Obstacles to the widespread use of recycled concrete in building construction in Germany - causes and possible solution approaches

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List of Abbreviations

ANOVA	Analysis of variance
CR	Concentration ratio
DC	Discrete choice
DGNB	German Sustainable Building Council
FE	Fixed effect
GLM	Generalised linear model
HHI	Herfindahl-Hirschman Index
LR	Likelihood-ratio
ME	Mixed effect
MRS	Marginal rate of substitution
MWTP	Marginal willingness to pay
OECD	The Organisation for Economic Co-operation and Development
OLS	Ordinary least squares
R&D	Research and development
RE	Random effect
R-concrete	Recycled concrete
SIA	Swiss Association of Engineers and Architects
SE	Standard error
TFEU	Treaty on the Functioning of the European Union

1 Introduction

1.1 Motivation and problem statement

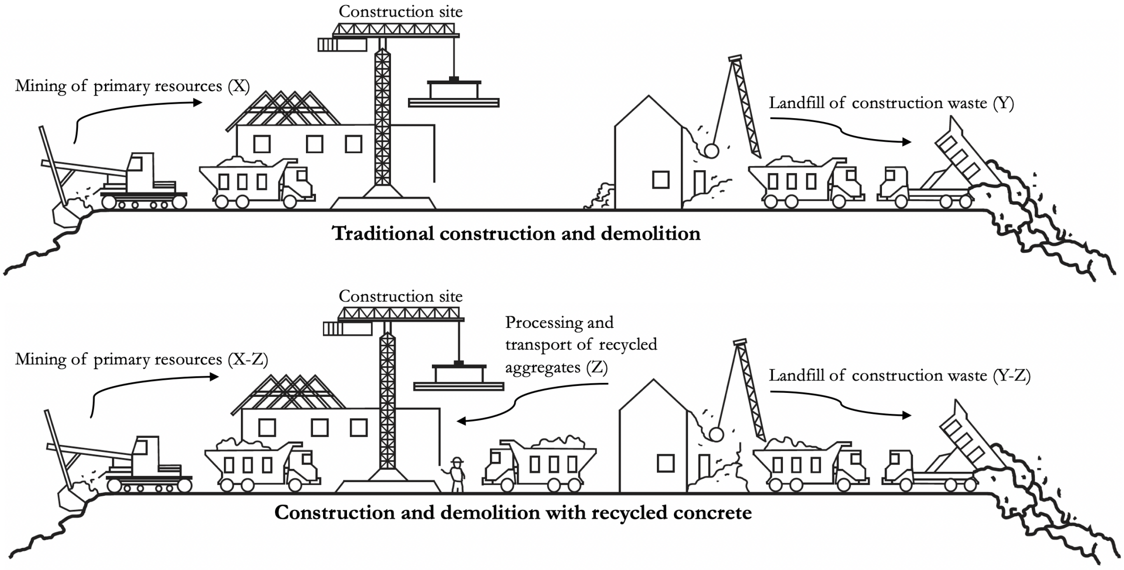
In Germany construction and demolition waste represents the largest waste fraction, accounting for more than 50% of the total waste volume. In 2016 recycling rates for mineral construction waste in Germany were relatively high - 86.1% of excavated soil, dredged material and railway ballast were recycled. The recycling rates for building rubble, road construction waste and construction waste exceeded 90% in 2016. (Basten, 2016)

In 2016, mineral waste from the fractions construction waste, road construction waste, soil and stones amounted to 85.8 million tonnes, from which 72.2 were processed to recycled aggregates. From these, 52% were used in road construction, 20% in asphalt and concrete production, 16% in earthworks and 4.2% for other objections (Basten, 2016). The construction waste in Germany is mainly added to low-value recovery measures such as landfill construction or backfilling of excavations (Heuser et al., 2007). Only a small proportion of recycled aggregates is reused in concrete production for building construction. Despite the high recycling rates, the current practice appears to be sub-optimal, as the processed materials are mainly used for non-equivalent applications and the potential to produce high quality materials such as concrete is not used - this phenomenon is described in the technical literature as *downcycling* (Meyer, 2009; Müller et al., 2011; Müller, 2018; Roos, 2002; Ministry for Environment, Climate and Energy Baden Würtemberg, 2014).[1]

Classic concrete used in construction 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). This demand is mainly covered by the mining of primary aggregates such as sand and gravel. An alternative to the use of primary aggregates is the processing of construction waste - the recycled granulate obtained from this can be used as a substitute for primary aggregates. The concrete produced in this way is referred to as recycled concrete (r-concrete). The production of r-concrete and its subsequent use in building construction offers a possibility for high-quality recycling of construction waste. The advantages of an ideal-typical application of recycled concrete in building construction can be illustrated by Figure 1. In conventional construction, the primary resources are mined, transported to the construction site and used there. After demolition, the construction waste is disposed in the landfill. In a construction process where recycled concrete is used, construction waste is processed into recycled aggregates and transported to a construction site where these are processed into concrete - this

[1] The term *downcycling* is used in a value-neutral way, without any negative connotation. It refers to the method of recycling after which the value of the end product decreases.

Figure 1: Conceptual illustration of the use of recycled concrete in building construction



Source: Presentation based on Lauritzen (1998).

reduces the amount of construction waste to be landfilled on the one hand and the need for primary aggregates on the other.

In numerous research and construction projects it has been shown that, technically, a significantly higher share of recycled aggregates from building construction can be reused in building construction and relatively large proportion of construction projects can be built with recycled concrete (Knappe, 2014; Nobis & Vollpracht, 2015; Stürmer & Kulle, 2017; Müller, 2018, Ministry for Environment, Climate and Energy Baden Würtemberg, 2011). For most applications in building construction it makes only a minor difference from a technical and physical point of view whether conventional or recycled concrete is used (Nobis & Vollpracht; 2015; Stürmer & Kulle, 2017). The use of recycled concrete is possible and permissible in Germany from a regulatory point of view - Eurocode 2 applies to r-concrete in general, just like conventional concrete. DIN EN 1992-1-1 refers to DIN EN 206 for concrete properties (DIN EN 1992-1-1, 2011; DIN EN 206, 2017). In addition, DIN 1045-2 is the national application document for DIN EN 206 (DIN 1045-2, 2008; DIN EN 206, 2017). DIN EN 206 refers to DIN EN 12620 when using recycled aggregates (DIN EN 206, 2017; DIN EN 12620, 2008).

In Germany recycled concrete is not used in building construction, except for a handful of individual building projects (Figure 2). However, the situation is quite different in Germany's immediate neighbourhood. In technical literature, Switzerland is referred as an example for comprehensive use of r-concrete[2] in building construction

[2]In Switzerland, concrete is only considered to be r-concrete from a recycled aggregate content of 25 % (Stürmer & Kulle, 2017) - concrete with a recycled aggregate content of less than 25 % is not separately registered and is classified and treated as conventional concrete. In Germany there

Figure 2: Projects in Germany where recycled concrete was used in building construction

Only projects that could be identified in the publicly available sources; objects completed or under construction. Status: June 2020.

(Nobis & Vollpracht, 2015; Mettke et al., 2015; Stürmer & Kulle, 2017; Müller, 2018; Hinzmann et al., 2019). Already in 2012, the share of r-concrete in the total concrete volume used in Switzerland was 7% (Hoffmann et al., 2012). Long run experience in numerous building construction projects in Switzerland show that approx. 90% of the concrete demand can be covered by r-concrete (Stürmer & Kulle, 2017; Knappe, 2014). Stürmer & Kulle (2017) point out that the market share of r-concrete in Switzerland is at least 13 % - however, this estimate is based on a presentation by Hoffmann (2015) at Swiss Concrete Forum. In Switzerland, the use of recycled

are no comparable regulations.

concrete in building construction is not systematically monitored. For this reason, no precise statements can be made about the actual market share of r-concrete in Switzerland.[3] Despite the disadvantageous data situation, two statements can be made with a relatively high degree of certainty. Firstly, at least 1804 buildings have been constructed in Switzerland that are certified with Minergie-Eco label and correspondingly have a proportion of r-concrete of at least 50% (Minergie, 2020). Secondly, all public buildings in City of Zürich must be generally built with recycled concrete (Zürich, 2020) - between 2005 and 2018, an average 18,400 m^3 of concrete per year was used in public building projects, of which 90 % was made from recycled aggregate (European Commission, 2019).

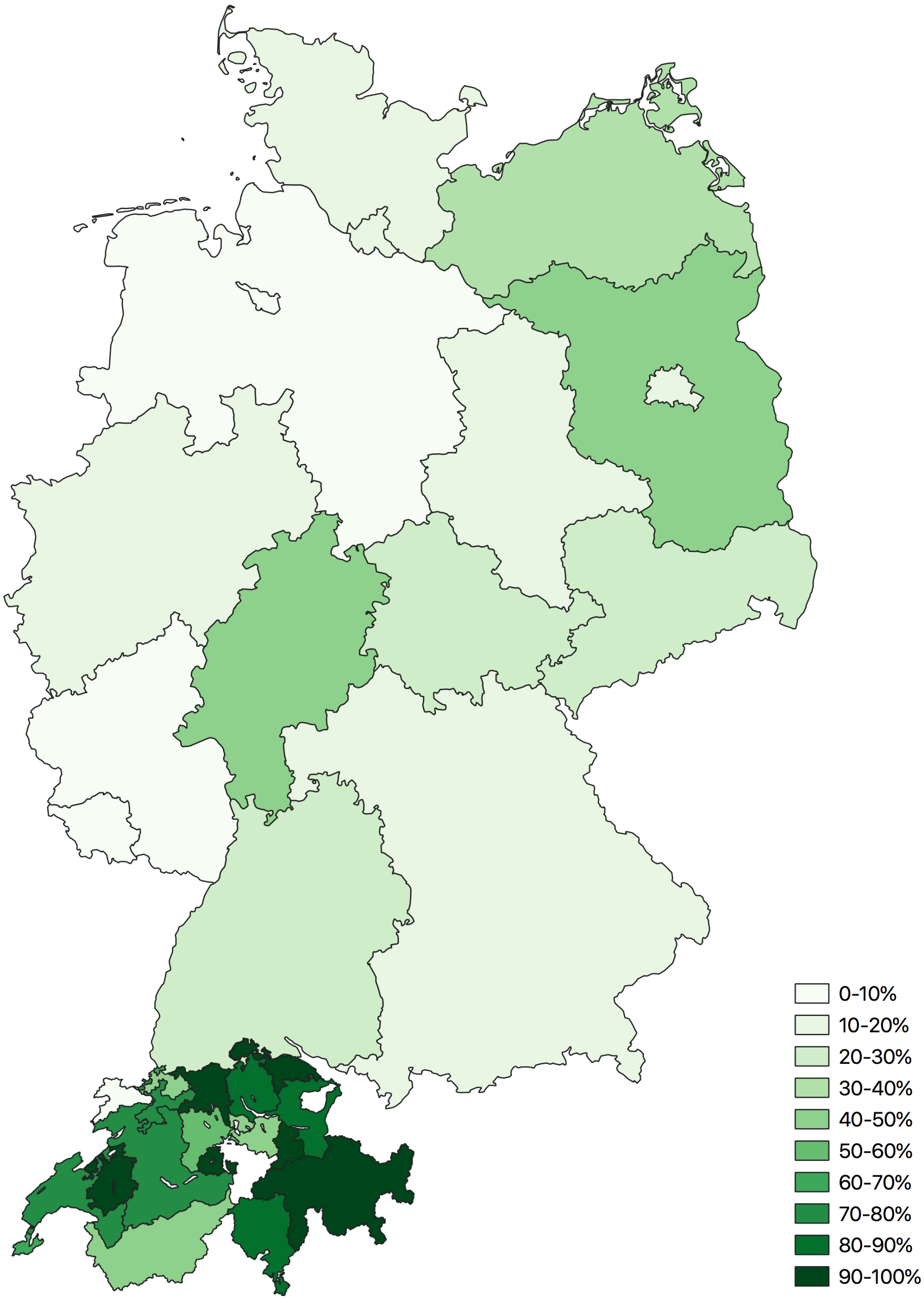
Given the restrictive availability of data on the actual use of r-concrete in Switzerland, the data generated by a survey presented in Chapter 4 will be used here. Figure 3 illustrates the differences in the experience with recycled concrete between Germany and Switzerland. This is the share of architects and engineers who stated to have experience with recycled concrete by federal state and canton in Germany and Switzerland. The darker the marking, the higher the proportion of architects and engineers who already have experience with r-concrete - the basis here is the total number of architects and engineers surveyed within the federal state or canton. While in most cantons in Switzerland the percentage of architects and engineers who have experience with r-concrete is between 80 and 100 %, in most German federal states it is between 10 and 30 %.[4] In total, 19% of respondents in Germany stated to have experience with r-concrete, compared to 82 % in Switzerland. Despite the fact that the use of r-concrete in building construction was not directly surveyed, these results support the indication that there are strong differences in the use of r-concrete between Germany and Switzerland. The country-specific differences can be further illustrated in the empty fixed and mixed effects models using the experience with recycled concrete as dependent variable (Table 1). Both models include only the country-specific fixed effects (model 1) or the random component (model 2). As can already be assumed from Figure 3, the country affiliation explains a relatively high proportion of the variation in the existing experience with r-concrete. The influence of country affiliation is highly significant in the fixed effects model and negative for Germany. The likelihood-ratio test in the mixed effects model confirms that the

[3] At first glance, current data on the market share of concrete in Switzerland appear to be available. However, if one takes a closer look, most statements are referred to Hoffmann et al. (2012) or Hoffmannn (2015).

[4] The results should be viewed with caution, as the number of respondents varies greatly between the federal states and cantons. Furthermore, it is plausible to assume that the willingness to participate in the survey is higher if the architects and engineers have already worked with r-concrete, which can potentially distort the results. For a detailed description of the study, the reader is referred to Chapter 4.

effect of country affiliation on the experience with r-concrete is not negligible.

Figure 3: Share of engineers and architects who have experience with recycled concrete in Germany and Switzerland



N=708, 374 for Germany and 334 for Switzerland.
No data are available for white areas.

Table 1: Empty model on the experience with recycled concrete

Variables	**Coefficients**	
	(1)	(2)
	FE	ME
Country FE (Germany=1)	-2.973***	.
	(0.194)	.
Country RE (Variance)	.	2.208
	.	(2.227)
Observations	708	708
Likelihood-ratio test vs. log. model	.	0.000
Pseudo-R^2	0.309	.

*Standard errors in parentheses; *p<0.05, **p <0.01, ***p<0.001.*
Dependent variable is the answer to the question: "Do you have experience with recycled concrete?".
Dependent variable is coded as $1 = Yes$ and $0 = No$.
Data refer to the study presented in Chapter 4.

The indications from technical literature, data on the number of buildings certified by Minergie-Eco, specifications in City of Zürich to use recycled concrete in all public construction projects and empirically observable differences in experience with r-concrete all strongly indicate that r-concrete is used in building construction in Switzerland in a considerable larger extent than in Germany. Despite the technical and regulatory possibilities, high-quality recycling of construction waste in building construction hardly takes place in Germany, whereas in Switzerland recycled concrete is widely used as a building material. In the context of the fact that current recycling practice in Germany can be characterised by downcycling, inevitably the questions arise, why recycled concrete has so far been used to a very restrictive extent and how its use in building construction can be increased. Thus, the objectives of the present work are the empirical investigation of the obstacles to the use of r-concrete in building construction and the derivation of a political recommendation how to increase the use of r-concrete in building construction in Germany.[5]

This work is intended to contribute to closing the material cycles in the construction sector, thus reducing both the extraction of primary resources and the production of construction waste. Since recycled concrete has been used successfully and extensively in building construction in Switzerland for many years, a partially comparative perspective to Switzerland will be adopted while dealing with the research questions. However, this is not an exclusively comparative work - the comparison with Switzerland acts only in certain aspects as an auxiliary and supporting tool for identifying obstacles and developing measures to increase the use of recycled concrete in Germany.

[5]This is an empirically oriented work in economics. For this reason, the technical and regulatory specifics relevant for the use of r-concrete are only briefly outlined. For a comprehensive review of the technical and physical properties of recycled concrete, readers are referred to Stürmer & Kulle (2017), Nobis & Vollpracht (2015), Müller (2018) and Knappe et al. (2012).

1.2 Overview of possible barriers to the use of recycled concrete in Germany

As indicated in the previous section, the objectives of the work are the empirical investigation of the obstacles to the use of recycled concrete and the derivation of the economic policy recommendation to increase the use of r-concrete in building construction in Germany. Before the particular aspects of these objectives can be scientifically investigated, it is necessary to identify possible obstacles and measures to increase the use of r-concrete in the existing literature. In the later course of the work these will provide the starting point for further empirical investigations. For this reason, in the following an overview of the existing literature on possible barriers to the use of recycled concrete and the most important differences in the regulations between Germany and Switzerland will be provided.

1.2.1. Regulatory barriers and government demand

Due to the harmonisation of technical standards in the European Union and Switzerland, very similar requirements apply to the use of recycled concrete in building construction (Stürmer & Kulle, 2017). However, there is a considerable difference in the maximum permissible proportion of recycled aggregates in concrete. In exposure classes[6] XC0 , XC1, XC1-3 and XC4, up to 100 % recycled granulate of type[7] C can be added in Switzerland to the concrete. In these exposure classes, a maximum of 45 % of recycled aggregates of comparable type 1 can be added in Germany. In Switzerland, up to 100 % of recycled aggregates of type M can be used for the exposure classes XC0 and XC1; for exposure classes XC1-3 and XC4 up to 100% are also permissible after prior examination (Hoffmann & Jacobs, 2010). In these exposure classes, the limit values for comparable recycled aggregates of type 2 in Germany are 35 % (Stürmer & Kulle, 2017). Also internationally, the limit for the maximum amount of recyclate that can be mixed in is set in some cases higher than that in Germany. In USA, Japan and Austria, the limit values are 100 % and there is no reference in the relevant regulations to the impermissible exposure classes (Hoffmann & Jacobs, 2010). In the exposure classes XC0, XC1, XF1 the limit values for recycled aggregates in Denmark are also 100 %. The relatively low maximum proportion of recycled aggregates that can be added to the concrete, compared to

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[6]Depending on the expected environmental and corrosive effects, construction components are classified into exposure classes, which are associated with certain technical and constructional requirements for the component. The important component and material properties that are assigned to the exposure classes are concrete composition, compressive strength classes, calculation values of the crack width, minimum concrete cover of the reinforcement and curing time. (DIN EN 1992-1-1, 1992)

[7]Depending on their composition, the recycled aggregates are grouped into different types. The granulate types C and M in Switzerland are comparable with granulate types 1 and 2 in Germany (Stürmer & Kulle, 2017).

international standards, can be considered as an obstacle to the use of recycled concrete. In this context Nobis and Vollpracht (2015) point out that additional storage capacities must be created for the production of r-concrete - the associated investment costs cannot be always borne, especially if relatively small quantities of recycled aggregates are used.

