.10
	Foam glass	0.32	Panels	0.32
	Mineral wool	0.18	Mineral wool	0.16
			Rock wool	0.21
	Polyethylene	0.18	Foam	0.18

5 Discussion

5.1 Discussion of the Results for Product Circularity

A circular economy is still at its infancy stage in Germany's construction industry. This was confirmed by product circularity scores ranging from 0.1 to 0.52, with more than 60% – i.e. 55 out of 89 products – obtaining the lowest circularity score of 0.10 (see Appendix II). The assumption of high shares of linear material flows was confirmed by the calculation of input and output recycling shares. Only a few products combine recyclable outputs and recycled input materials. In most cases, recyclable outputs exceed recycled inputs, showing that implementation of circularity strategies seems to be more common at the end-of-product life. This may also be due to the fact that outputs are not necessarily returned to circles for the same product but may also serve as input for different products. Reuse of materials seems to be a new strategy (Kristensen & Moosgaard, 2020), which explains why CRU takes the value of 0 for all products analyzed.

Due to lacking information on efficiencies for production of recycled input material and end-of-life processes in OBD as well as in the literature, the calculation of waste flows was based on the standard value of 0.75 for E_F and E_C provided by Madaster Services B.V. (2018). E_F and E_C, though, play an important role for the calculation of linear flow indices and thus material circularity scores. For the recycling efficiencies, the LFI calculation does not differentiate between different materials composing a product. However, as products are composed of multiple materials, one would normally need multiple values for the recycling efficiencies (Ellen MacArthur Foundation & Granta Design, 2019). Such criticism relates to the whole MCI-approach, which focuses on material flows and leaves raw materials aside, even though raw material differentiation would be important in the context of considering different circularity strategies (Linder et al., 2017). With this specific focus of the MCI-approach, which omits other parameters such as emissions, the advantages are only on a product or company level, but it doesn't claim to be a holistic approach. Including more parameters on a product level, a Life Cycle Approach would be more appropriate. In that vein it has to be noted that the MCI contains in its calculation several "Rs", such as reuse and recycle. By doing this, a single strategy, e.g. reuse and closed loop supply chains, cannot be measured by itself. Since OBD does not provide data for different product components, raw materials could not be considered even if approaches for circularity measurement including raw materials were already available (Ellen MacArthur Foundation & Granta Design, 2019).

Due to the high importance of the completeness and actuality of data for accurate calculation, OBD dataset categories being subject to external audits should be preferred, as they fulfill the data transparency criterion according to Linder et al. (2017).

The control variable K_0 was assumed to amount to zero in most cases, as the mass of inputs equals the sum of all outputs in case of complete datasets. Negative control variables indicating a mass of outputs inferior to the mass of inputs were added to the waste flows. Contradicting the initial assumption, K_0 also took positive values in the dataset analyzed. Important positive K_0 greater than 15% were observed for 17 products in total (see Appendix II). In any cases of positive values for K_0, the waste flows were reduced accordingly, which improved the respective product circularity indicators. The addition of the mark-up between 10% and 30% for generic datasets may explain these deviations, since many products with generic data show deviations amounting to exactly 20%.

However, out of the products showing relatively small deviations of K_0 between -15% and 15%, the majority of the products result from generic datasets, indicating that datasets that are subject to external audits often show high deviations. Thus, we conclude that assumption (3) (see table 4) was incorrect or incorrectly implemented.

In accordance with the principle of only including materials that are finally used for the product (Ellen MacArthur Foundation & Granta Design, 2019), outputs in the production phase were not considered, as especially these production wastes do not enter into the final product. Data analysis in OBD reveals that the consideration of the production phase (A1-A3) leads to important deviations for negative K_0. Our analysis focused on products with information for lifecycle stages covering raw material supply to manufacturing as well as demolition to disposal due to data availability in OBD. A focus of this kind may lead to deviations which cannot be explained by the existing data. Resource usage during the production phase increases total material usage during that stage even if the corresponding wastes only occur at the end-of-product life. Such a scenario may explain cases where the mass of inputs is inferior to the total mass of outputs. Negative K_0 could be explained by losses during lifecycle stages, which are outside the scope of this analysis. In total, K_0 deviations can only be explained through different types of datasets. Other lifecycle stages could not be taken into account due to incomplete datasets.

According to Heisel & Rau-Oberhuber (2020), such analysis requires precise knowledge of the mass and of the precise moment in time when different materials are being used or being released. The database used here only partially fulfills this criterion, as it does not contain a sufficient number of products with complete data for all product stages and, furthermore, does not differentiate between different raw materials for products.

The method applied fulfills four out of the five criteria designated by Elia et al. (2017) but omits the aspect of reducing CO2 emissions, which would be worth taking into account especially for the construction industry. OBD already provides such data for analysis. Furthermore, attention should be paid to the use of toxic substances. Also, logistics and transportation are very important additional factors, which affect a more holistic evaluation, e.g. through a Life Cycle Assessment, by a lot. Especially for heavy construction products such as concrete, short transportation distances are a key success factor for environmental and economic sustainable evaluation.

The analysis showed that a comparison of linear products with lifetimes below the industry average is not feasible, since such products reach a total evaluation of 0.0 despite different LFI-values. For such products, a comparison of I_R and O_R would be more useful in order to better compare material flows. Such differentiation may also help to identify potentials for improvement. A comprehensive comparison should thus always include several indicators.

Pomponi & Moncaster (2017) highlight the necessity to perceive buildings and the construction materials included as a unity. The indicator developed only partly fulfills this criterion by ensuring that the individual product lifetime does not exceed the average lifetime for buildings.

The analysis does not contain any evaluation of practical methods for introducing circularity strategies, as is done in the approach of Madaster Services B.V. (2018). Potential qualitative losses during the recycling process were not considered (Ellen MacArthur

Foundation & Granta Design, 2019). In this vein, the calculation of product use that omits functional units (Assumption 2) is helpful and reasonable for comparison purposes (Ellen MacArthur Foundation & Granta Design, 2019).

5.2 Discussion of Category Results

The calculation of results per category was based on product aggregation. The main category 'metals' obtained the highest scores, especially driven by the results of the sub-category 'steel and iron' achieving an MCI of 0.46. The literature confirms good recyclability of steel (Heisel et al., 2019).

The category aggregation leads to information losses and conceals outliers. The application of arithmetic means per category attributes equal weights per product. In practice, a different weighting, i.e. one based on market shares, would better reflect the status quo of circularity in the German construction industry. However, such weighting requires market data. In the future, one could imagine evaluating circularity on company level by aggregating all products of a company into a combined circularity scoring, potentially under consideration of product market shares.

6 Conclusion and Outlook

A circularity evaluation of construction materials was based on an adapted version of the *Material Circularity Indicator* by evaluating material flows throughout the product lifecycle on a scale from 0 to 1, with 1 indicating a product being entirely circular. The calculation of inputs was based on data for the production phase, whereas output data were derived from the recycling phase by calculating the share of linear flows within a product. The linear flows were weighted based on product lifetime. The results for material circularity indicators range from 0.1 to 0.52 for a product lifetime equal to the industry average. With these results, this article is adding value to the research on measuring circularity as well as on the construction industry. First, with more than 60% of the 89 products analyzed achieving the lowest circularity score, the results underline the initial assumption that the change towards a circular economy in the German construction industry is only about to start, and that there is a huge potential for keeping materials in the loop and maintaining their value. Companies, as well as the governments, could use such results to compare and benchmark different circular strategies and business models.

Second, the literature statements which criticize a lack of well-developed circularity indicators for products cannot be confirmed. Besides the MCI used in this article, there are various other indicators, which add value with regard to their respective applications. One important value added by this article is the application of the (adapted) MCI indicator and its application to a publicly available database. However, the availability of accurate data indicating when and which amounts of materials are being used or being released (Heisel & Rau-Oberhuber, 2020) currently represents the main obstacle to properly evaluating circularity on the product level. The database used in this article only partially fulfills this data criterion as, for example, differentiation between different raw materials within a product is lacking. Furthermore, the database does not provide a sufficient number of complete datasets for all stages of the product lifecycle.