Regarding the "informal"[8] regulation of the use of recycled concrete in building construction, there are partially substantial differences between Germany and Switzerland. In a certification system Minergie-Eco[9], which is widely used in Switzerland, minimum quality standards for ecological construction are defined as a set of exclusion criteria that must be complied with mandatory - one of these exclusion criteria is the use of r-concrete (Minergie, 2020a). While Minergie-Eco in Switzerland stipulates a minimum volume of 50 % r-concrete in building components, the label of the German Sustainable Building Council (DGNB), which is the most widely used building certification in Germany, makes no mention of r-concrete or recycled aggregates and therefore does not reward their use (Stürmer & Kulle, 2017). The only exception where the building to be certified with Minergie-Eco can have a r-concrete content of less than 50 % is only if no concrete plant offers recycled concrete within a radius of 25 km from the construction site (Minergie, 2020a). Since the certification system widespread in Germany does not provide incentives for the use of r-concrete, the lack of consideration of r-concrete in building certificates can be stated as one of the possible reasons for the low use of r-concrete in building construction in Germany. According to Stürmer & Kulle (2017) direct reward for the use of r-concrete as an alternative to conventional concrete by trained auditors in the DNGB system could contribute significantly to increasing the use of recycled concrete in building construction.

In 2018, the public sector accounted for 27.5 % of turnover in the construction industry in Germany (Federal Statistical Office of Germany, 2020). The fact that the public sector is one of the largest property developers gives rise to the possibility of decisively influencing the sustainability in the construction sector and the use of recycled concrete through targeted material specific public tenders. There are significant differences between Germany and Switzerland in public tendering practice.

[8]Certification by a label can be considered as an informal regulation because the use of a label is not required by law. Buildings must meet the requirements of the building law, but it is up to each building owner and developer to decide whether to meet additional criteria and have the building certified by a label or not. Even certification through a label is not mandatory, it is often demanded in practice, especially by investors and real estate agents. In this context, Stürmer & Kulle (2017) point out that in the real estate market it is hardly possible nowadays to rent a non-certified building to a globally active company.

[9]The basic certificate is Minergie. All Minergie certificates can be certified with Eco-supplement. By July 2020, 45820 buildings in Switzerland have been certified with the Minergie building standard - almost 4 % of which have an Eco supplement (Minergie, 2020).

In one of most densely populated Swiss City of Zürich[10], r-concrete must be used for all public buildings - granulate of type M or C for exposure classes X0, XC1 and XC2, and granulate of type C for exposure classes XC3 and XC4 (Zürich, 2020). The use of primary concrete is only permitted if recycled concrete does not meet the structural requirements of the building components or is not available within a radius of 25 kilometres transport distance. The use of r-concrete is not explicitly mentioned in public tenders, but is binding for all public buildings (Zürich, 2020). Volk et al. (2019) and Hinzmann et al. (2019) point out that the failure to take recycled building materials into account in public tenders is one of the reasons for the low spread of r-concrete in Germany. As a result, the possibility of providing a decisive impulse for the development of the r-concrete market by creating government demand for recycled materials is not realised. Despite the possibility of defining sustainability as a further criterion in public tenders, r-concrete is only considered in public tenders in exceptional cases in Germany (Dageförde, 2017; Stürmer & Kulle, 2017). Predominantly, primary building materials are tendered preferably while secondary materials are not permitted or only allowed via secondary offers (Knappe et al., 2012). Regarding the handling of recycled concrete in public tenders, there are strong regional differences. For example, the municipalities in Rhineland-Palatinate are obliged to give preference to recycled building materials if they are suitable for specified purposes and the resulting costs are reasonable (§2 LKrWG RP). In Thuringia, preference is to be given to products from resource-conserving or low-waste production or from recycling in the planning and specification of construction projects (§2 ThürAGKrWG). In Saxony, objectives of the environmental conversion and protection are to be considered in procurement, planning and construction measures as long as these are associated with acceptable additional financial burdens (§10 SächsKrwBodSchG). In Germany, the public authorities are generally allowed to specify certain raw materials and source materials in the production process for the service put out to tender, if specifications are non-discriminatory (Dageförde, 2017). According to the Procurement and Contract Regulations for Construction Services, it is stipulated that technical specifications in public tenders may not refer to products of a certain origin or products that have been created as a result of a certain production process if this favours or excludes certain companies or certain products (§7 VOB/A). While the use of r-concrete as a further award criterion for the contract can be specified without any particular legal complications, conflicts and ambiguities may arise in the fulfilment of the anti-discrimination clause of the Public Procurement and Contract Regulations for Construction Services when the

[10] 434 008 inhabitants in 2019, which corresponds to ≈5 % of the population in Switzerland (Zürich, 2019).

use of recycled concrete is specified as compulsory in the public tender. Given the fact that the obligation for the use of recycled materials in public tenders for building construction is in many cases dependent on individual situation, the use of recycled building materials can be specified as compulsory in the public tenders for underground engineering (Dageförde, 2017). In this context, the legal situation in Switzerland appears to be clearer - r-concrete or the use of recycled aggregates can easily be made mandatory in public tenders (Hoffmann & Jacobs, 2010; Eco Devis, 2020).

1.2.2. Economic barriers

A common argument against the use of recycled concrete, which is discussed in the technical literature, is often the insufficient price competitiveness of r-concrete compared to conventional concrete (Knappe et al, 2012; Nobis & Vollpracht, 2015; Hinzmann et al., 2019). However, it is emphasised that the price of r-concrete is often dependent on the individual situation - on the one hand, higher costs are often incurred due to extensive preparation and additional inspection of recycled aggregates, and on the other hand, in many cases costs can be reduced due to shorter transport distances between aggregate producers and concrete plants, which enables r-concrete to be supplied at the same price as conventional concrete (Stürmer & Kulle, 2017). The consensus is largely that price competitiveness is most likely to be ensured if the recycled aggregates are located in the immediate surrounding area of the production site for ready-mixed concrete and can therefore be delivered more cost-effectively than the primary aggregates (Stürmer & Kulle, 2017; Nobis & Vollpracht, 2015; Müller, 2018; Knappe et al., 2012). Mettke et al. (2015) point out that the additional costs resulting from the use of r-concrete primarily result from the fact that a much higher amount of demolished concrete must be processed to produce split required for recycled concrete. In addition, the incoming inspection of the demolished concrete fraction and the proof of the environmental compatibility of the recycled aggregates lead to further costs. In many cases, additional capacities must also be created in the respective ready-mixed concrete plants for the temporary storage of the recycled aggregates (Mettke et al., 2015; Nobis & Vollpracht, 2015). The experience of the Federal State of Berlin in the construction of the research and laboratory building for Humboldt University of Berlin shows that the amount of recycled aggregates were sold to concrete producers for 16.10 Euros per tonne - comparable gravel would be available in the region for 15 Euros per tonne (Mettke et al., 2015). In addition, the environmental compatibility of recycled aggregates for the production of concrete for the building construction required approval from the highest building supervisory authority, which resulted in costs of 930 Euros (Mettke et al., 2015). In this project, the use of r-concrete resulted in total additional costs of between 5.30 and 5.73 Euros per cubic metre.[11] These result primarily from the fact that recycled concrete was used in building construction in the region for the first time, which made numerous examinations for quality and environmental assurance necessary (Mettke et al., 2015). In this context Mettke et al. (2015) point out that based on the experiences of the other federal states from past projects, it can be assumed that r-concrete can be produced and supplied at the same cost as primary concrete if the demand continues to grow. In the technical literature, further obstacles to the use of r-concrete in Germany are pointed out - low demand and supply for recycled aggregates and r-concrete prevents the widespread use of r-concrete in building construction (Stürmer & Kulle, 2017; Nobis & Vollpracht, 2015; Hinzmann et al., 2019).

1.2.3. Technical barriers

The economic obstacles outlined above are closely related to the technical properties and the production process of recycled concrete. In many cases, the possible impairment of price competitiveness is a direct consequence of the technical characteristics of recycled concrete. In this context, the fact that the production of r-concrete requires an adjustment of the recipe (Stürmer & Kulle, 2017) should be emphasised. Nobis and Vollpracht (2015) point out that r-concrete has qualitative limitations compared to conventional concrete in numerous properties - this is particularly due to the increased water absorption and the less favourable grain shape of the recycled aggregates. However, the authors note, that possible disadvantages can be compensated for by concrete technology with a higher cement content or admixture dosage (Nobis & Vollpracht, 2015; Stürmer & Kulle, 2017). Knappe et al. (2012) point out that the quality and material composition of recycled aggregates are influenced to a high degree by deconstruction methods. Therefore, for the production of high-quality recycled aggregates, a selective demolition process has to be adapted or, if necessary, even developed and implemented. The quality and composition of the recycled aggregates produced in the course of selective demolition must be comprehensively monitored on site - for some applications of recycled aggregates an additional test in a laboratory specialised for this purpose must be carried out (Knappe et al., 2012; Stürmer & Kulle, 2017). The changed technical properties of recycled aggregates, need for selective deconstruction and resulting additional costs can be considered as a further, technologically induced obstacles that can lead to a reduction in the price competitiveness of r-concrete.

[11] For the construction of the diaphragm wall in this project $\approx 1700\ m^3$ of ready-mix concrete were used (Mettke et al., 2015). With the additional costs of 5.30 Euros per cubic meter of concrete, the total additional costs resulting from the use of recycled concrete would amount to 9010 Euros. The total construction costs according to the public tender for this project amounted to 33.8 million Euros (Berlin, 2010).

1.2.4. Acceptance

Although recycled concrete could be used in most construction projects in compliance with all construction, environmental and legal requirements, it is used to a very limited extent in Germany. In the technical literature, reference is made to the low acceptance and poor image of recycled building materials among the actors in the value chain, for which various factors are responsible (Hinzmann et al., 2019). Knappe et al. (2012) refer to the bad experiences that have determined the attitude towards recycled materials among decision-makers for decades. Stoll (2014) points out the widespread ignorance and lack of knowledge about the possible uses and technical properties of recycled building materials. However, many municipalities are simply unaware of the latest developments in processing technology and quality assurance (Knappe, 2014). In many cases, the public sector lacks knowledge about the legal possibilities of including secondary materials in the tendering procedure (Stoll, 2014). Nobis and Vollpracht (2015) point out that the acceptance of local authorities and construction administrations regarding the use of recycled aggregates varies regionally. There are municipalities that advocate the use of recycled aggregates due to positive experiences with recycled construction materials, while other municipalities exclude the use of recycled aggregates when tendering specifications (Knappe, 2014). In contrast to Germany, in Switzerland the use of recycled building materials appears to be widely accepted by different actor groups - not least because of the recognition of r-concrete through an environmental certificate, higher limits for the proportion of recycled aggregates in concrete, consideration in public tenders, and general stipulation of the use of recycled concrete in City of Zürich.

Against the background of the low use of recycled concrete in building construction, Knappe et al. (2012) point out that without far-reaching measures, secondary building materials in high-quality applications will not be able to assert themselves on the market without fundamental changes in construction practice and respective regulations. For this reason, a mix of instruments is required that addresses the factors that inhibit increased recycling and the use of secondary building materials. Various measures are discussed in the technical literature that could increase the use of r-concrete in building construction. Stürmer & Kulle (2017) point out the need of consideration of recycled materials in DGNB-certification and public tenders. Nobis and Vollpracht (2015) emphasise that the minimum quality requirements for concrete are in many cases fulfilled even with higher proportions of recycled aggregates, which may lead to the conclusion that the maximum permissible proportion of recycled aggregates in concrete can be increased. Knappe et al. (2012) propose specifications for the use of recycled materials in new buildings, information campaigns, implementation of lighthouse projects for the high-quality use of recycled building materials, building construction subsidies linked to the use of recycled concrete, clear and uniform specifications for the quality of recycled building materials, and the introduction of a building pass.

1.3 Overview of empirical literature on the barriers to the use of recycled concrete in building construction

The objectives of the present study are to identify the obstacles to the use of recycled concrete and to derive an empirically based policy recommendation to increase the use of r-concrete in building construction in Germany. Due to the empirical orientation of this work, it is essential to consider the previous research when addressing the defined research objectives. For this reason, an overview of the empirical work already available on this topic will be provided below.

In Germany, very few attempts have been made so far to empirically investigate the obstacles to the use of r-concrete. In order to determine the degree of awareness of recycled concrete and to consciously contribute to its popularity, Stürmer and Kulle (2017) conducted surveys with architects (N=46), structural engineers (N=57) and concrete manufacturers (N=12) in Baden-Württemberg as part of a project on the possibilities of using recycled aggregates. The relevance of certain obstacles to the use of r-concrete was examined there from the point of view of different actors. Among other results, it was found that 12 % of the structural engineers, 4 % of the architects and 100 % of the concrete manufacturers have already worked with recycled concrete. The main obstacles to the use of r-concrete were the unwillingness to bear additional costs (63% of the architects and 75 % of the concrete manufacturers surveyed) and concerns about quality and experience in the use of r-concrete (51 % of the structural engineers and 75 % of the concrete manufacturers surveyed).

In the international technical literature, the obstacles to the use of recycled concrete have been discussed from different perspectives. In order to compare concrete recycling situations between Australia (N=54) and Japan (N=80) questionnaire survey and structured interviews were conducted by Tam (2009). In this study, the main obstacles to the use of r-concrete were identified as the high recycling costs and the difficulties in placing equipment on the construction site. In addition, Tam (2009) examined measures to increase the use of r-concrete - on average, the information provided by the respondents suggests that more detailed classification of recycled aggregates and government financial support for companies could be considered as recommendable measures. Following on from this, Jin and Chen (2015) conducted a similar survey of construction industry actors in the USA and compared the responses in the USA with those in Japan and Australia as collected by Tam (2009). It was found that the main obstacles in the USA are the lack of industry and governmental awareness and support toward concrete recycling. Participants of the survey identified following items as recommended measures to increase the use of recycled concrete: identifying and classifying of r-concrete applications, considering concrete recycling in design and developing techniques and developing the best management practices for recycled concrete (Jin & Chen, 2015). Furthermore, Jin et al. (2015) examined the current status of sustainable concrete production in USA through a questionnaire survey of concrete suppliers and prefabricators (N=34). The increase in costs due to the use of recycled aggregates was identified as one of the main obstacles to the production of r-concrete from the perspective of concrete producers. In summary, the following conclusions can be drawn from a review of the available empirical literature on the obstacles to the use of recycled concrete:

- The empirical evidence on the perception of obstacles to the use of recycled concrete in building construction in Germany is extremely limited.
- There is no empirical evidence on the effectiveness of measures to increase the use of recycled concrete in Germany.

1.4 Purpose and structure of the work

The existing knowledge about the obstacles to the use of recycled concrete in Germany as well as possible economic policy measures to increase the use of r-concrete is largely based on theoretical considerations and in many cases directly evident from regulatory frameworks or construction practice. There is only a very limited empirical evidence available about what obstacles actually play a role in the use of r-concrete in Germany and how these are evaluated by different groups of actors. Furthermore, there is no empirical evidence for Germany whether the removal of the obstacles outlined in the previous sections would achieve the desired environmental policy effect. In this context, the limited empirical evidence for Germany can be identified as a research gap. Thus, the objectives of the present work are to identify barriers to the use of recycled concrete and to derive empirically based policy recommendations to increase the use of r-concrete in building construction in Germany. This is intended to expand the existing literature on the relevance of the obstacles to the use of r-concrete in Germany and to create empirical evidence on the effectiveness of possible measures. Since the use of r-concrete in building construction is more widespread in Switzerland than in Germany, the comparative perspective is taken in certain research aspects. The long-term goal of this work is to provide policy makers with a scientifically sound basis on which measures to increase the use of r-concrete can be developed and implemented.

The thesis consists of four studies, in which different topics regarding the use of recycled concrete in building construction are investigated. Following this introduction, labelled as **Chapter 1**, **Chapter 2** contains a study based on a survey of the executing companies in the construction value chain in Germany and Switzerland. There, the obstacles to the use of r-concrete in building construction and the effectiveness of possible economic policy measures to increase the use of recycled concrete in building construction are investigated. The study presented in **Chapter 3** is based on the survey of students of architecture, civil and environmental engineering in Germany and Switzerland. In addition to the comparative analysis of the perception of sustainability and recycled concrete-relevant study contents, it is examined whether students in Switzerland have a more pronounced attitude towards sustainability and thus a higher willingness to pay for sustainability-related attributes. The study in **Chapter 4** is based on the survey of architects and engineers in Germany and Switzerland. The thematic focus of this is the combination of the research questions from previous chapters. On the one hand, in Chapter 4 the obstacles to the use of r-concrete in building construction and the effectiveness of possible economic policy measures to increase the use of r-concrete in building construction are examined. On the other hand, it is assessed whether architects in Switzerland are characterised by a higher willingness to pay for sustainability-related attributes. **Chapter 5** presents a study that examines the geographical and economic determinants of the willingness to produce r-concrete from the perspective of ready-mixed concrete producers.

Chapters 2 to 5 are based on empirical studies and thus have a very similar structure. The first sections of respective chapters introduce to the problem and derives the related research hypotheses. Subsequently, the methodological foundations, the procedure for data collection and the structure of the questionnaires used are explained in detail. Subsequently, suitable empirical models are specified and applied to the investigation of defined research hypotheses. At the end of the respective chapters, the research results are summarised briefly but not discussed in detail. A detailed discussion of the research results takes place in **Chapter 6**. Based on the research results, an economic policy recommendation for increasing the use of recycled concrete in building construction in Germany is derived and discussed there. The results of the entire work are summarised in **Chapter 7**. In **Appendix**, the used questionnaires as well as further materials relevant for the understanding of the presented studies are attached.

2 Barriers to the use of recycled concrete from the perspective of executing companies

The aim of the present work is to derive empirically based economic policy recommendations for increasing the use of recycled concrete in building construction. In order to ensure that the desired policy goal is achieved and that no adverse effects are caused, it is essential to integrate the expertise of all relevant actors of the value chain when developing appropriate measures. In the context of the use of r-concrete, the relevant actors in the construction value chain can be divided into two groups - planning and executing actors. The planning actors are the architects and engineers[12], who accompany the construction project through different project stages. These include, for example, the preparation of a preliminary design of the building, cost estimates, the preparation of plans containing all the provisions of building law, calculation and dimensioning of the building taking into account all physical impacts, and the choice of construction method and building materials. The executing parties, on the other hand, are enterprises that carry out concrete work during the execution phase of the construction project. This includes, for example, construction work, concrete production, production of sand and gravel, preparatory site work and much more.

Both the executing and the planning actors are equally relevant for the use of r-concrete in building construction. Both groups of actors have expertise and experience in their field and can provide valuable information on the main obstacles to the use of recycled concrete in building construction and on the measures that can be taken in order to increase the use of r-concrete. Thus, in the study presented in this chapter, the obstacles to the use of r-concrete and possible economic policy measures to increase the use of recycled in building construction will be examined from the perspective of the executing companies.[13] In particular, the following questions will be answered and the resulting hypotheses examined:

- What are the most important obstacles to the use of recycled concrete in building construction from the contractors point of view?
- Are there differences in the relevance of the obstacles to the use of recycled concrete between Germany and Switzerland?
- What measures can be taken in order to increase the use of recycled concrete in building construction in Germany?

[12] This formulation refers to architects and engineers in general, regardless of their professional specialisation and type of occupation.

[13] Further actors will be considered in the following chapters.