Taking into consideration the above-mentioned limitations, the indicator developed enables product circularity evaluation and therefore provides a new approach regarding how to measure circularity of the construction industry and its products. Since calculation methods were not modified in dependency on different product types, different product types can be compared to each other. However, the aggregation into a single indicator implies information losses, which could be compensated by considering different indicators. The relation of the product, product type circularity and their respective industry circularity is given due to calculation method, which uses an industry average for the product lifetimes. This means, that the results are in some way compared to an external threshold. Under perfect conditions, the indicator could generally aggregate into an industry average, but with the current data availability, such aggregations are misleading. In particular raw material requirements and greenhouse gas emissions should be considered for a comprehensive product comparison in the construction industry. Differentiation between circular inputs and outputs may furthermore contribute to identifying improvement potentials. In addition to that, the supply chain between different construction products needs further to be considered and it should be ensured, that information is not lost along the way.

Circularity indicators for products may support a change towards a circular economy in the construction industry. However, the micro level only constitutes one out of three levels for the introduction of circularity strategies. In total, such change comprises the implementation of circularity strategies on the social, economic, and ecologic levels (Kristensen & Mosgaard, 2020). The future thus requires cross-industry concepts for such change at all levels which can be fostered by political regulation. Such regulation could require minimum circularity level for products, for their components, or even for entire buildings.

The circularity evaluation conducted may be extended by aggregating all circularity scores for the products produced by a company into an aggregated circularity indicator on the company level. For external researchers, those data can hardly be gathered, since a database like EBD does not provide holistic company data. Especially for global companies, which produce in different countries, researchers should be careful about premature conclusions and companies should not wrongly be incentivized to produce in countries with a lower documentation.

The dataset used during the analysis could represent the basis for a holistic analysis approach of this kind. The different materials used for a product and their recycling potential at the end-of-product life should be documented in order to enable a sophisticated analysis based on raw materials. Such a requirement could be introduced through European directives on minimum standards for product information or minimum standards for material recyclability. Overall, more transparency and accountability can boost circular approaches within the construction industry and therefore have positive consequences for saving natural resources and for

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Appendix I

Production			**Constructio n**		**Use**							**End-of-life**			
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4
Raw material supply	Transport	Manufacturing	Transport	Construction	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Demolition	Transport	Waste processing	Disposal

Appendix II

$X = 1 \Rightarrow F(X) = 0.90$ ∀ Products
In a calculation with a product lifetime that corresponds to the building lifetime, the product utility reaches a value of 1 for all products. Accordingly, the utility factor for all products is 0.90.

Material circularity indicators for MC Insulation products

SC	PC	Product	K_0	LFI	MCI_P
Polystyrol expanders (EPS)	EPS grey	EPS hard foam (gray) with thermal radiation absorber	-99.56%	1.00	0.10
		Insulation panel with Neopor Plus	-99.64%	1.00	0.10
	EPS white	EPS hard foam (Styrofoam) for ceiling/floors and for perimeter insulation B/P-040	-97.72%	1.00	0.10
		EPS hard foam (Styrofoam) for walls and roofs W/D-040	-97.72%	1.00	0.10
		EPS hard foam (Styrofoam) for ceilings/floors and for perimeter insulation B/P-035	-97.71%	1.00	0.10
		EPS hard foam (Styrofoam) for walls and roofs W/D-035	-97.71%	1.00	0.10