- H_1: The consideration of sustainability (use of recycled materials) as a further award criterion in the public tender increases the likelihood that the executing companies apply to the tender using r-concrete.
- H_2: The recognition of recycled materials usage by the label increases the likelihood that the executing companies apply to the public tender using r-concrete.
- H_3: Reimbursement of additional costs resulting from the use of recycled materials increases the likelihood that the executing companies apply to the public tender using r-concrete.

In order to investigate the defined research questions and resulting hypotheses, a combined item-based and factorial survey of the relevant executing companies in the construction value chain has been carried out. The study presented in this chapter begins with a detailed description of the research methodology. Subsequently, the survey data are descriptively analysed from a comparative perspective between Germany and Switzerland. An empirical model is then specified with which the research hypotheses on measures to increase the use of recycled concrete in construction are tested. In the last section of the chapter the research questions, methodology and main results are briefly summarised.

2.1 Research strategy and data collection

The aim of this study is to identify obstacles to the use of r-concrete from the perspective of the executing companies and to analyse the effectiveness of possible measures to increase the use of recycled concrete in building construction. Methodologically, the present study consists of two parts. In the first part, the obstacles on r-concrete usage will be identified by means of the classical item-based firm survey based on benchmark with Switzerland. In the second part, the effectiveness of selected economic policy measures to promote the use of r-concrete will be examined through factorial survey.

The online questionnaire begins with general information on data protection requiring consent. In order to ensure that the questionnaire is only answered by those companies that also have appropriate expertise in the field of recycled concrete, the question whether it is known what r-concrete is about was asked before the actual survey began. In case of a negative answer, the survey was immediately terminated. The survey starts with a block of general questions about the company and the perception of r-concrete. The subsequent survey part consists of an experimental situation (factorial survey), which is presented to the respondents.

In factorial surveys, hypothetical object or situation descriptions (vignettes) are presented to the respondents for evaluation, in which characteristics (dimensions) are experimentally varied in their manifestations (levels). In this way the influence of different dimensions on the respondent's decision can be determined (Rossi & Anderson, 1982). Compared to the "classical" item-based survey, factorial surveys have several important advantages. Firstly, the orthogonality of the individual dimensions is guaranteed, which allows a separate determination of their respective influence on judgement and decision. Secondly, complex assessment and decision problems can be simulated in the factorial survey by using a variety of features and its combinations. Compared to laboratory-based research, an advantage arises, since larger samples can be realised with factorial survey. The disadvantage of the methodology is that the investigation conditions are not controlled and, in complex decision-making situations, the judgement power of the respondents can be impaired (Auspurg et al., 2009).

Based on experimental situation, factorial survey presented to the interviewees is intended to test the effectiveness of possible economic policy measures to increase the use of recycled concrete in building construction. In order to prevent cognitive fatigue (Jasso, 2006) and because respondents tend to use only few dimensions to form opinions (Berk & Rossi, 1977), the vignette was limited to three dimensions and only one vignette per respondent was presented. Three possible instruments were examined regarding their potential effect on the use of r-concrete in the building construction: recognition of r-concrete in an environmental label, consideration of sustainability (use of recycled materials) as further award criterion in public tender and reimbursement of additional costs arising from the use of recycled materials. The characteristics of dimensions were randomly[14] varied between the respondents as follows: recognition of the use of recyclates through a label (*Yes*, *No*), consideration of sustainability in public tenders (*Yes*, *No*), refund of additional costs arising from the use of recycled materials (0 %, 25 % , 50 %, 75 %, 100 %). The *vignette universe* is calculated as the Cartesian product of the characteristics of all dimensions and counts 20 possible combinations ($2 \times 2 \times 5$). A relatively small number of all possible combinations ensures that the entire vignette universe in the survey is exhausted and that the effects of the individual dimensions can be estimated with the highest possible efficiency. If the number of respondents is large, the exhaustion of the vignette universe is equivalent to dividing the respondents into experimental groups - all respondents within the experimental group were presented the same situation. Thus, the respondents were confronted with the following exemplary vignette:[15]

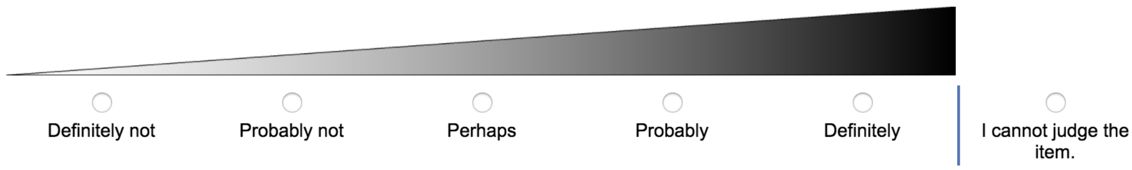
[14]Sample draw with replacement: for each interviewee, a characteristic of the respective dimension was drawn at random from the urn of all possible characteristics and then "put back" into the urn. Thus the probability that the respondent will be shown a certain characteristic of a certain dimension is $\frac{1}{d}$. d denotes the number of all possible characteristics of a respective dimension.

[15]One of 20 possible vignettes is shown here.

You are becoming aware of a comprehensive public tender. There, the production of aggregate, ready-mixed concrete and the construction of a building are announced. The tender explicitly mentions that when deciding on the award, the aspect of sustainability (use of recycled materials) is considered as a further criterion in addition to the price. If additional costs arise from the use of recycled materials, you will be reimbursed with 75 % of additional costs. The use of recycled materials is not recognised by any of the well-known labels.

How likely is it that you as a company will apply for this tender using r-concrete?

Figure 4: Factorial survey response options



The factorial survey was followed by questionnaire blocks on the perception of advantages and obstacles in the use of recycled concrete and general questions on the market and competition.

To increase the comprehensibility of the answer categories and to avoid undesired distortions, all used question scales were fully verbalised (Krosnick & Fabrigar, 1997; Toepoel & Dillman, 2011). The rating scales are balanced and thus have the same number of positive and negative categories, avoiding directional distortion of the answers. Various experimental studies have concluded that the specification of a middle or neutral category can reinforce the tendency towards the middle and lead to a less thorough response (Kalton et al., 1980; Krosnick & Fabrigar, 1997). For this reason, with a few exceptions, symmetrical 4-point Likert scales were used. Since respondents without a relevant attitude would otherwise feel pressured to give a substantive answer instead of communicating the lack of a relevant attitude (Katz, 1942; Payne, 1950; Vaillancourt, 1973; Schuman & Presser, 1981), an opt-out category was introduced for all questions (*I cannot judge the item*). To minimise the distortion caused by individual interpretation, the response scales were graphically anchored.[16]

The designed online survey is aimed at the executing companies in the construction value chain which are relevant for the use of recycled concrete. The online

[16] An example of the graphic anchor used in the survey is shown in Figure 4.

questionnaire was implemented using the SoSci Survey (Leiner, 2019) and made available to the participants at *www.soscisurvey.de*. The invitation to take part in the survey was sent by e-mail to 27234 companies in Germany and Switzerland within one week in October 2019 and could be answered within one month. The e-mail addresses were extracted from the Dafne and Amadeus company database which are operated by Bureau Van Dijk - A Moody's Analytics Company and contain the public information from the annual reports of the companies localised in Germany and Switzerland. The primary European classification of economic activities (Nace rev. 2) of targeted firms is shown in Table 2 (European Commission, 2008). The transcript of the complete survey can be found in Table A1 in Appendix.

Table 2: Classification of economic activities of targeted enterprises

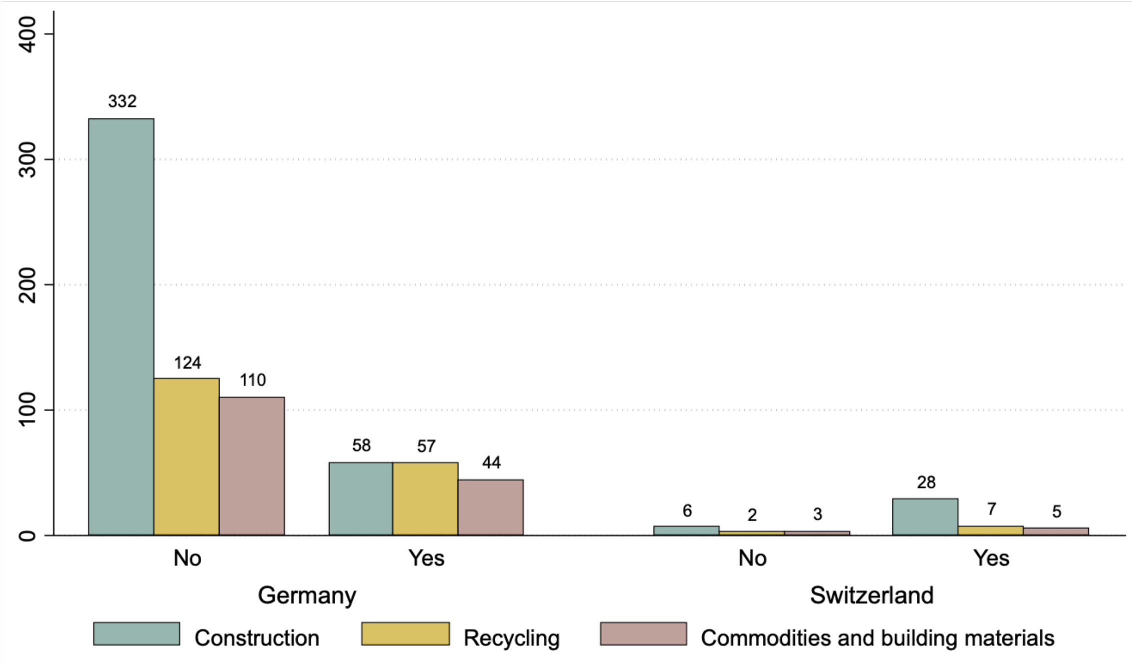
Nace Rev. 2	Activity
081	Quarrying and mining of stone, sand, clay; operation of gravel and sand pits
2361	Manufacture of concrete products for construction
2363	Manufacture of ready-mixed concrete
2364	Manufacture of mortars
2369	Manufacture of other articles of concrete
2370	Cutting, shaping and finishing of stone
2399	Manufacture of other non-metallic mineral products
3811	Collection of non-hazardous waste
3821	Treatment and disposal of non-hazardous waste
3832	Recovery of sorted materials
412	Construction of residential and non-residential buildings
4311	Demolition
4312	Site preparation

2.2 Barriers to the use of recycled concrete and possible regulation measures

Out of the 27234 companies that were invited to participate in the survey, 951 started the questionnaire. The companies that are not part of the construction and concrete value chain or stated not to have expertise in the field of recycled concrete have been excluded from the analysis. Thus, the number of questionnaires that can be evaluated is 658 and can vary in the context of respective question, as survey questions could be skipped.[17] The question on the already existing experience with

[17]Enabling the individual questions of the survey to be skipped was a fundamental decision for the entire work. The reason for this decision is the assumption that many respondents would answer the questions selectively and, in the case of the obligation to answer an unwanted question, would simply cancel the survey.

Figure 5: Existing experience with recycled building materials by country and industry



Bar height refers to industry affiliation, which is coded as a dummy variable - multiple entries were possible. N=531; refers to the simultaneous response to the questions about industry affiliation, experience with recycled materials and country affiliation.

recycled building materials was answered by a total of 534 companies.[18] There is a strong difference between the two countries - 81 % companies in Germany stated to have no experience with it; in Switzerland correspondingly only 19 %. The differences were tested with the two-sample t-test with unequal variances and proved to be significant ($p = 0.002$). The response distribution of industry affiliation by country and existing experience with recycled building materials is shown in Figure 5.[19]

2.2.1. Descriptive analysis

In the present section, the aim is to identify the obstacles to the use of r-concrete and to compare them between Germany and Switzerland. The main barriers to the use of recycled concrete in construction in Germany are shown in Table 3. The survey questions on obstacles to the use of recycled concrete were coded from 1 to 100.[20] A total of 24 possible obstacles to the use of r-concrete were presented to the respondents for assessment. Lack of governmental support in its various manifestations is perceived as the most important reason why recycled concrete is not used in building construction. Furthermore, market related factors such as low

[18] Question: "Does your company currently produce recycled aggregates, recycled concrete, recycled concrete products or uses recycled concrete in construction or have made it before?".

[19] The graph does not illustrate the number of responses within the categories. The industry affiliations may overlap, as one company could select several industries.

[20] *1=not relevant at all* to *100=very relevant*. The question was answered by using a slider that could be moved to the corresponding numerical values.

demand and supply for recycled concrete have been identified as further important obstacles.

Table 3: Main barriers to the use of r-concrete in Germany from the perceptive of the executing companies

Rank	Barriers	Median	N
1	No governmental support (t202_15)	91	211
2	Demand is too low (t202_11)	89	241
3	Considerable uncertainty regarding governmental regulation (t202_13)	84	193
4	No subsidies (t202_21)	81	193
5	Inconsistent governmental regulation regarding r-concrete (t202_25)	81	197
6	Supply is too low (t202_12)	81	228
7	No tax incentives (t202_20)	76,5	196
8	No recognition by labels and certifications (t202_19)	75	203
9	No knowledge and experience with r-concrete (t202_07)	76	252
10	Quality assurance of the demolition material is too cost-intensive (t202_23)	69	245

To identify the most relevant differences between Germany and Switzerland, a relative median difference ranking was calculated (Table A2 in Appendix). It corresponds to the ratio of actual group median difference and the highest possible median difference:

$$R = \frac{|M_G - M_S|}{Diff_{max}} \tag{1}$$

with M_G as median response for Germany and correspondingly M_S as median response for Switzerland. $Diff_{max}$ is the highest possible difference of the ordinal response. When scaling between 1 and 100 (scale of questions on barriers to the use recycled concrete), this is 99; by 5-stage ordinal scales, the highest possible median difference would be 4. Based on the relative median difference, the most relevant differences in the obstacles to the use of recycled concrete in building construction can be identified. As shown in Table 4, strong differences in the perception and relevance of the barriers to the use of r-concrete in construction can be observed - non-parametric two-sample equality-of-medians test indicates highly significant differences between the companies in Germany and Switzerland. The greatest differences in the perception of obstacles in the use of r-concrete can be observed in the absence of recognition of recycled concrete by labels and certifications ($Median_G = 75$ and $Median_S = 3$). This is followed by a lack of knowledge and experience with r-concrete ($Median_G = 76$ and $Median_S = 11$) and a too low demand ($Median_G = 89$ and $Median_S = 26$).[21]

[21] The complete list of differences in the perception of obstacles in the use of recycled concrete is presented in Table A2 in Appendix.

Table 4: Main differences in barriers to the use of r-concrete between Germany and Switzerland

Rank	Barriers	Median_G	N_G	Median_S	N_S	X^2	Rel. diff.
1	No recognition by labels and certifications (t202_19)	75	203	3	29	24.142***	0,727273
2	No knowledge and experience with r-concrete (t202_07)	76	252	11	31	22.053***	0,656566
3	Demand is too low (t202_11)	89	241	26	30	24.698***	0,636364
4	Price of r-concrete is not competitive (t202_22)	54	189	7	30	17.118***	0,474747
5	Quality assurance of the demolition material is too cost-intensive (t202_23)	69	245	22	30	21.356***	0,474747
6	Cost difference of r-material compared to normal grain is too high (t202_16)	53,5	186	8	30	14.641***	0,459596
7	Processing of construction waste is too cost-intensive (t202_01)	52	247	7	30	12.659***	0,454545
8	Lack of a suffcient number of appropriately trained staff (t202_06)	51	216	10,5	30	18.374***	0,409091

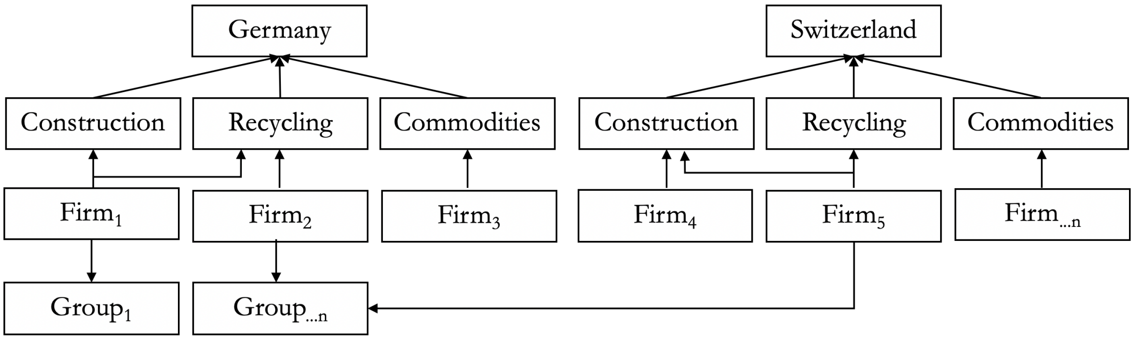
**p<0.05, **p<0.01, ***p<0.001.*
Results according to non-parametric equality of medians test.

2.2.2. Empirical model

The data basis of the empirical model is the factorial survey, which is used to test the effectiveness of three potential instruments for increasing the use of recycled concrete in the building construction. In particular, the relationships between the willingness to participate in the public tender using r-concrete and factors such as recognition of r-concrete by a label, reimbursement of costs resulting from the use of recycled concrete and the consideration of sustainability in the public tender are investigated empirically. Since the readiness to participate in the public tender is an ordinal scaled variable, the ordinal logistic regression can be considered as a suitable tool. The ordinal logistic regression estimates the causal relationship between the ordinal response variable and one or more independent covariates (Fagerland & Hosmer, 2016). The structure of the data can be illustrated by Figure 6.

The data is partially non-hierarchical since each firm belongs to two higher level units: an industry and an experimental group level. Firms are nested in industries and industries are nested in countries; but also, firms are nested in experimental groups. Thus, the data contains one three-level hierarchy (firms within industries and industries within countries) and one two level hierarchy (firms within experimental groups), which must be considered by the empirical model. For the modelling of partially hierarchical structures two approaches are suitable - fixed effects and multilevel mixed effects models (Beck & Katz, 2007; Schurer & Yong, 2012). Since the firms are nested in industries and countries as well as in experimental groups, the group-specific fixed effects can exist at the state and industrial level. (Angrist & Pischke, 2009). By introducing a dummy variable at the industry and at the country

Figure 6: Exemplary data structure: factorial survey on willingness to apply for public tender using recycled concrete



The actual data set contains 20 experimental groups.
Firm may belong to several industries and the experimental group may consist of firms from different countries.

level, group-specific differences in the explanatory variables can be controlled. Fixed effects are controlling for observed and unobserved heterogeneity between groups and thus rely on reasonable amount of variation of dependent variables within each group. Since the key policy variables are invariant within experimental groups and experimental groups were assigned completely randomly, the inclusion of fix effect for experimental group is not necessary - randomisation should have eliminated any correlations with inherent characteristics at experimental group level. Moreover, fixed effect for the experimental group level would be collinear with the combination of policy variables such as label, public tender and cost reimbursement. However, the possible distortions of the standard errors should be corrected by the introduction of cluster robust standard errors at experimental group level (Bertrand et al., 2004; Wooldridge, 2003; Wooldridge, 2010; Moulton, 1986). It is assumed that errors are uncorrelated across experimental groups, while errors for firms belonging to the same experimental group may be correlated.

Long and Freese (2014) point out that there are different procedures to derive the models for ordinal outcomes that all lead to the same mathematical models. In this context the authors point out that the ordinal regression model is commonly presented as a latent variable model. Since the willingness to attend public tender using recycled concrete is a categorical variable, when calculating the ordinal regression model, it is assumed that underlying the observed ordinal response variable y_{ig} for subject i in the group g is a latent (unobserved) continuous response y^*_{ig}. A threshold model determines the observed response - 4 thresholds values (a_c) are calculated to define the transition between categories. Thus, an individual response falls into category c when y is equal or exceeds the threshold value a_{c-1} but does not exceed the threshold value a_c (Rema & Hedecker, 2005). It follows that a cumulative generalised linear model for an ordinal response is equivalent to a system composed of a set of thresholds a_c and a linear regression model for an underlying continuous variable (Grilli & Rampichini, 2012). Following Fullerton (2009), this approach was found to be particularly appropriate, since the dependent variable is ordinally scaled, but represents a continuous variable, namely the probability of participation in the public tender. Thus, following Long and Freese (2014), the baseline structural model for ordinal regression model with clustered standard errors at the group level can be described in terms of a latent linear response as:[22]

$$y^*_{ig} = \mathbf{x}'_{ig}\boldsymbol{\beta} + \varepsilon_{ig} \tag{2}$$

where y^*_{ig} is latent continuous variable underlying the willingness to participate in the public tender using r-concrete of the firm $i = 1..., I$ belonging to the experimental group $g = 1..., G$ as a function of the vector of the independent variables x_{ig} and the logistically distributed error term ε_{ig}. In line with Long and Freese (2014) the observed response categories are tied to the latent variable by the measurement model:

$$y_{ig} = \begin{cases} 1\ (Definitely\ not) & if\ y^*_{ig} < c_1 \\ 2\ (Probably\ not) & if\ c_1 \leq\ y^*_{ig} < c_2 \\ 3\ (Perhaps) & if\ c_2 \leq\ y^*_{ig} < c_3 \\ 4\ (Probably) & if\ c_3 \leq\ y^*_{ig} < c_4 \\ 5\ (Definitely) & if\ c_4 \leq y^*_{ig} \end{cases} \tag{3}$$

The full structural model for the ordinal logistic regression for estimating the effect of possible economic policy measures to increase the usage of recycled concrete in building construction can be presented as follows:

$$\begin{aligned} y^*_{ig} = \beta_0 + \beta_1 \times label_{ig} + \beta_2 \times sustainability\ in\ public\ tender_{ig} \\ + \beta_3 \times cost\ reimbursment_{ig} \\ + \beta_{4...n} \times control\ variables_{ig} + \varepsilon_{ig} \end{aligned} \tag{4}$$

2.2.3. Results

The estimation results are shown in Table 5. Four regression models with different specifications were estimated. The first model is a reduced design that contains only policy variables of main interest, without any additional controls. In the second model control dummies for country and industry were introduced. In model (3) the estimate was extended by additional controls and variables of interest. To facilitate

[22]Notation in terms of structural latent linear models is maintained throughout the entire work.

the interpretation of predicted probabilities, the dependent variable[23] in a model (4) was decoded from 5-point to 3-point Likert scale. The dependent variable is the probability of participation in the public tender using recycled concrete.

The main assumption of ordered logistic regression is the proportional odds assumption (McCullagh, 1980). It implies that $ß_i$ is same for all equations of the dependent variable, regardless of which categories are tested. Violation of the assumption can lead to distortions in the estimation results. The likelihood-ratio (LR) test of proportionality of odds across response categories can be used in ordinal regression models to test the parallel regression assumption (Wolfe, 1997). It tests whether the coefficients of covariates are the same for all response categories. However, LR test can only be used for non-categorical variables in main-effects models (1) and (2). Since the results are non-significant, it can be assumed that the proportional odds assumption is not violated.

In addition to the odds ratio coefficients, Pseudo-R^2 (McFadden, 1974) are also presented in Table 5. Those estimate the proportion of variance explained by the model by analogy with the determination coefficient R^2 in classic linear regression models. In comparable logistic models, the Pseudo-R^2 are usually lower than the coefficient of determination in the linear regression (Norušis, 2005), so that Pseudo-R^2 values between 0.2 and 0.4 are considered as very successful (Tabachnik & Fidell, 2007). The ordinal version of the Hosmer-Lemeshow test (Fagerland & Hosmer, 2013; Fagerland & Hosmer, 2016), Pregibon-Tukey test (Pregibon, 1979; Tukey, 1949) and Pulkstenis-Robinson test (Pulkstenis & Robinson, 2004) were used to measure the goodness of fit in considered models. The null hypothesis for the goodness-of-fit tests is that the model fits the data well. A small p-value is therefore an indication that the model is misspecified (Fagerland & Hosmer, 2016). The test results do not indicate that the models (1) to (4) are misspecified. Only in model (4), the Hosmer-Lemeshow test proves to be significant. Since Pulkstenis-Robinson test work best when lack of fit is associated with categorical variables, whereas the Hosmer-Lemeshow test is best suited for continuous covariates (Fagerland & Hosmer, 2016), the significant results for Hosmer-Lemeshow test are negligible - specified model consists largely of categorical variables. In the further analysis, models (3) and (4) should be emphasised, since these include experimental parameters, controls for country and industry affiliation as well as further variables of interest.

All three regulatory approaches considered - sustainability criterion in a public tender, reimbursement of additional costs when using recycled materials and recognition of recycled materials through a label - prove to be highly significant. Thus, the hypotheses H_1 and H_3 can be confirmed - the consideration of sustainability (use of

[23]Scaled as: 1=*definitely not*; 2=*probably not*; 3=*perhaps*; 4=*probably*; 5=*definitely*.

Table 5: Regression results: willingness to attend in public tender using recycled concrete

Dependent variables			**Odds ratios**	
	(1)	(2)	(3)	(4)
Label	0.535***	0.530***	0.484***	0.438***
	(0.087)	(0.080)	(0.133)	(0.116)
Cost refund	1.007***	1.007***	1.014***	1.015***
	(0.002)	(0.002)	(0.005)	(0.005)
Public tender	1.722***	1.814***	2.569***	1.894**
	(0.261)	(0.245)	(0.697)	(0.539)
Country (bb07, Germany=1)	.	0.351***	0.336*	0.185**
	.	(0.074)	(0.204)	(0.126)
Industry: construction (dz01_1)	.	0.934	0.957	0.692
	.	(0.254)	(0.353)	(0.291)
Industry: recycling (dz01_2)	.	1.230	2.044*	1.704
	.	(0.268)	(0.809)	(0.628)
Industry: commodities (dz01_3)	.	1.487	1.838**	1.942**
	.	(0.399)	(0.568)	(0.637)
Advanced training (bb06)	.	.	1.166***	1.275***
	.	.	(0.069)	(0.117)
Employees (dz02)	.	.	0.999	0.999
	.	.	(0.001)	(0.000)
Previous experience (bb01)	.	.	0.885	1.033
			(0.363)	(0.470)
Assessment of r-concrete (bb02)				
negative	.	.	1.084	0.203
	.	.	(1.393)	(0.208)
positive	.	.	2.696	0.885
	.	.	(3.195)	(0.818)
very positive	.	.	4.811	1.543
	.	.	(5.569)	(1.438)
Cluster robust SE (experimental group level)	Yes	Yes	Yes	Yes
Obs.	376	376	175	175
Pseudo-R^2	0.023	0.036	0.115	0.169
Prob $>\chi^2$	0.000***	0.000***	0.000***	0.000***
Goodness of fit			**P-values**	
Hosmer-Lemeshow	0.290	0.343	0.8075	0.0153
Pulkstenis-Robinson	0.742	1	1	1
Pregibon-Tukey	0.988	0.959	0.768	0.729
Likelihood-ratio test of proportionality of odds	0.706	0.178	.	.

*Standard errors in parentheses; *p <0.05, **p <0.01, ***p<0.001.*
Initial coding: $y = 1$ definitely not, $y = 2$ probably not, $y = 3$ perhaps, $y = 4$ probably, $y = 5$ definitely.
y as 5-level-response in (1)-(3); as 3-level-response in (4).
Label, public tender, previous experience with r-concrete and industry affiliation are incorporated as dummies.
Simultaneous affiliation to several industries is possible.

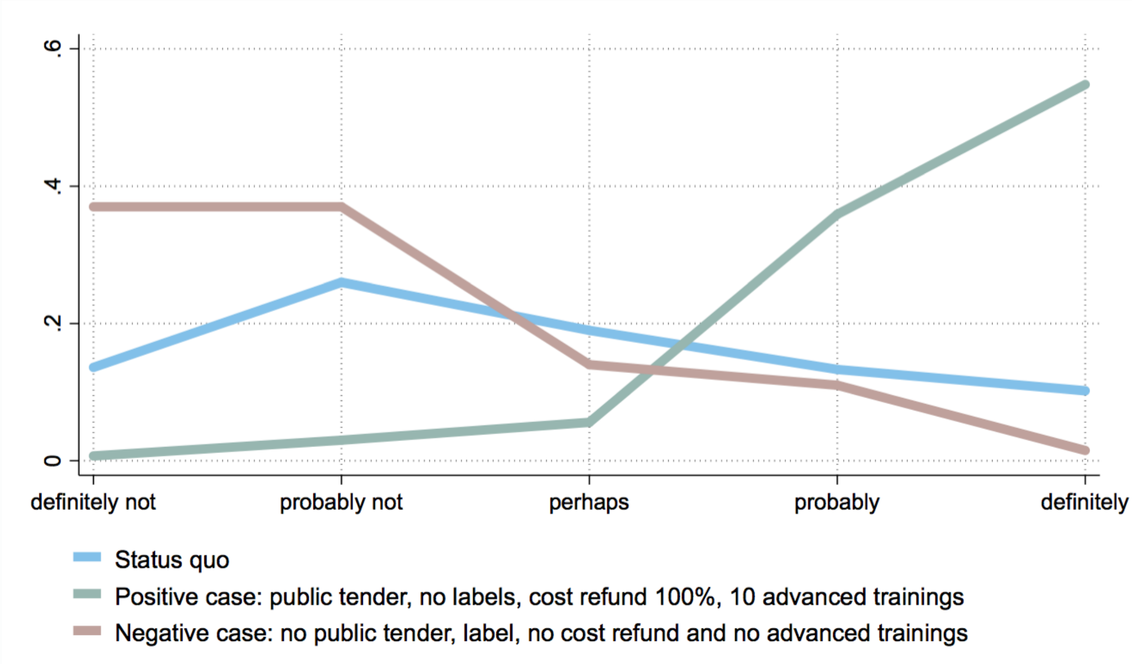
recycled materials) as a further award criterion in the public tender and additional cost reimbursement increases the likelihood that the executing companies apply to the tender using r-concrete. Since the odds ratio coefficient for "label" is <1, the hypothesis H_2 can be rejected - the recognition of recycled materials usage by the label decreases the likelihood that the executing companies apply to the tender using r-concrete. The relationships remain even if one checks for industry, country, firm size, existing experience with recycled concrete, number of professional trainings on recycled concrete as well as general attitude towards r-concrete in the firm.

If sustainability is considered in the public tender, the odds of high willingness to participate in public tender using r-concrete versus the combined lower categories are 2.6 times greater, given the other variables are held constant in the model. Also, for a one unit increase in cost refund the odds of high willingness to participate in public tender versus the combined lower categories are 1.01 times greater. At first sight, the effect of the possible reimbursement of costs on the willingness to participate in the public tender seems to be relatively small. This observation can be put into perspective if one considers the fact that the cost reimbursement is coded as a continuous variable and can take on values between 1 % and 100 % - increasing the reimbursement from 0 to 100 % increases the odds of a higher willingness to participate in the public tender by using r-concrete by more than twice. Where recycled materials are recognised in a label, the odds of high willingness to participate in a public tender using r-concrete versus the combined lower categories are 0.48 times lower, given the other variables are held constant. Furthermore, the probability of participating in a public tender using r-concrete is increased by training measures; additionally the positive relationship exists if the company belongs to the recycling or commodity production industry. In all estimated models a significant impact of the country affiliation can be observed - if the respondent is an employee of a company in Germany, the probability of participation in the public tender using recycled concrete decreases.

From the odds ratios of the model (3) presented in Table 5, predicted probabilities can be calculated for each response category (Figure 7). In context of possible regulation for increasing the sustainability in construction, three scenarios were calculated: *status quo*, positive as well as negative case scenarios. The predicted probabilities in the status quo scenario correspond to the situation where the covariates of the model are set to their mean values. The positive scenario used to model a (relatively realistic) situation, in which the probability of participation in the public tender using r-concrete is maximised. It was assumed that sustainability was considered as a further award criterion in the public tender, usage of recycled materials was not recognised by a label, the additional cost reimbursement accounted 100 % and the decision makers in a company have completed 10 training courses on recycled concrete in the last 2 years. In the negative scenario, the use of recycled materials was recognised by a label; sustainability was not considered in the public tender; neither cost reimbursement nor training measures have taken place.

When comparing scenario estimates, the positive influence of proposed economic

Figure 7: Predicted probability estimates: best- and worst-case scenarios

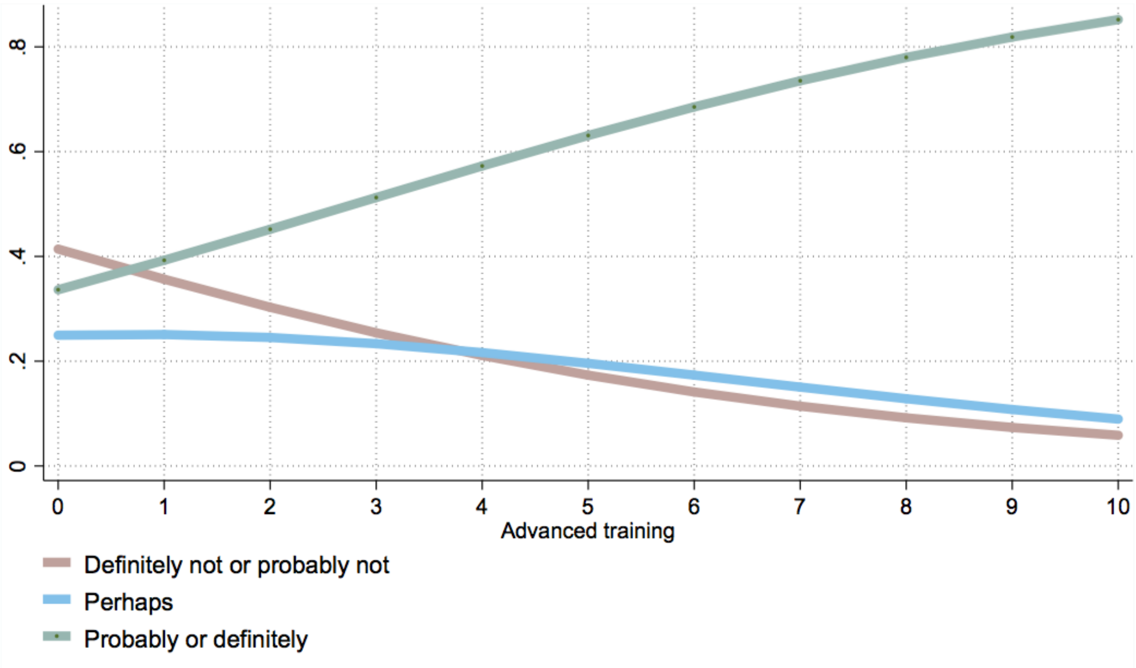


The figure refers to model 3 in Table 5.

policy measures on the willingness to participate in the public tender using r-concrete can be clearly observed. Recommended to increase the sustainability in the construction through the usage of r-concrete would be the increase of training measures on the subject of r-concrete, additional cost reimbursement for the use of recycled concrete and the consideration of sustainability in the public tender as a further award criterion.

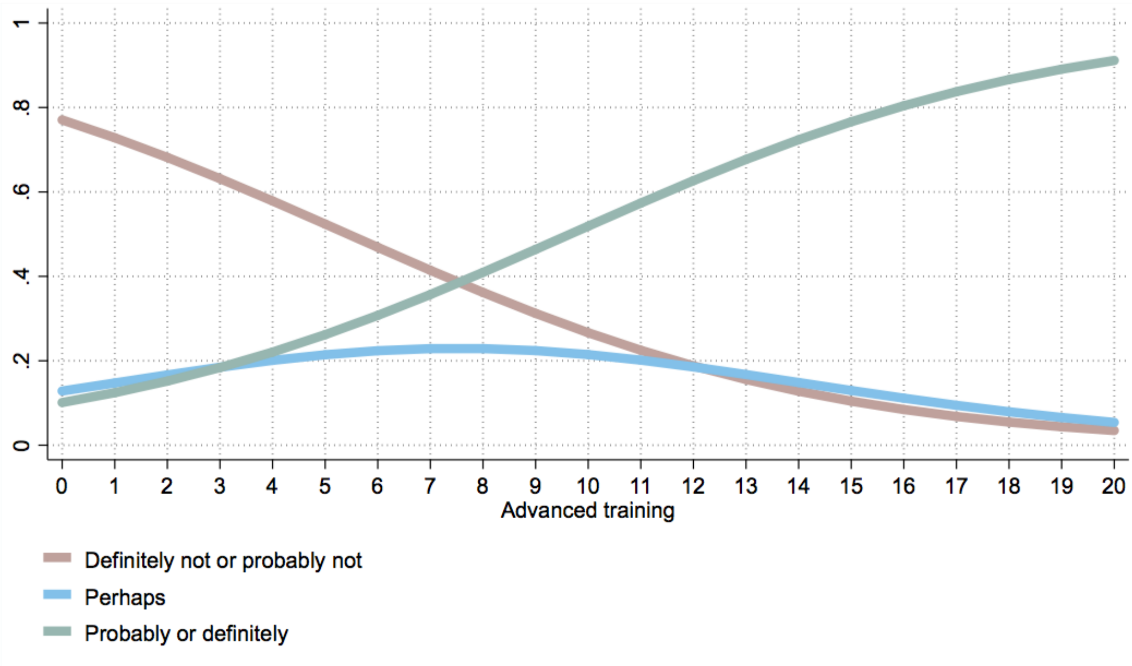
When looking at predictive margins as a function of the number of training events on recycled concrete, it is clearly visible that already from one event onwards, companies are more likely to participate in the public tender using r-concrete (Figure 8). Since the number of training courses was varied and the other variables were set to their means, the present analysis is only of limited use in deriving the economic policy measure. The estimate takes into account the "mean"-situation in which the companies could have a positive attitude towards r-concrete, have already used or would use r-concrete anyway. However, to promote sustainable construction, it is particularly important how the "sceptics" can be persuaded to use recycled concrete. For this reason, the predictive margins were estimated as a function of qualification events for the most unfavourable realistic situation - a situation in which the companies are characterised by the fact that they have no experience with r-concrete and have a fundamentally negative attitude towards sustainability and recycled concrete; cost reimbursements and consideration of the use of recycled materials in the public tender do not take place. In contrast, the use of recycled materials is recognised by a label. The results are presented in Figure 9. Regarding

Figure 8: Predictive margins estimates: the role of advanced training



The figure refers to model 4 in Table 5.