SC	PC	Product	K_0	LFI	MCI_P
Mineral wool	Mineral wool	Blow-in insulation mineral wool	1.38%	1.00	0.10
		Mineral wool (Interior insulation)	11.73%	0.89	0.20
		Mineral wool (façade insulation)	11.63%	1.00	0.10
		Mineral wool (Pitched roof insulation)	11.45%	0.88	0.21
		Mineral wool (Flat roof insulation)	11.51%	0.98	0.12
		Mineral wool (floor insulation)	11.51%	0.86	0.23
	Rock wool	ROCKWOOL Rock wool insulation material in low bulk density range	0.00%	0.88	0.21
		ROCKWOOL Rock wool insulation material in medium bulk density range	-0.10%	0.88	0.21
		ROCKWOOL Rock wool insulation material in high bulk density range	0.00%	0.88	0.21

SC	PC	Product	K_0	LFI	MCI_P
Foam glass	Panels	FOAMGLAS S3	0.00%	0.75	0.32
		FOAMGLAS T4+	0.00%	0.76	0.31
		FOAMGLAS W+F and FOAMGLAS T3+	0.00%	0.77	0.31
		FOAMGLAS F	0.00%	0.74	0.33

SC	PC	Product	K_0	LFI	MCI_P
Polyethylene	Foam	CLIMAFLEX SPIRAL made of NMC NATUREFOAM	0.00%	0.68	0.39
		CLIMAFLEX made of NMC NATUREFOAM	-3.51%	0.83	0.26
		CLIMAFLEX STABIL / EXENTROFLEX COMPACT made of NMC NATUREFOAM	32.61%	0.70	0.37

SC	PC	Product	K_0	LFI	MCI_P
Thermal insulation composite system	Thermal insulation composite system	Thermal insulation composite system with glued EPS insulation panel	-16.74%	1.00	0.10
		Thermal insulation composite system with glued and dowelled EPS	-18.51%	1.00	0.10
		Thermal insulation composite system with glued and dowelled mineral fiber insulation panel	0.03%	0.92	0.17
		Thermal insulation composite system with glued mineral fiber lamella insulation panel	0.06%	0.92	0.17
		Thermal insulation composite system with rail fastening	-24.65%	1.00	0.10
		Thermal insulation composite system adhesion and coating mineral scratch plaster	10.10%	1.00	0.10
		Thermal insulation composite system adhesion and coating synthetic resin plaster	10.07%	1.00	0.10
		Thermal insulation composite system adhesion and coating mineral lightweight plaster	8.37%	1.00	0.10
		Thermal insulation composite system adhesion and coating mineral decorative plaster	8.97%	1.00	0.10
		Thermal insulation composite system adhesion and coating silicone resin plaster	11.68%	1.00	0.10

Material circularity indicators for MC Plastics

SC	PC	Product	K_0	LFI	MCI_P
Roofing membranes	Bitumen roofing membranes	Bitumen membranes PYE PV 200 S5 (unslated) (thickness 0.004 m)	19.52%	1.00	0.10
		Bitumen membranes PYE-PV 200 S5 ns (slated) (thickness 0.004 m)	19.52%	1.00	0.10
		Bitumen membranes V 60 (thickness 0.005 m)	19.52%	1.00	0.10
		Bitumen membranes G 200 S4 (thickness 0.004 m)	19.52%	1.00	0.10
	PVC roofing membranes	Sikaplan G	0.84%	0.60	0.46
		Sikaplan SGmA	0.81%	0.60	0.46
		Tectofin RV	78.62%	1.00	0.10
		Wolfin M	78.83%	1.00	0.10

SC	PC	Product	K_0	LFI	MCI_P
Sealants	Bitumen	Bitumen emulsion (40% Bitumen. 60% water)	29.48%	1.00	0.10
		Bitumen cold adhesive (60% Bitumen. 23%LM. 17% water)	29.48%	1.00	0.10

Material circularity indicators for MC Metals

SC	PC	Product	K_0	LFI	MCI_P
Steel and iron	Steel profiles	Profil - König GmbH & Co. KG – Wall profile galvanized CW75	-1.07%	0.60	0.46
		Profil - König GmbH & Co. KG - Wall profile galvanized CW100	-0.95%	0.60	0.46
		Profil - König GmbH & Co. KG - Wall profile galvanized CW125	-0.83%	0.60	0.46
		Profil - König GmbH & Co. KG – Wall profile galvanized CW150	-0.74%	0.60	0.46
		Profil - König GmbH & Co. KG - Wall profile galvanized CW50	-1.30%	0.61	0.45
		Profil - König GmbH & Co. KG - Wall profile galvanized Hutdecke 98	-1.55%	0.61	0.45
		Profil - König GmbH & Co. KG - Wall profile galvanized UD28/48	0.09%	0.60	0.46
		Profil - König GmbH & Co. KG - Wall profile galvanized CD60/27	-1.60%	0.61	0.45