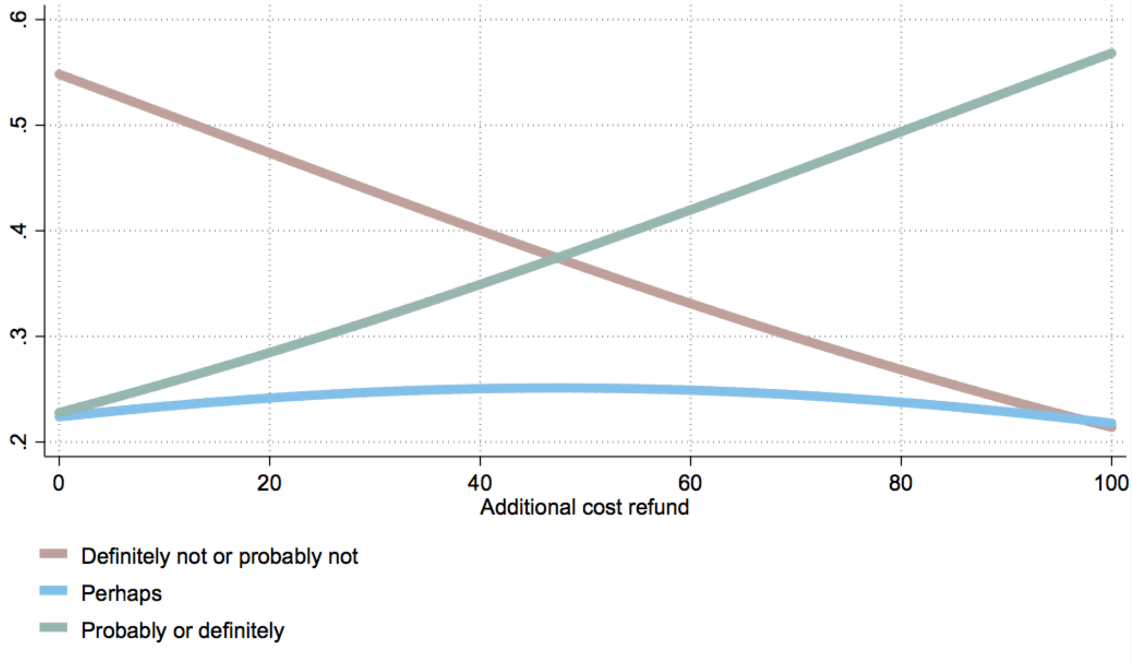
Figure 9: Predictive margins estimates: the role of advanced training in the negative scenario



The figure refers to model 4 in Table 5.

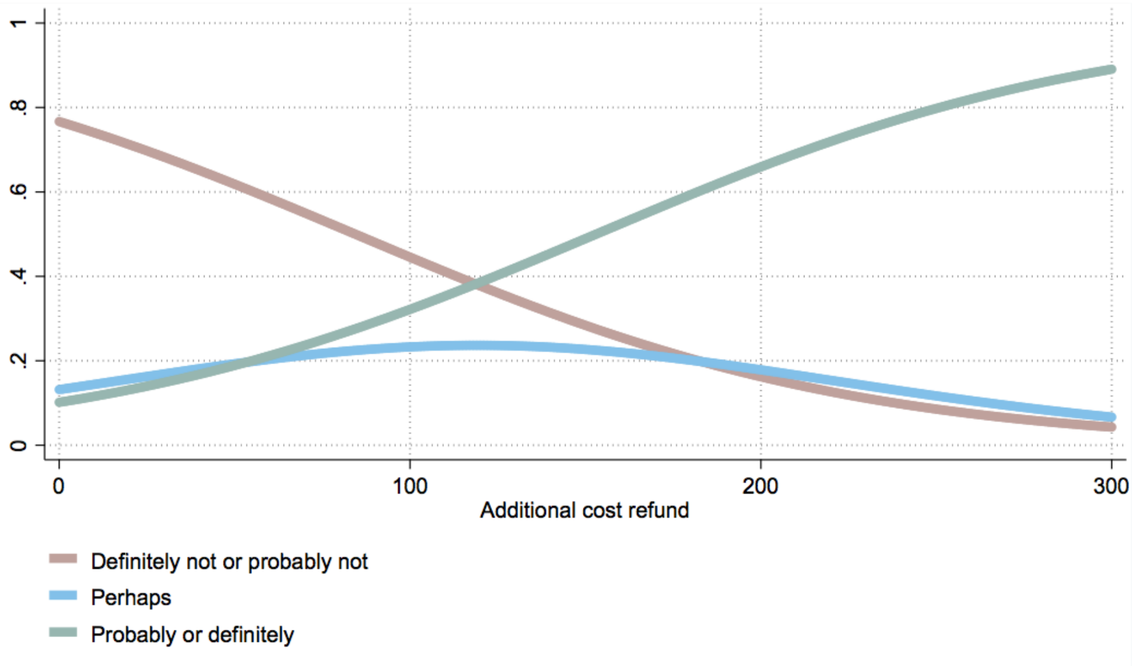
the estimates considered above, in a negative scenario, at least 8 training sessions are needed to make companies more willing to participate in public tender using r-concrete. In context of the fact that a preferably negative scenario was assumed, 8 training courses on r-concrete per two years seem to be a thoroughly realistic and feasible measure to increase the usage or r-concrete in building construction.

Figure 10: Predictive margins estimates: the role of additional cost refund in %



The figure refers to model 4 in table 5.

Figure 11: Predictive margins estimates: the role of additional cost refund in the negative scenario in %



The figure refers to model 4 in table 5.

Similar to the graphs mentioned above, predictive margins were calculated for the reimbursement of additional costs for the use of r-concrete. For the status quo case, the reimbursement of at least 50 % would be necessary to make companies more willing to participate in the tender using recycled concrete (Figure 10). In a negative case (Figure 11), 120 % cost reimbursement would be necessary to make the usage of r-concrete more likely. It means that not only a complete additional costs refund of 100%, but also the subsidy of 20 % would be necessary.

2.2.4. Robustness check

To check the robustness, model (3) from Table 5 has been estimated using different methods. The regressions results are shown in Table 6. The multilevel mixed ordered logistic regression was used in the first and second columns - firm and experimental group level by (1) and firm, industry and country level by (2). In columns (3) and (4), the dependent variable has been transformed into a metric variable and the model has been estimated as a linear regression model (OLS) and fractional response generalised linear model (GLM) - the ordinal response category 5 was recoded to 1; 4 to 0.75 etc..

The main effects such as the existence of the label, reimbursement of additional costs, consideration of r-concrete in public tenders and training events have proven to be robust and are still significant even if the model specification is changed. The direction of the effects has not changed and only minor changes in the coefficients can be observed in the multi-level models. Likelihood-ratio test compares the mixed effects ordered logistic model with standard ordered logistic regression - lack of significance indicates that the model specification without random effects for group levels, such as modelled in previous subsection (Table 5, model 3), is a more appropriate estimator than the multi-level models.

2.3 Conclusion

In this chapter, the obstacles to the use of recycled concrete have been examined from the point of view of the executing companies in Germany and Switzerland. A combined item-based and factorial survey of the executing companies in the construction value chain in Germany and Switzerland has been carried out. By comparing the responses between the two countries, main reasons why r-concrete is used only rarely in building construction in Germany were identified. By means of the factorial survey, selected economic policy measures were examined with regard to their effectiveness in promoting the use of recycled concrete in building construction.

Lack of governmental support in its various manifestations is perceived as the most important reason why recycled concrete is not used in the construction in Germany. Furthermore, market related factors such as low demand and supply for recycled concrete have been identified as central obstacles to the use recycled concrete in Germany. The major differences in the perception of the relevance of possible obstacles to the use of r-concrete between Germany and Switzerland are mainly the absence of recognition of recycled materials through labels and certifications, and the lack of knowledge and experience in the field of r-concrete. The results of an ordinal logistic regression model, which was carried out on the basis of the survey

Table 6: Robustness check: willingness to attend in public tender using recycled concrete

Dependent variables	**Odds ratios**		**Coefficients**	
	(1)	(2)	(3)	(4)
	2-level-ME	3-level-ME	OLS	GLM
Label	0.476**	0.456***	-0.108**	-0.108**
	(0.147)	(0.131)	(0.044)	(0.042)
Cost refund	1.014***	1.015***	0.002***	0.002***
	(0.004)	(0.004)	(0.001)	(0.001)
Public tender	2.610***	2.358***	0.136***	0.136***
	(0.822)	(0.685)	(0.042)	(0.041)
Country (bb07, Germany=1)	0.346**	.	-0.149*	-0.149**
	(0.180)	.	(0.072)	(0.070)
Industry: construction (dz01_1)	0.972	.	-0.001	-0.001
	(0.383)	.	(0.054)	(0.052)
Industry: recycling (dz01_2)	2.061**	.	0.098*	0.098**
	(0.629)	.	(0.049)	(0.047)
Industry: commodities (dz01_3)	1.835*	.	0.088**	0.088**
	(0.602)	.	(0.041)	(0.039)
Advanced training (bb06)	1.168*	1.227**	0.024***	0.024***
	(0.098)	(0.104)	(0.008)	(0.008)
Employees (dz02)	0.999	0.999	0.000	0.000
	(0.001)	(0.001)	(0.000)	(0.000)
Previous experience (bb01)	0.868	1.186	-0.008	-0.008
	(0.315)	(0.411)	(0.057)	(0.055)
Assessment of r-concrete (bb02)				
negative	1.175	1.027	0.015	0.015
	(1.409)	(1.194)	(0.158)	(0.152)
positive	2.874	2.650	0.116	0.116
	(3.088)	(2.780)	(0.142)	(0.137)
very positive	5.190	4.896	0.209	0.209
	(5.709)	(5.259)	(0.139)	(0.134)
Experimental group level	Yes	.	.	.
Country level	.	Yes	.	.
Industry level	.	Yes	.	.
Cluster robust SE (experimental group level)	.	.	Yes	Yes
Obs.	175	175	175	175
Adj.-R^2	.	.	0.2997	.
LR test	0.3651	0.4155	.	.

*Standard errors in parentheses; *p<0.05, **p<0.01, ***p<0.001.*
Dependent variable y is the response to the factorial question "How likely is it that you as a company will apply for this tender using r-concrete?".
Coding: $y = 1$ definitely not, $y = 2$ probably not, $y = 3$ perhaps, $y = 4$ probably, $y = 5$ definitely.
Label, public tender and previous experience with r-concrete are incorporated as dummies.
Industry affiliation is incorporated as dummies in (1), (3) and (4).
Industry affiliation decoded to categorical variable as combination of all possible industry affiliations in (2).

data, show that the consideration of sustainability in the public tender, advanced qualification measures on the topic of recycled concrete as well as the reimbursement of additional costs resulting from the use of recycled materials increases the probability of participation in the public tender using r-concrete. However, the recognition of recycled materials by a label reduces the likelihood of participation in the public tender by the executing companies.

The study contributes to the understanding of the obstacles to the use of recycled concrete in Germany from the point of view of the executing companies. In context of promoting sustainable construction, the results point to the need to consider recycled materials in the public tender, stronger governmental support and further training and qualification measures on the subject of recycled concrete.

3 Teaching recycled concrete and attitude towards sustainability

In the previous chapter, obstacles to the use of recycled concrete in building construction as well as possible economic policy measures were examined from the contractors point of view. It was found that the consideration of sustainability as a further criterion in the public tender, cost reimbursements as well as the qualification measures on the topic of recycled concrete increase the probability of participating in the public tender using r-concrete. In addition, it has become apparent that no knowledge and experience with r-concrete as well as the lack of sufficiently trained employees are perceived as two of the main reasons why recycled concrete is not used in building construction. There are significant differences between Germany and Switzerland - for the lack of knowledge and experience with recycled concrete, the median for Germany is 76 and for Switzerland 3; for the lack of appropriately trained employees, the median for Germany is 51, while in Switzerland it is 10.5.[24] In the context the recycled concrete usage in building construction, this result may indicate that the workforce in the construction value chain in Switzerland tends to have a higher level of knowledge about r-concrete. University education is one of the educational paths most relevant for the implementation of highly complex tasks such as the conception, planning and execution of a construction projects. Thus, the question arises whether the study contents can be considered as a cause of the restrained use of r-concrete in building construction in Germany.

How can the study contents influence the use of recycled concrete in building construction? In principle, two mechanisms are conceivable here, which are closely related to each other. On the one hand, it can be assumed that sustainability and recycled concrete related contents are treated to a higher degree during university education in Switzerland, which could contribute to the more widespread use of r-concrete in Switzerland. On the other hand, it can be assumed that students in Switzerland have in general developed a more pronounced attitude towards sustainability through their studies, which could lead to a more sustainable behaviour in professional life. Since students of architecture, civil and environmental engineering are future decision makers in the construction value chain, a more pronounced attitude towards sustainability could well lead to a more widespread use of r-concrete in building construction.

It is conceivable that more in-depth treatment of sustainability- and recycled concrete-related content in Switzerland could raise the awareness of future engineers and architects regarding the circular economy. Attitude towards sustainability

[24] Items are coded from 1=*not relevant at all* to 100=*very relevant.*

combined with expertise on circular economy and recycled concrete could potentially result in the increased use of r-concrete. Thus, the present study aims to investigate whether there are differences between Germany and Switzerland in terms of study contents and attitudes towards sustainability by future architects and engineers. In particular, the following questions and resulting hypotheses will be investigated:

- Are there differences in attitude towards sustainability between students in Germany and Switzerland? If students in Switzerland are more sustainable, then a higher willingness to pay for sustainability-related attributes should be observable in an experimental situation.
  - H_1: Students in Switzerland are characterised by higher willingness to pay for sustainability-related attributes.
- Are there differences in the coverage of sustainability-related contents in university training of future architects and engineers between Germany and Switzerland? What role do the study contents play in the perception of the substitutability of recycled concrete in underground and building construction? It is plausible to assume that the students, whose theoretical and practical contents have a more pronounced reference to sustainability, perceive the substitutability of r-concrete in underground and building construction as higher.
  - H_2: Sustainability-related contents are covered to a larger extent in Switzerland.
  - H_3: Sustainability-related theoretical and practical contents of the study have a positive impact on perceived substitutability of recycled concrete in underground and building construction.

To answer the research questions and to test the defined hypotheses, a combined item-based and discrete choice survey of students of architecture, civil and environmental engineering in Germany and Switzerland was conducted. In the following sections the survey design and the theoretical foundations underlying the discrete choice experiment are described in detail. Subsequently, the data from the survey are analysed descriptively and an empirical model is specified to investigate the established research hypotheses. In the last section of the chapter the research questions, methodologies and central results are briefly summarised.

3.1 Research design

As mentioned before, in order to answer the research questions and examine the considered hypotheses, an online survey among students of architecture, civil and environmental engineering was conducted. From a methodological point of view, the present study consists of two parts - a classical item-based survey and a discrete choice experiment.

The questionnaire starts with general information on data protection requiring consent. In the first questionnaire block, questions about student's socio-demographic characteristics are asked. Subsequently, a discrete choice experiment on the choice between different variants of the thermal insulation composite systems for the renovation of a single-family house is carried out. This is followed by question blocks on sustainability in the study contents and perception of recycled concrete. The full transcript of the survey can be found in Table A3 in Appendix.

In discrete choice experiments (DC), respondents choose the most preferred option from a range of alternatives (choice sets). By varying the attributes of the alternatives, it is possible to determine the influence of attributes of the alternatives on the decision making (Louviere & Woodworth, 1983). Methodologically discrete choice models are derived from the random utility theory and thus based on the assumption that individuals benefit from the characteristics of a good and not of a good by itself (McFadden, 1974; Manski, 1977; Louviere et al., 2000). Individual attributes can be assigned to different specifications, the attributes and their specifications can be combined to form different scenarios (Lancaster, 1971). It is assumed that under otherwise constant conditions - the higher the level of a desirable attribute of an alternative, the greater the utility of this alternative and the higher the probability that this alternative will be chosen and vice versa (Bennett & Blamey, 2001). According to (Louviere et al., 2000), the decision situation can be formalised as follows:

$$U_{an} = V_{an} + \epsilon_{an} \tag{5}$$

where U denotes the latent unobserved utility of person n for the alternative a. V_{an} denotes the systematic observable component of the utility of the person n for the alternative a. ϵ_{an} indicates an unobservable component as an error term of the utility of the person n for the alternative a. From (5) follows:

$$P(a|C_3) = P\Big[\big(V_{an} + \epsilon_{an} > V_{jn} + \epsilon_{jn}\big) \wedge \big(V_{an} + \epsilon_{an} > V_{kn} + \epsilon_{kn}\big)\Big] \tag{6}$$

Similar to Liebe[25] (2007), in a situation with three possible choice options, the probability of person n to choose option a from the choice set C is equal to the probability that the systematic and random components of the option a exceeds the systematic and random component of the option j and of the option k.

The discrete choice experiment presented to the students is intended to test the hypothesis whether students in Switzerland are characterised by higher willingness

[25] In Liebe (2007) an example of the decision situation between two alternatives was presented.

to pay for sustainability-related attributes (H_1). In general, different products are suitable to provide a basis for the decision situation. To ensure that all respondents are able to make a conscious and informed decision, the product must meet the condition that this has been covered in all universities and study programmes. For this reason, a thermal insulation composite system was chosen as a product for the experimental decision situation[26]. A hypothetical situation was designed where the students had to decide which composite thermal insulation system they would use when renovating their family house. Each student was presented with three choice sets with three alternatives each. Each alternative was characterised by 4 attributes that randomly[27] vary across students, choice sets and alternatives. After the description of the hypothetical situation and the presentation of the choice sets the students were asked which variant of the thermal insulation system they would choose.

Table 7: Attributes and levels for discrete choice experiment

Attribute	**Level**
Deconstruction costs [$Euros\ p.\ m^2$]	50, 100, 150, 200
Recyclability	cannot be recycled 25 % can be recycled 50 % can be recycled 75 % can be recycled
Energy efficiency	A, B, C, D
Costs [$Euros\ p.\ m^2$]	50, 150, 250, 350

Attributes and the levels of discrete choice experiment are shown in Table 7. Recyclability is defined as the proportion of the external thermal insulation composite system that can be recycled at the end of the product life cycle and is indicated in percent. The cost-related attributes refer to the external thermal insulation composite system and are listed in Euros per square meter. The energy efficiency classes are based on the energy label according to Directive 2002/91/EC of the European Union on the energy performance of buildings. It is expected that the costs of the composite thermal insulation system as well as future costs of deconstruction have a negative impact on the selection probability of the alternative. On the contrary, the energy efficiency of the building ensured by the insulation system and recyclability are expected to have a positive impact on the probability of choosing an alternative. The

[26]In a work on recycled concrete it would be obvious to specify the discrete choice experiment based on r-concrete as a product dimension. However, at the time the survey was designed and conducted, it was unclear to what extent recycled concrete was covered in the study and whether it was even known to the students.

[27]Sample draw with replacement: for each interviewee, a characteristic of the respective dimension was drawn at random from the urn of all possible characteristics and then "put back" into the urn. Thus the probability that the respondent will be shown a certain characteristic of a certain dimension is $\frac{1}{d}$; d denotes the number of all possible characteristics of a respective dimension.

attribute levels have been chosen as realistically as possible - the energy efficiency of the building due to insulation is limited to class D; recyclability of insulation system to 100 % is unrealistic and thus limited to 75 %.

In the application of discrete choice experiments a question arises whether to label the alternatives or not (Hensher et al., 2005). The unlabelled form involves assigning the given alternative a label such as “Product A” or “Product B”, wherever the labelled form involves assigning labels that communicate information regarding the alternative (Adamowicz et al., 1994). However, the inclusion of alternative-specific labels provides additional (and not controlled) information and thus reduces the attention that respondents give to the attributes and distort the estimation results (de Bekker-Grob et al., 2010). Furthermore, labelling often presupposes the adaptation of alternative specific attribute levels - for example travel by car is usually faster than by foot. Since the trade-offs between attributes require a precise estimate and are of particular interest in the present study, unlabelled choice alternatives were used in the survey. To minimise the likelihood that respondents would orientate themselves on additional, unobserved individual specific information, the decision situation was anchored verbally.

In general, discrete choice experiments can be conceived as full factorial and fractional factorial design. The use of full factorial design requires that the entire universe of choice combinations is exploited. The set of all possible combinations is formed by the Cartesian product of all attributes, levels and alternatives. With 4 attributes and 4 levels each ($4 \times 4 \times 4 \times 4 = 256$) and 3 alternatives ($256 \times 256 \times 256$) there are 16 777 216 combinations of possible choice sets in a full factorial design. Since not all choice sets can be presented for valuation, the present discrete choice experiment corresponds to a fractional or reduced factorial design. Under certain conditions, the reduced designs have almost the same statistical properties as the full factorial designs. According to Huber & Zwerina (1996) those are orthogonality (1), level balance (2), minimal overlap (3) und utility balance (4). Condition (1) means the maximum uncorrelatedness of the attributes, which is fulfilled in the present design, since the parameters of the attributes vary randomly across individuals, choice sets and alternatives. Condition (2) means that the levels of each attribute occur with same frequency, which is fulfilled as well, since all attributes have 4 randomly varying levels. Minimal overlapping of the characteristics in a common choice set (3) is to be considered as fulfilled, since the probability of two equal levels of respective attribute in the same choice set is 6,25 % and 1,5625 % for three equal levels. No adjustment regarding utility balance (4) was made, since criteria (1) and (2) are sufficient for efficient design and can only be slightly improved by (4) (Lusk & Norwood, 2005). For the reasons above, the present discrete choice design can be considered as suitable for estimation and comparison of substitution effects regarding the attributes of thermal insulation system choice. An exemplary choice set is shown in Table 8; the hypothetical situation presented to the students is shown below:

> *As an architect or engineer, you have decided to take over the renovation and insulation of the exterior walls of your detached house by yourself. The house was built in 1973, measures 130 square meters of living space; solid construction with plastered facade. There is a choice of three composite thermal insulation systems with different properties.*
>
> *Please take a careful look at all three variants of all sets presented and answer the question below.*
>
> ***Which thermal insulation system would you choose?***
> *(If you do not want to choose any of the above alternatives, leave the selection box in its initial position.)*

Table 8: Exemplary choice set of discrete choice experiment

	Variant 1	Variant 2	Variant 3
Deconstruction costs [*Euros p.* m^2]	200	50	100
Recyclability	50 % can be recycled	25 % can be recycled	75 % can be recycled
Energy efficiency	B	A	B
Costs [*Euros p.* m^2]	50	350	150

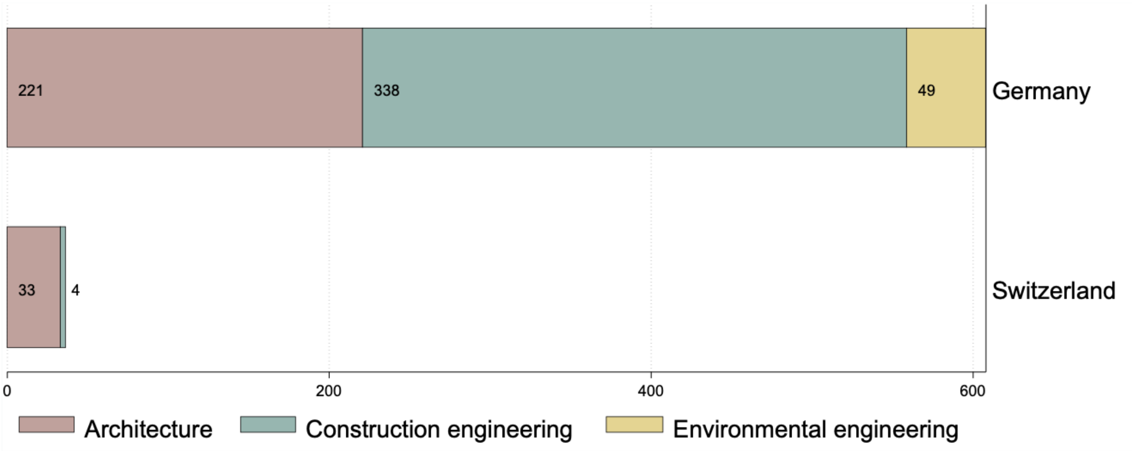
The online survey was aimed at students of architecture, civil and environmental engineering in Germany and Switzerland. The online questionnaire was implemented using the SoSci Survey (Leiner, 2019) and made available to the participants at *www.soscisurvey.de* in October and December 2019. Since direct access to the students' e-mail addresses was not possible, 1815 professors[28] of architecture, civil and environmental engineering in Germany and Switzerland were asked to forward the survey to the targeted students internally. To increase the incentives to participate, 30 × 10 Euro Amazon vouchers were raffled among respondents at the end of the survey.

3.2 Sustainability-related contents in Germany and Switzerland

In this section, the study contents will be analysed from a comparative perspective between Germany and Switzerland. In particular, the hypothesis that sustainability-related content is treated to a greater extent in Switzerland within the framework of the study programs will be tested. In the following section the hypothesis will be examined whether the theoretical and practical sustainability-related contents have a positive impact on the perceived substitutability of recycled concrete. Subsequently,

[28]The contact details of the professors have been compiled manually using internet search.

Figure 12: Frequency of respondents across countries and faculties



using an econometric model based on the data from the discrete choice experiment, it will be investigated whether the respondents in Switzerland are characterised by higher willingness to pay for sustainability-related attributes.

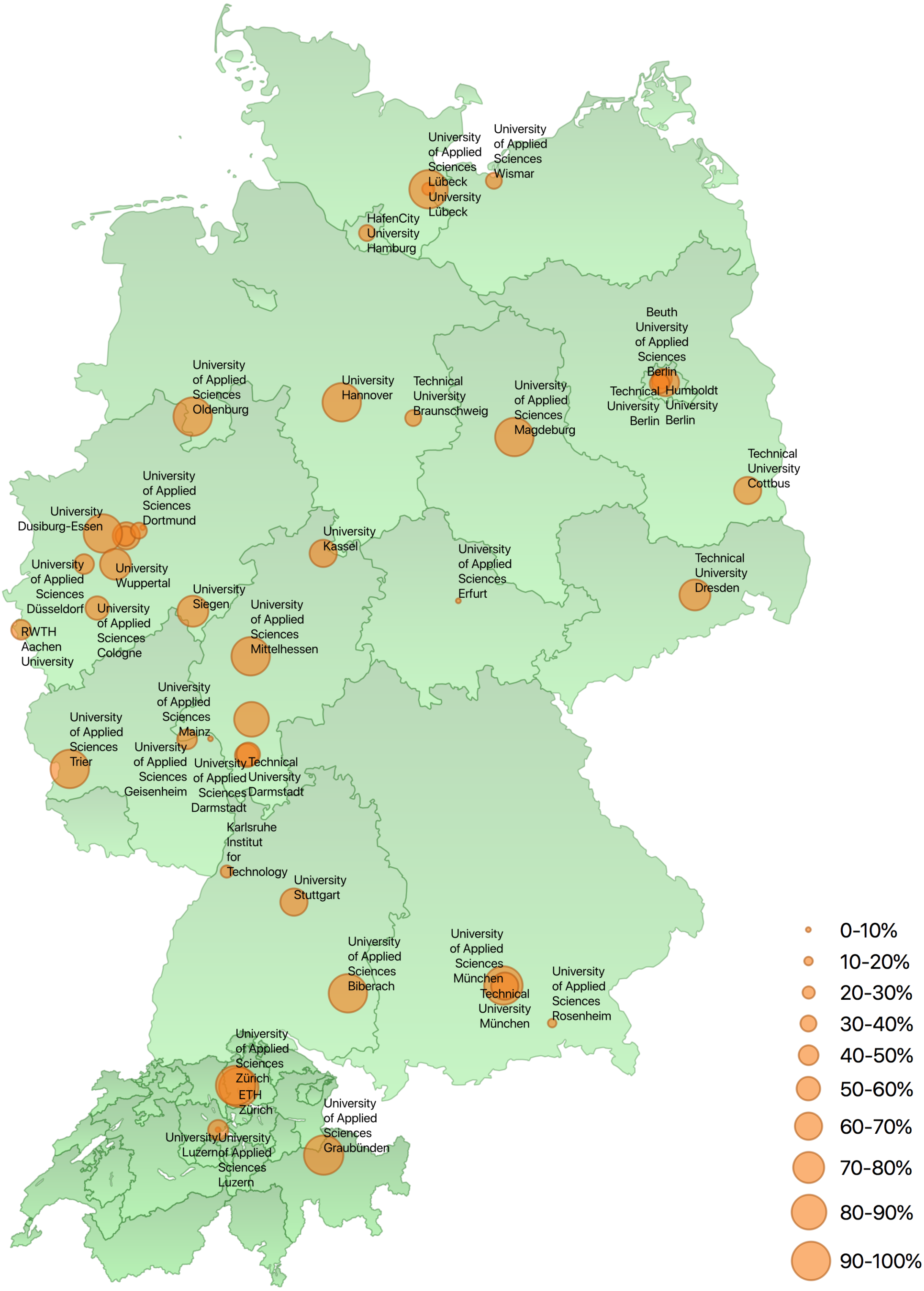
A total of 871 students began the survey - 645 respondents answered the questions on country and faculty affiliation. The response rate cannot be reported, since the invitations to participate in the survey were not sent directly but via professors of respective faculties - how many professors did forward the survey to the students cannot be tracked. The response distribution between faculties and countries is shown in Figure 12. In total, respondents from 51 universities and universities of applied sciences in Germany and Switzerland took part. The number of respondents varies considerably between universities, ranging from 1 (University of Koblenz) to 149 (RWTH Aachen University).[29]

In the survey, the question was asked whether the students had already heard of recycled concrete. There are differences between the countries in the proportion of students who have heard of r-concrete during their studies. In Switzerland 74 % of the respondents stated to have heard about r-concrete - in Germany it is 52 %. The differences were tested with the two-sample t-test with unequal variances and proved to be significant ($p = 0.006$). The proportional distribution of respondents by country and university who have already heard of recycled concrete can be illustrated by Figure 13.[30]

[29]The distribution of respondents across universities is illustrated by Figure A1 in Appendix.

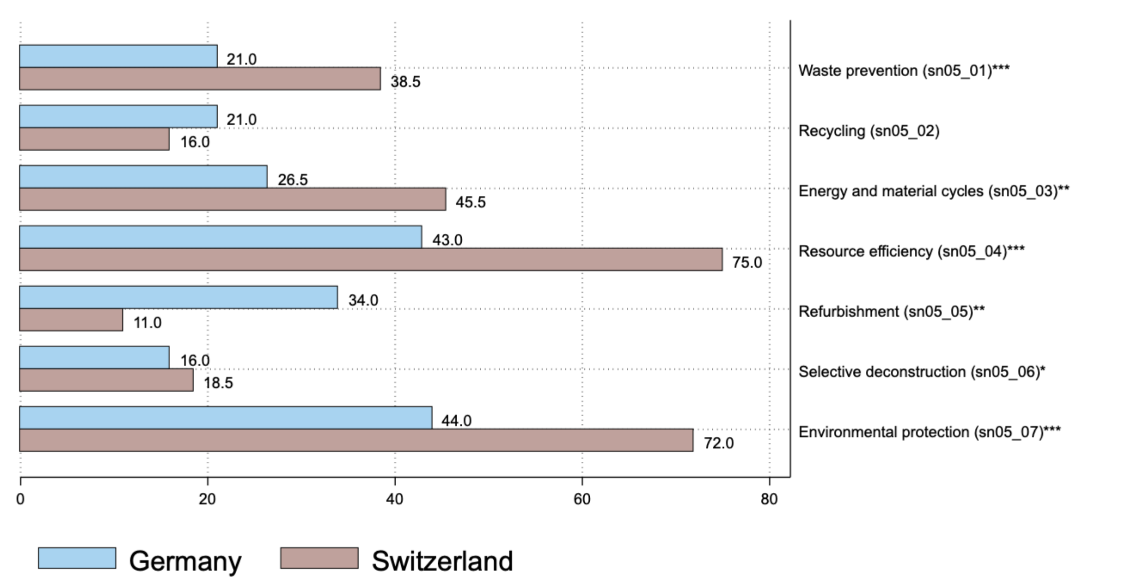
[30]The present observations should be treated with caution, as the results may be biased - students who have already heard of r-concrete are more likely to participate in the survey.

Figure 13: Share of engineers and architects who have experience with r-concrete in Germany and Switzerland



In the survey students were asked questions about sustainability-related content and recycled concrete. Thus, it can be examined whether there are differences in the depth of coverage of sustainability-related contents between the students in Germany and Switzerland (H_2). On a scale of 1 (*not intensively at all*) to 100 (*very intensively*),

Figure 14: Coverage perception of study contents in Germany and Switzerland (median)



**p<0.05, **p<0.01, ***p<0.001; refers to non-parametric equality of medians test.*

respondents were asked to rate how intensively sustainability-related topics have been covered during their studies. The results are shown in Figure 14 and Table A4 in Appendix. Regarding the perception of particular contents, differences between Germany and Switzerland can be observed - topics such as waste prevention, energy and material cycles, resource efficiency, selective dismantling and environmental protection were perceived to be covered more intensively in Switzerland. Two-sample equality of median tests indicate significant differences. For the contents illustrated in Figure 14, only recycling and refurbishment are perceived to be treated more intensively in Germany. However, the differences in recycling are not significant.

The comparison of additional study elements, which are relevant regarding r-concrete, is shown in Table 9. There are significant differences in the perception of the substitutability of recycled concrete and the coverage of r-concrete relevant contents. Furthermore, there are significant differences in the perception of coverage in theoretical and practical contents of the study. The present results indicate that the hypothesis H_2 can be largely confirmed - there are mostly significant differences in the perceived depth of the coverage of sustainability and r-concrete-related contents. In most of the dimensions considered, sustainability- and r-concrete-related contents are perceived to be discussed to a greater extent in Switzerland.

Table 9: Perception of r-concrete related contents in Germany and Switzerland

Variables	$Median_{Ger}$	$Median_{Sw}$	χ^2_{median}	$Mean_{Ger}$	$Mean_{Sw}$	$Diff_{mean}$
On the whole, circular economy is an integral part of my studies (sn01; 4=strongly agree)	2.000	3.000	8.108***	2.401	2.968	-0.566***
Practical elements of the studies have a strong connection to circular economy (sn06; 4=strongly agree)	2.000	3.000	15.877***	2.078	2.692	-0.615***
I have heard about r-concrete (1=Yes; sr01)	1.000	1.000	.	0.522	0.742	-0.220**
R-concrete was mentioned, but was not discussed in detail) (1=Yes); sr02	1.000	0.000	.	0.762	0.348	0.414***
Technical and chemical properties of r-concrete were covered extensively within the course of study (sr03; 4=strongly agree)	2.000	3.000	17.388***	2.008	2.905	-0.897***
Regulatory aspects of r-concrete were covered extensively within the course of study (sr04; 4=strongly agree)	2.000	3.000	14.893***	1.906	2.905	-0.999***
Regarding the application in building construction, I consider r-concrete as a complete substitute for classical ready-mixed concrete (sr05; 4=strongly agree)	3.000	3.000	8.445	2.524	3.125	-0.601***
Regarding the application in underground construction, I consider r-concrete as a complete substitute for classical ready-mixed concrete (sr06; 4=strongly agree)	3.000	3.500	11.107***	2.722	3.357	-0.635***

**p<0.05, **p<0.01, ***p<0.001.*
In order to test the differences two-sample t-test and non-parametric equality of medians test were used.

3.3 Study contents and perceived substitutability of recycled concrete

At the beginning of this chapter the hypothesis has been established that sustainability-related theoretical and practical contents of the study have a positive impact on perceived substitutability of recycled concrete in underground and building construction (H_3). How can this hypothesis be tested based on the available data? One of the plausible options would be the specification of a regression model for estimating the relationship between perceived substitutability of recycled concrete in building and underground construction on the one hand and the perception of particular sustainability-related contents on the other. However, this approach is not appropriate for several reasons. Firstly, not all study contents can be considered as explanatory factors for the perceived substitutability of recycled concrete, as they either correlate or (in the case of categorical variables) are equally distributed across different response categories. Secondly, it can be assumed that there may be reverse causality between the dependent and independent variables or that the uncontrolled confounding variable exists. Regardless of the causes, it can be expected that in

Table 10: Perception of the substitutability of r-concrete in underground construction and specific study contents

	(1) Strongly disagree or disagree		(2) Strongly agree or agree		
Variables	N_1	$Median_1$	N_2	$Median_2$	**p-Value**
Waste prevention (sn5_01)	57	20.000	118	37.000	0.017**
Recycling (sn5_02)	61	20.000	116	34.500	0.171
Energy and material cycles (sn5_03)	60	22.500	112	45.000	0.025**
Resource efficiency (sn5_04)	63	43.000	113	56.000	0.069*
Refurbishment (sn5_05)	63	33.000	111	44.000	0.322
Selective deconstruction (sn5_06)	59	21.000	112	24.000	0.284
Environmental protection (sn5_07)	63	43.000	118	68.000	0.000***

Refers to the item: "Regarding the application in underground construction, I consider r-concrete as a complete substitute for classical ready-mixed concrete." Question: "Do you agree with this statement?".

Table 11: Perception of the substitutability of r-concrete in building construction and specific study contents

	(1) Strongly disagree or disagree		(2) Strongly agree or agree		
Variables	N_1	$Median_1$	N_2	$Median_2$	**p-Value**
Waste prevention (sn5_01)	76	20.500	102	36.000	0.034**
Recycling (sn5_02)	80	26.000	99	35.000	0.404
Energy and material cycles (sn5_03)	80	34.000	96	50.500	0.226
Resource efficiency (sn5_04)	83	43.000	97	56.000	0.049**
Refurbishment (sn5_05)	83	41.000	96	41.500	0.809
Selective deconstruction (sn5_06)	75	21.000	99	23.000	0.419
Environmental protection (sn5_07)	83	48.000	101	64.000	0.037**

Refers to the item: "Regarding the application in building construction, I consider r-concrete as a complete substitute for classical ready-mixed concrete." Question: "Do you agree with this statement?".

estimating the perceived substitutability of r-concrete predictor variable would be correlated with the error term. For the above-mentioned reasons, the hypothesis is not to be tested by means of a regression model, but within the framework of sub-sample comparison.