SC	PC	Product	K_0	LFI	MCI_P
Copper	Copper pipes	Internally tin-plated copper domestic installation pipes	-92.99%	1.00	0.10
		Blank copper domestic installation pipes	-89.20%	1.00	0.10
		PE foam coated copper domestic installation pipes	-83.29%	1.00	0.10
		PE coated copper domestic installation pipes	-92.99%	1.00	0.10
		PVC coated copper domestic installation pipes	-82.99%	1.00	0.10
		PU foam coated copper domestic installation pipes	-86.79%	1.00	0.10

Material circularity indicators for MC Mineral construction materials

SC	PC	Product	K_0	LFI	MCI_P
Mortar and concrete	Screed dry	Synthetic resin screed	20.12%	1.00	0.10
		Calcium sulfate screed	10.11%	1.00	0.10
		Cement screed	10.11%	1.00	0.10
	Adhesive and adhesive mortar	Tile adhesive	20.12%	1.00	0.10
		Reinforcement (synthetic resin filler)	20.12%	1.00	0.10
		Adhesive for gypsum panels	10.11%	1.00	0.10
	Masonry mortar	Cement mortar	7.51%	1.00	0.10
		Lime-cement mortar	20.12%	1.00	0.10
		Masonry mortar – Light masonry mortar	17.00%	0.94	0.16
	Plaster and plaster mortar	Lime-cement plaster mortar	10.11%	1.00	0.10
		Lime plaster mortar	10.11%	1.00	0.10
		Gypsum plaster (Gypsum)	10.11%	1.00	0.10
		Primer (Silicate dispersion)	20.12%	1.00	0.10

		Lime-gypsum interior plaster	10.11%	1.00	0.10
		Synthetic resin plaster	10.11%	1.00	0.10
		Primer (Synthetic resin)	20.12%	1.00	0.10
		Gypsum plaster (Gypsum-lime plaster)	10.11%	1.00	0.10
		Lime interior plaster	10.11%	1.00	0.10

SC	PC	Product	K_0	LFI	MCI_P
Stones and elements	Tiles and panels	Ceramic tiles and panels	0.00%	0.60	0.46
		TERRART façade panel	0.17%	0.85	0.24
	Gypsum panels	Gypsum plasterboard (perforated panel)	10.11%	1.00	0.10
		Gypsum plasterboard (fire protection)(thickness 0.0125 m)	10.11%	1.00	0.10
		Gypsum fiberboard (thickness 0.01 m)	10.11%	0.95	0.14
		Gypsum wall board (thickness 0.1 m)	10.11%	1.00	0.10
		Gypsum plasterboard (impregnated) (thickness 0.0125 m)	10.11%	1.00	0.10
	Dry screed	Dry screed (gypsum plasterboard) (thickness 0.025 m)	10.27%	1.00	0.10
		Dry screed (gypsum fiberboard) (thickness 0.025 m)	10.25%	0.95	0.14
	Brick	Masonry brick	-2.89%	0.00	0.52
		Masonry brick (insulation filled)	-2.89%	0.53	0.52
		Facing brick, paving brick and brick slips	0.00%	0.59	0.47

SC	PC	Product	K_0	LFI	MCI_P
Binder	Gypsum	Gypsum stone (CaSO4-Dihydrate)	10.11%	1.00	0.10
		Gypsum (CaSO4-Beta-semi-hydrate)	10.11%	1.00	0.10
		Gypsum (CaSO4-Alpha-semi-hydrate)	20.12%	1.00	0.10