The survey included questions on whether the study participants agree with the statement that recycled concrete is a complete substitute for conventional concrete.[31] Thus, the respondents can be divided into two groups - those who stated that they strongly disagree or disagree with the statement, and those who stated that they agree or strongly agree. The median assessment of the depth of treatment of the sustainability-related contents surveyed, grouped according to the perceived substitutability of concrete in underground engineering, is shown in Table 10. It is clearly evident that the median assessment of the depth of treatment of all sustainability-related contents is higher in the group in which the respondents indicated that concrete is perceived as a complete substitute for conventional concrete in underground construction. This tendency is also clearly evident when considering the perceived substitutability of recycled concrete in building construction (Table 11). Even though the medians of group (2) exceed

[31]Item sr05: *"Regarding the application in building construction, I consider r-concrete as a complete substitute for classical ready-mixed concrete"*; Item sr06: *"Regarding the application in underground construction, I consider r-concrete as a complete substitute for classical ready-mixed concrete"*; Question: *"Do you agree with this statement?"* (was asked for each of the items). Reply options: 1=*strongly disagree*; 2=*disagree*; 3=*agree*; 4=*strongly agree.*

Table 12: Perception of the substitutability of r-concrete in building and underground construction and general study contents

			Underground construction		
	(1) Strongly disagree or disagree			(2) Strongly agree or agree	
Variables	N_1	$Mean_1$	N_2	$Mean_2$	**P**
Sustainability in general (sn01)	60	2.350	116	2.724	0.005***
Sustainability in practice (sn06)	56	1.839	103	2.505	0.000***
Regulatory aspects (sr04)	63	1.794	116	2.302	0.000***
Technical and chemical properties (sr03)	63	1.968	117	2.376	0.003***
Proportion of courses taken with reference to sustainability (sn02)	59	34.322	116	37.672	0.194
Proportion of optional courses with reference to sustainability (sn04)	50	34.600	96	40.521	0.068*
			Building construction		
Sustainability in general (sn01)	79	2.519	100	2.720	0.115
Sustainability in practice (sn06)	68	2.118	94	2.394	0.047**
Regulatory aspects (sr04)	82	1.963	100	2.260	0.028**
Technical and chemical properties (sr03)	83	2.012	100	2.410	0.002***
Proportion of courses taken with reference to sustainability (sn02)	79	35.633	100	37.600	0.414
Proportion of optional courses with reference to sustainability (sn04)	67	36.940	85	40.294	0.270

Items sn02 and sn04 were recoded into continuous variables.

the medians of group (1) in all study contents, both in building and underground construction, only the differences in contents such as waste prevention, resource efficiency and environmental protection are statistically significant. Looking at the averages of the statements on the perception of general sustainability-related contents, it is striking that in both civil engineering and building construction, group (2) is characterised by higher average ratings in all dimensions (Table 12). Despite the clearly identifiable trend, the differences are statistically significant only in the assessment of the role of sustainability in the practical study content and the depth of coverage of the regulatory, chemical and physical properties of recycled concrete.

What do these results imply regarding the hypothesis that sustainability-related theoretical and practical contents of the study have a positive impact on perceived substitutability of recycled concrete in underground and building construction? It is clearly evident that, on average/median, students who assess the depth of coverage of sustainability-related theoretical and practical contents in their studies as higher also perceive the substitutability of concrete as higher. The differences identified are statistically significant in the contents waste prevention, resource efficiency, environmental protection, emphasis on sustainability in the practical elements of the study and the depth of treatment of the regulatory, technical and chemical aspects of r-concrete. Despite the fact that no causal relationship between the perceived substitutability of r-concrete and study contents can be determined on the basis of the available data, the available results strongly indicate that the positive relationship may exist. Based on this, the empirical evidence is to be regarded as sufficient to

Table 13: Empty fixed effects model for influence of university affiliation on the perceived substitutability of concrete

	Underground construction	**Building construction**
	(1)	(2)
University FE	Yes	Yes
Faculty FE	Yes	Yes
Clustered SE (university level)	Yes	Yes
Observations	181	184
Pseudo-R^2	0.207	0.235
Pregibon-Tukey	0.242	0.567

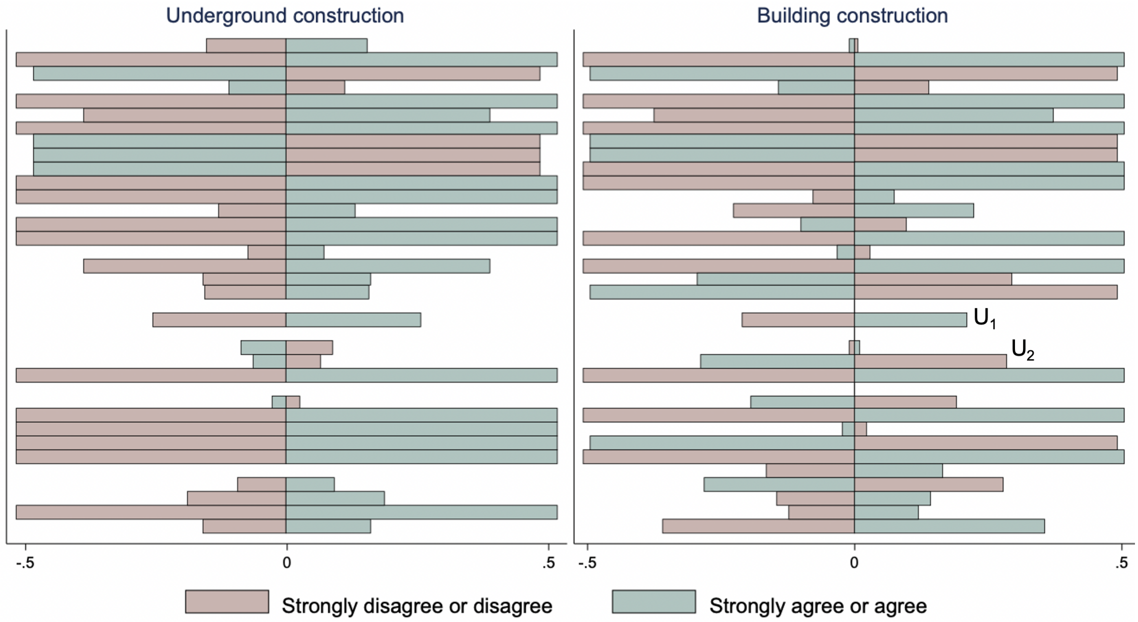
Dependent variable is the recoded assessment of the substitutability of recycled concrete in building or underground construction; coded as dummy variable with 1=strongly agree or agree and 0=strongly disagree or disagree.
University affiliation is incorporated as dummy variables; 32 from 37 university dummies are highly significant (p<0.001).

confirm the hypothesis H_3.

During the implementation of this survey, a lot of interesting feedback has been received from students. Among many comments was a very important one - a student of the Technical University of Dortmund informed that regarding the attitude towards recycled concrete and thus perception of its substitutability, it is a matter of coincidence which professor one comes across in the lectures and what personal attitude he or she has towards r-concrete. It has been argued that some professors are well-disposed towards recycled concrete and therefore deal with it in greater detail in the lecture; some professors are hostile to r-concrete and pass this opinion on to the students. Based on this argumentation, it is quite conceivable that students at universities with numerous professors, who systematically or by chance have a positive attitude towards recycled concrete, pass this on to students and thus contribute significantly to the (positive) perception of the substitutability of r-concrete. Within the scope of the study, the influence of the individual professors on the perception of r-concrete substitutability cannot be examined. However, the influence of university affiliation on the perception of substitutability can be investigated. It is quite conceivable that some universities could consist of particularly sustainability-oriented professors or that the universities as an institution attach great importance to sustainability and thus contribute to a positive perception of r-concrete substitutability.

In order to analyse the relationship described above, a simple empty logistic regression model with fixed effects at the university level can be estimated (Table 13). The dependent variables are the binary coded perceptions of substitutability of recycled concrete in underground and building construction, as already applied in the previous course of work when comparing the study contents. Since the respondents study at several faculties and the faculties can differ greatly in the depth of treatment of sustainability-related content, the faculty affiliation was controlled. In addition,

Figure 15: Average marginal effect of university affiliation on perceived substitutability of r-concrete



For factor levels dy/dx is the discrete change from the base level.
Each bar refers to a university.
The estimation refers to the model shown in Table 13.

the possible distortions of the standard errors were corrected by the introduction of cluster robust standard errors at university level. In the reduced models it is striking that university and faculty fixed effects explain a high proportion of the variation in the dependent variable (Pseudo-R^2 of 0.207 and 0.235). Of 37 dummy coefficients for university affiliation, 32 are highly significant. For the model specification shown in Table 13 average marginals effects of university affiliation on perceived substitutability of recycled concrete in underground and building construction can be calculated and presented in Figure 15. It is clearly evident that the university exerts a strong influence on whether the respondents consider recycled concrete to be a substitute for traditional ready-mixed concrete in underground engineering or building construction. It is interesting to note that in some cases university affiliation increases the respondent's likelihood of considering concrete substitutability as high (strongly agree or agree) by close to 50 %; in other cases university affiliation decreases it by close to 50 %. For example, on average, studying at university U_1 increases the likelihood of the respondent to asses the substitutability of recycled concrete in building construction as high (agree or strongly agree) by about 25 %. Studying at university U_2, on the other hand, increases the probability of assessing the substitutability of recycled concrete in building construction as low (strongly disagree or disagree) by about 30 %.

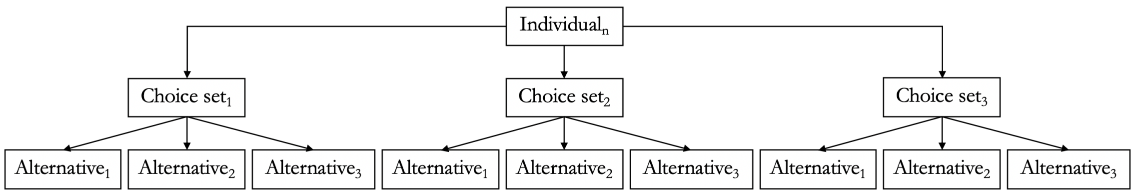
Based on the available results it can be stated, that affiliation to a particular university has a large impact on the perception of substitutability of concrete in building and underground construction. University explains a considerable proportion of the variation in the perception of the substitutability of recycled concrete. Given the fundamental influence of universities in the formation of opinion and the prominent role of future engineers and architects in the possible efforts to close the material cycles, the results suggest the need to raise teachers' awareness of the possibilities and advantages of using concrete. However, it should be taken into account that the empirical model applied is a very restrictive estimation, without any further control variables and robustness tests. The results of the model should act as a possible indication of a potentially existing causal relationship and should be considered as a side result of the work.

3.4 Marginal willingness to pay for sustainability-related attributes by students

The aim of the empirical model in this section is to estimate the marginal utilities of cost- and sustainability-related attributes and to calculate the resulting marginal willingness to pay for sustainability-related attributes. Thus, based on the data from discrete choice experiment, the hypothesis H_1 will be tested empirically.

3.4.1. Empirical model

Figure 16: Structure of the data: marginal willingness to pay for sustainability-related attributes by students



The structure of the data for the empirical model can be illustrated in Figure 16. Each respondent was presented with three choice sets and each choice set contained three alternatives, which varied randomly across respondents. Exemplary extract from discrete choice dataset is shown in Table 14. "Choice" is the dependent variable and indicates whether the certain alternative was chosen. "Choice set" specifies to which choice set the alternatives belong. "Alternative" denotes the presented alternative. In given case, this variable is of no further importance, as the alternatives are generic and vary randomly between respondents - this means, for example, that alternative 3 is different for each respondent. "ID" denotes individual; X_1 and X_2 are experimental alternative specific variables. For the modelling of hierarchically organised structures such as discrete choice data approaches such as (conditional) fixed effects and multilevel mixed effects models are suitable (Beck & Katz, 1995; Schurer & Yong, 2012).

Table 14: Exemplary extract from the data set

ID	Choice set	Choice	Alternative	X_1	X_2
1	1	1	1	2	3
1	1	0	2	2	1
1	1	0	3	3	2
1	2	0	1	4	3
1	2	1	2	1	4
1	2	0	3	3	1
1	3	1	1	4	4
1	3	0	2	2	2
1	3	0	3	2	4
2	4	0	1	3	2
2	4	1	2	1	1

In principle, both in a fixed and in a mixed effects model, further socio-economic individual-specific control variables should be introduced. This is not done for two reasons. Firstly, individual level variables as sole parameters cannot have any significant influence on the dependent variable due to the experimental design. Within the framework of the model, the influence of the randomly varying parameters of an alternative on the decision to select this alternative was considered. However, the alternatives are not firmly anchored - the alternatives are unlabelled or generic and differ only in the observed attributes. Thus, the influence of the experimental parameters of an alternative on the probability of choice can be modelled and interpreted, but not the influence of further individual-specific variables as sole coefficients. The consideration of individual-specific variables would be only possible as interaction terms with alternative specific variables. Each additional control variable would have to interact with each experimental variable and its categories, which greatly increases the number of dependent variables and makes the experimental parameters uninterpretable.[32] Secondly, the aim of the empirical model is to estimate the marginal willingness to pay for sustainability-related attributes for Germany and Switzerland and not to examine social-demographic characteristics such as age and income. For the above reasons, it is proposed not to introduce additional control variables. Thus, following Baetschmann et al. (2014), the baseline structural model for the logistic regression with individual fixed effects can be presented in a linear notation as follows:

$$y^*_{csi} = \mathbf{x}'_{csi}\boldsymbol{\beta} + a_i + \epsilon_{csi} \tag{7}$$

[32]For example, to control for a metric variable, a model with 3 metric and 1 non-metric variable with 4 categories would require the introduction of 7 interaction terms.

where y^*_{csi} is latent continuous variable[33] underlying the choice of the product alternative c in the choice set s by the individual i. x_{csi} indicates the vector of alternative specific covariates. a_i denotes individual fixed effect; ϵ_{csi} indicates an error term of individual i for choice set s and choice c. It should be noted that the empirical model is a binomial logistic regression model - the dependent variable indicates the choice of alternative and is coded as 0 or 1. The experimental decision, however, is multinomial, since the respondents choose between three alternatives. The full structural model for fixed effects logistic regression can be presented as:

$$y^*_{csi} = \beta_1 \times costs_{csi} + \beta_2 \times dismantling\ costs_{csi} + \beta_3 \times efficiency_{csi} + \beta_4 \times recyclability_{csi} + a_i + \epsilon_{csi} \quad (8)$$

Given the data structure, a random effects estimator can be considered as further possible estimation instrument for the model. The advantage is that in the random effects model the choice set can be taken into account - in the fixed effect estimator this is not possible due to the collinearity of choice set and individual level. The discrete choice data is organised hierarchically since each choice (level 1) is nested in a choice set (level 2) and choice sets are nested by individuals (level 3). Following Raman and Hedeker (2005), to account for the potential lack of independence within these groups the basic structural multilevel model for mixed effects logistic regression with random effects on higher levels (2 and 3) can be specified and presented in the linear notation as follows:

$$y^*_{csi} = \mathbf{x}'_{csi}\boldsymbol{\beta} + v^{(2)}_{si} + u^{(3)}_{i} + \epsilon_{csi} \quad (9)$$

where y^*_{csi} is latent continuous variable underlying the choice of the product alternative c (level 1) in the choice set s (level 2) by the individual i (level 3). x_{csi} denotes the vector of alternative specific covariates. $v^{(2)}_{si}$ denotes the random effect of choice set s by individual i. $u^{(3)}_{i}$ marks a random effect at individual level. The full structural model for multilevel mixed effects regression can be presented as:

$$y^*_{csi} = \beta_0 + \beta_1 \times costs_{csi} + \beta_2 \times dismantling\ costs_{csi} + \beta_3 \times efficiency_{csi} + \beta_4 \times recyclability_{csi} + v^{(2)}_{si} + u^{(3)}_{i} + \epsilon_{csi} \quad (10)$$

Since the dependent variable only indicates the choice (of a stets varying alternative), the fixed or random effects are expected to be trivial. To investigate if random or fixed effects at the individual and choice set level are present, an empty 3-level

[33] The utility that is obtained from the alternative.

random effects and (individual) fixed effects models can be specified. The empty model consists only of the dependent variable and the fixed or random effect. As shown in Table 15, random effect variance coefficients at the level of individuals and choice sets are converging towards zero in an empty model; the values of Pseudo-R^2 in the fixed effect models are close to 0. The results indicate that, the fixed and random effects are basically negligible.

Table 15: Empty random and fixed effect models

	Germany	**Switzerland**	**Germany**	**Switzerland**
	3-lvl.-RE	3-lvl.-RE	FE	FE
Individual RE (var.)	2.78e-33	1.85e-32	.	.
Choice set RE (var.)	1.95e-35	2.88e-35	.	.
Individual FE	.	.	Yes	Yes
Pseudo-R^2	.	.	0.001	0.001

Dependent variable is a choice; $y = 1$ if the alternative n has been choosen; otherwise $y = 0$.
Respective models consist only of fixed and random effects.
Random effects are indicated as variance.

This result is not surprising given the experimental design - the alternatives of the choice set are generic and differ only in observed attributes. Since the dependent variable indicates the choice and alternatives vary between respondents and choice sets, choice sets and individuals can not have any systematic influence in the model. Nevertheless, from a theoretical point of view, it should be considered in the course of estimation. For this reason, the model is estimated as standard logistic regression, but also, for verification and robustness purposes, as fixed and random effects model.

In the course of the experiment, the dismantling costs and costs for the composite thermal insulation system were presented in Euros. Since Germany and Switzerland are two different economies with different currencies, the comparison of marginals willingness to pay in Euros would be not very meaningful, as one Euro has a different purchasing power in Switzerland than it does in Germany. To ensure comparability, the euro prices are transformed into purchasing power parity adjusted international Dollars in the following way:

$$\pi^i = \frac{p_{ij}}{PPPj} \tag{11}$$

π^i denotes the (purchasing power adjusted) price in international Dollar. p_{ij} is the price for good i in country j in national currency, whereas PPP marks the purchasing power parity adjustment factor of the country j. The purchasing power parity adjustment factor in 2019 (2010 as a basis) is 0.742 in Germany and 1.155 in Switzerland (OECD, 2020). Since PPP is measured in terms of national currency per US dollar, the Euro price in Switzerland must be transformed into national price. The average annual exchange rate between the Euro and Swiss Frank was 1,112 in 2019 (European Central Bank, 2020). Thus, the price adjusted for purchasing power for Germany in international Dollars is:

$$\pi^i_{Germany} = \frac{P_{Euro}}{0.742} \tag{12}$$

and for Switzerland:

$$\pi^i_{Switzerland} = \frac{P_{Euro} \times 1.112}{1.155} \tag{13}$$

The conversion of the costs for a square meter of thermal insulation composite system and deconstruction costs took place before the regression. This transformation ensures that cost-related attributes are linked to the same purchasing power in Germany and Switzerland, thereby making the marginal willingness to pay to be calculated interpretable.

3.4.2. Results

The empirical model is applied to test the hypothesis whether the students in Switzerland have higher willingness to pay for sustainability-related attributes (H_1). For this reason, the models have been estimated separately for Germany and Switzerland. Regressions results for the models with experimental parameters are shown in Table 16. Models (1) and (2) are classic logistic regressions with clustered standard errors on individual level. Models (3) and (4) are individual fixed effects models, whereas models (5)-(8) are multi-level mixed effects models with random effects on the individual and choice set level. As expected, there are only minor differences in odds ratio estimates, regardless of whether the model was estimated as a classical regression, fixed or mixed effects model. As observed in models (5) and (7), random effects are negligible in the multi-level estimates for Germany. Although small individual level random effects are present in the estimates for Switzerland in (6) and (8), the reported likelihood-ratio test indicates that there is not enough variability between individuals to favour a mixed-effects ordered logistic regression over a standard ordered logistic regression. The results of Pregibon-Tukey test in a fixed effects model for Germany may indicate that the model does not fit well into the data. For the calculation of the marginal willingness to pay for sustainability-related attributes, a classical logistic regression model will be used. This decision is based on several factors. Firstly, due to the experimental design, no systematic influences of choice set and individuals can be exerted on the dependent variable, since the latter only indicates the choice of alternative and the alternative results from the random variation of the experimental parameters. Secondly, there is no empirically robust evidence in the estimated models (Table 15 and Table 16) that could indicate the existence of systematic influence of the choice set and individual level. The ultimate model specification used for further analysis is the logistic regression model with cluster robust standard errors at the individual level, as estimated in Table 16, columns (1) and (2). Thus the fixed and mixed effects models act as a robustness check.

The influence of experimental parameters on the probability of choosing a variant of a thermal insulation composite system proves to be highly significant in most cases. Only in the model (2) for Switzerland the effect dismantling costs appears to be insignificant. As expected, sustainability-related attributes have a positive effect on the probability of choosing an alternative. In contrast, cost-related attributes have a negative influence. Given the present model specification there is no evidence that models (1) and (2) are misspecified or do not fit into the data.

Table 16: Regressions results: choice of an external thermal insulation system

Variables				**Odds ratios**				
	DEU (1) Logit	CHE (2) Logit	DEU (3) FE	CHE (4) FE	DEU (5) 2-Lvl.-ME	CHE (6) 2-lvl-ME	DEU (7) 3-lvl-ME	CHE (8) 3-lvl-ME
Costs (PPP-adj.)	0.996***	0.995***	0.996***	0.994***	0.996***	0.995***	0.996***	0.995***
	(0.000)	(0.001)	(0.000)	(0.001)	(0.000)	(0.001)	(0.000)	(0.001)
Dismantling costs (PPP-adj.)	0.997***	0.998	0.997***	0.997	0.997	0.997***	0.997	0.997
	(0.000)	(0.002)	(0.000)	(0.002)	(0.000)	(0.002)	(0.000)	(0.002)
Recyclability	1.022***	1.024***	1.026***	1.031***	1.022***	1.025***	1.022***	1.025***
	(0.001)	(0.005)	(0.001)	(0.006)	(0.001)	(0.006)	(0.001)	(0.006)
Efficiency								
C	1.927***	1.810	1.972***	2.796*	1.927***	1.893	1.927***	1.894
	(0.209)	(0.787)	(0.223)	(1.356)	(0.208)	(0.847)	(0.208)	(0.847)
B	4.988***	3.389***	5.507***	4.411***	4.988***	3.521**	4.988***	3.521**
	(0.566)	(1.353)	(0.605)	(2.022)	(0.513)	-1.504	(0.513)	(1.504)
A	6.508***	6.430***	8.117***	12.45***	6.508***	6.965***	6.507***	6.964***
	(0.740)	(2.850)	(0.902)	(5.953)	(0.666)	(3.156)	(0.666)	(3.156)
Clustered SE (individual level)	Yes	Yes	.	.	.	.	.	.
Individual FE	.	.	Yes	Yes	.	.	.	.
Individual RE (var.)	.	.	.	.	1.11e-33	0.080	1.53e-34	0.080
					(4.25e-18)	(0.201)	(2.45e-18)	(0.201)
Choice set RE (var.)	.	.	.	.			3.96e-34	1.26e-37
							(2.35e-18)	(2.06e-19)
Observations	5,535	351	4,869	297	5535	351	5535	351
P> χ^2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
LR test vs. logit	.	.	.	.		0.331		0.331
Pseudo- R^2	0.160	0.154	.	.	.			
AIC	5625.216	365.595	3630.153	226.519	5625.216	367.404	5625.216	367.404
BIC	5671.548	392.621	3669.097	248.682	5671.548	398.290	5671.548	398.290
Pregibon-Tukey	0.520	0.823	0.021	0.974	.	.	.	.
Hosmer-Lemeshow	0.5328	0.909	.	.	.	.	.	.

*Standard errors in parentheses; *p<0.05, **p<0.01, ***p<0.001.*
Dependent variable is a choice; $y = 1$ if the alternative n has been chosen; otherwise $y = 0$.

Predictive margins can be calculated from the odds ratios for each dependent variable. These indicate how much the probability of choosing an alternative is changed if the dependent variable changes by one unit or one category. The ratio of two parameters of an estimation corresponds to the marginal rate of substitution (MRS). MRS indicates by how much a variable product property must be changed to compensate for the change of one unit in another property. Thus, the marginal rate of substitution can be formalised as follows:

$$MRS = \frac{\frac{\partial y}{\partial x_i}}{\frac{\partial y}{\partial x_p}} \tag{14}$$

The numerator denotes the marginal utility of a sustainability-related attribute and the denominator indicates the marginal utility of a cost-related attribute. The predictive margins (marginal utilities) for models (1) and (2) have been estimated separately for Germany and Switzerland. The results are shown in Table 17. If there is a cost-related attribute in the denominator (equation 14), the marginal rate of substitution corresponds to the marginal willingness to pay for the attribute in numerator. Thus, willingness-to-pay has been calculated for recyclability and different efficiency classes of buildings that can be implemented with the external thermal insulation composite system. Under otherwise constant conditions, the willingness to pay for increasing the recyclability of external thermal insulation composite system by 1 % is 6.201 purchasing power adjusted Dollars in Germany and 4.415 in Switzerland. The willingness to pay for a composite thermal insulation system that achieves energy efficiency class A for the building is 516.124 purchasing power adjusted Dollars per square meter in Germany and is 346.760 in Switzerland. If, when calculating the willingness to pay, the future dismantling costs are used as denominator, it is striking that students in Switzerland then have higher willingness to pay for sustainability-related attributes than students in Germany. Students in Switzerland are willing to spend 9.717 international dollars of future dismantling costs in order to increase the recyclability of the thermal insulation composite system by 1 %. However, the dismantling costs represent an unreliable basis for calculating willingness to pay, as the estimated coefficient for Switzerland is not significant. For the reason above, the interpretation of the willingness to pay in terms of future dismantling costs should be dispensed with. When assessing the research hypothesis, only the present direct costs are taken into account - thus, the results indicate that the hypothesis (H_1) that the students in Switzerland are characterised by higher willingness to pay for sustainability-related attributes can be rejected.

Table 17: Marginal utilities and willingness to pay for sustainability-related attributes

Variables	$\partial y/\partial x$	
	Germany	Switzerland
Costs (PPP-adjusted)	-0.0006023***	-0.0008969***
	(0.0000373)	(0.000208)
Dismantling costs (PPP-adjusted)	-0.0004035***	-0.0004075
	(0.000716)	(0.0003293)
Recyclability	0.0037346***	0.0039597***
	(0.0001908)	(0.0007426)
Efficiency		
C	0.0835471***	0.0762478
	(0.0133878)	(0.0543788)
B	0.2552609***	0.1823693***
	(0.0163403)	(0.0572433)
A	0.3108617***	0.3110089***
	(0.0168739)	(0.0691737)
Observations	5535	297
MWTP **(ppp-adjusted US-Dollar)**		
$MWTP_{recyclability/costs}$	6.201	4.415
$MWTP^{A}_{efficiency/costs}$	516,124	346.760
$MWTP^{B}_{efficiency/costs}$	423.810	203.333
$MWTP^{C}_{efficiency/costs}$	138.713	85.012
$MWTP_{recyclability/dis.costs}$	9.266	9.717
$MWTP^{A}_{efficiency/dis.costs}$	770.413	763.212
$MWTP^{B}_{efficiency/dis.costs}$	632.617	447.532
$MWTP^{C}_{efficiency/dis.costs}$	207.057	187.111

*Standard errors in parentheses; *p<0.05, **p<0.01, ***p<0.001.*
Dependent variable is a choice; $y = 1$ if the alternative n has been chosen; otherwise $y = 0$.

3.5 Conclusion

This chapter investigated whether students of architecture, civil and environmental engineering in Switzerland are characterised by a higher willingness to pay for sustainability-related attributes. Furthermore, it was examined whether sustainability-related study contents are treated to a higher degree in Switzerland than in Germany and whether sustainability-related theoretical and practical contents of the study have a positive impact on perceived substitutability of recycled concrete in underground and building construction. For this purpose a combined item-based and discrete choice survey of students of architecture, civil and environmental engineering in Germany and Switzerland was carried out.

Results indicate that sustainability and recycled concrete related contents are covered to a higher extent in Switzerland. Nevertheless, findings from the empirical model based on survey data indicate that students in Switzerland have a lower willingness to pay for sustainability-related attributes. It can be observed that the perceived coverage of the sustainability-related theoretical and practical contents has a strong influence on the perceived substitutability of recycled concrete in underground and building construction. The perceived substitutability of r-concrete in both underground and building construction depends to a large extent on the university affiliation of the respondents.

The present study contributes to understanding the reasons for the restrained use of r-concrete in the construction sector in Germany. In context of promoting sustainable construction, the results point to the need to increase the coverage of theoretical and practical sustainability and r-concrete related study contents. In view of the outstanding importance of the teaching staff in university education and thus the formulation of the opinion on the substitutability of recycled concrete, the teachers in particular shall be sensitised to the application possibilities and advantages of r-concrete.

4 Barriers to the use of recycled concrete from the perspective of architects and engineers and attitude towards sustainability

In previous chapters, various questions have been investigated that are relevant for the use of recycled concrete in building construction. The perspective of the executing companies and the students of architecture, civil and environmental engineering was taken. A relevant group of actors has not yet been considered - architects and engineers in Germany and Switzerland. However, with regard to the use of recycled concrete in building construction, they play one of the central roles, as architects and engineers plan and supervise the construction projects and therefore can influence the choice of building materials to a great extent. For the development of an empirically based economic policy recommendation to increase the use of recycled concrete, the perspective of all relevant actors in the value chain and thus that of the architects and engineers must necessarily be considered.

For this reason, the study conducted in present chapter aims to analyse the obstacles to the use of r-concrete in building construction from the perspective of architects and engineers in Germany and Switzerland. Furthermore, it is investigated whether architects and engineers in Germany and Switzerland are characterised by different attitudes towards sustainability, and which economic policy measures can increase the use of recycled concrete in building construction. In particular, the following questions and resulting hypotheses are examined:

- What are the main obstacles in the use of recycled concrete in Germany? Are there differences in the perception of the obstacles between Germany and Switzerland?
  - H_1: The relevance of barriers to the use of recycled concrete is perceived differently in Germany and Switzerland.
- Are there differences in attitude towards sustainability between architects and engineers in Germany and Switzerland? If architects and engineers in Switzerland are more sustainable, then a higher marginal willingness to pay for sustainability-related attributes should be observable. Another question in this context is whether there are differences in attitudes towards sustainability between current and future architects and engineers.[34]
  - H_2: The architects and engineers in Switzerland are characterised by higher willingness to pay for sustainability-related attributes.

[34] The future architects and engineers refer to students of architecture, construction and environmental engineering.

- H_3: Current and future architects and engineers are characterised by different willingness to pay for sustainability-related attributes.

- Which measures are suitable to increase the use of recycled concrete in building construction? What factors play a role here?
  - H_4: The consideration of sustainability (use of recycled materials) as a further award criterion in the public tender increases the likelihood that the engineers and architects plan to use r-concrete for the construction project.
  - H_5: The recognition of recycled materials usage in the DGNB-label increases the likelihood that the engineers and architects plan to use r-concrete for the construction project.
  - H_6: Increase in maximal permissible proportion of recycled aggregates in concrete increases the likelihood that the engineers and architects plan to use r-concrete for the construction project.
  - H_7: Additional costs through the usage of r-concrete decreases the likelihood that the engineers and architects plan to use r-concrete for the construction project.
  - H_8: With increasing city size the likelihood increases that the engineers and architects plan to use r-concrete for the construction project.[35]

To answer the research questions and to test the defined hypotheses, a combined item-based, discrete choice and factorial survey of architects and engineers in Germany and Switzerland was carried out. At the beginning of the chapter, the structure of the questionnaire as well as the methodological foundations of discrete choice experiment and factorial survey are described in detail. Subsequently, empirical models are specified with which the data from the discrete choice experiment and the factorial survey are analysed against the background of the defined hypotheses. After the final model specification, the research results are presented and tested for robustness. In the last section of the chapter the research questions, methodologies and central results are briefly summarised.

4.1 Research design and data collection

In order to answer research questions and to examine stated hypotheses, an online survey was conducted among architects and construction engineers in Germany and

[35]Whether r-concrete can be produced and used in building construction depends primarily on whether there is a regional supply of recycled aggregates. It is plausible to assume that larger cities are characterised by higher quantities of construction waste and thus potentially higher supply of recycled aggregates.

Switzerland. The questionnaire starts with general information on data protection requiring consent. In order to ensure that the questionnaire is only answered by those architects and engineers that also have appropriate expertise in the field of recycled concrete, the question whether it is known what r-concrete is about was asked before the actual survey began. In case of a negative answer, the survey was terminated. The first survey block consists of general questions on socio-demographic characteristics and individual attitude towards sustainability. This is followed by the discrete choice experiment and the factorial survey. In the last part of the survey, questions were asked about the perception of the barriers to the use and perceived substitutability of recycled concrete. The survey transcript can be found in Table A5 in Appendix.

In the context of the present study, the marginal willingness to pay for sustainability-related attributes is determined by means of a discrete choice experiment and compared between architects and engineers in Germany and Switzerland. The discrete choice experiment, in which the participants of the survey took part, is identical to the experiment that was carried out in the student survey. The description of the situation, attributes, and the characteristics of the attributes have not been changed. This ensures, that the willingness to pay for sustainability-related attributes can be compared not only between architects and engineers in Germany and Switzerland, but also between future and current architects or engineers. A detailed description of the discrete choice experiment can be found in the previous chapter.

In order to investigate possible economic policy measures to increase the use of recycled concrete in building construction, the factorial survey was carried out after the discrete choice experiment. In factorial surveys, hypothetical object or situation descriptions are presented to the respondents for evaluation, in which characteristics are experimentally varied in their manifestations. In this way the influence of different dimensions on the respondent's decision can be determined (Rossi & Anderson, 1982).

In the factorial survey, the following economic policy measures were examined with regard to their effectiveness in increasing the use of recycled concrete in building construction - recognition of recycled materials by DGNB-label, consideration of sustainability as a further award criterion in the public tender and the maximum amount of recycled granulate that can be added into concrete. In addition, city size and additional costs resulting from the use of r-concrete were considered as potential influencing factors. The fictitious situation, which has been presented to the interviewees for evaluation, is shown in Figure 17[36]. The characteristics of

[36]In order to minimise individual-specific influences on the decision, all vignettes were graphically anchored by the presentation of an exemplary student residence as shown in Figure 17.

dimensions considered were randomly[37] varied across respondents and vignettes - the attributes as well as the attribute levels are shown in Table 18. Three vignettes were presented to each interviewee for assessment. The *vignette universe* is calculated as the Cartesian product of the characteristics of all dimensions and counts 528 possible combinations ($2 \times 2 \times 4 \times 11 \times 3$). In view of the relatively large number of vignette responses (≈ 2100)[38], it can be reasonably assumed that the entire vignette universe is fully exhausted in the factorial survey.

Table 18: Vignette attributes and levels factorial survey

Attributes	Levels
DGNB-label	Yes, No
Sustainability as further award criterion in public tender	Yes, No
Maximal proportion of recycled aggregates in concrete	20, 40, 60, 80 %
Additional cost through usage of r-concrete	0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100 %
Location	Rural community, middle-sized town, big city

For all survey questions the Likert scales with an opt-out category (*I cannot judge the item*) were used. In order to increase the comprehensibility of the answer categories and to avoid undesired distortions, all question scales were fully verbalised (Krosnick & Fabrigar, 1997; Toepoel & Dillman, 2011) and anchored graphically (Figure 17). To prevent the tendency towards the middle (Kalton et al., 1980; Krosnick & Fabrigar, 1997), the middle category was used only in exceptional cases.

The survey is aimed at all architects and engineers in Germany and Switzerland, irrespective of the type of employment, specialisation or organisation of the company. The online questionnaire was implemented using the SoSci Survey (Leiner, 2019) and made available to the participants at *www.soscisurvey.de*. The invitation to take part in the survey was sent by e-mail to 35919 architects and engineers in Germany and Switzerland in January 2020 and could be answered within one month. The e-mail addresses were collected manually from publicly available sources such as the German Federal Chambers of Architects and the Swiss Association of Engineers and Architects (SIA).

[37] Sample draw with replacement: for each interviewee, a characteristic of the respective dimension was drawn at random from the urn of all possible characteristics and then "put back" into the urn. Thus the probability that the respondent will be shown a certain characteristic of a certain dimension is $\frac{1}{d}$. d denotes the number of all possible characteristics of a respective dimension.

[38] About 700 participants with 3 vignettes each.

Figure 17: Exemplary vignette

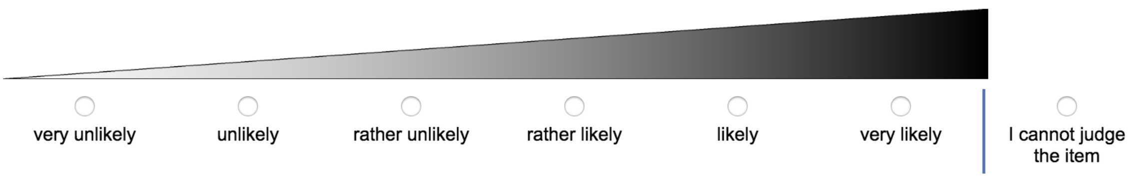
Source: Grahamalonian at English Wikipedia. / CC BY-SA (http://creativecommons.org/licenses/by-sa/3.0/)

Hypothetical situation is presented below. We are interested in how you would act in view of this constellation.

Note: Please read the situation description carefully and answer the question bellow.

> *You are becoming aware of a comprehensive public tender for the construction of a student housing complex in a rural community. The tender explicitly mentions that when deciding on the award, the aspect of sustainability (use of recycled materials) is considered as a further criterion in addition to the price. The use of recycled aggregates is not recognised in the DGNB-label. The maximum permissible proportion of recycled aggregates in concrete is 20 %. Compared to conventional concrete, the use of recycled concrete results in additional costs of 100 %.*

How likely is it that you plan to use recycled concrete for this construction project?



4.2 Descriptive analysis

The aim of the present section is to identify the central obstacles to the use of recycled concrete from the point of view of engineers and architects in Germany and Switzerland. In particular, the hypothesis will be tested whether the possible obstacles to the use r-concrete are perceived differently in Germany and Switzerland (H_1).

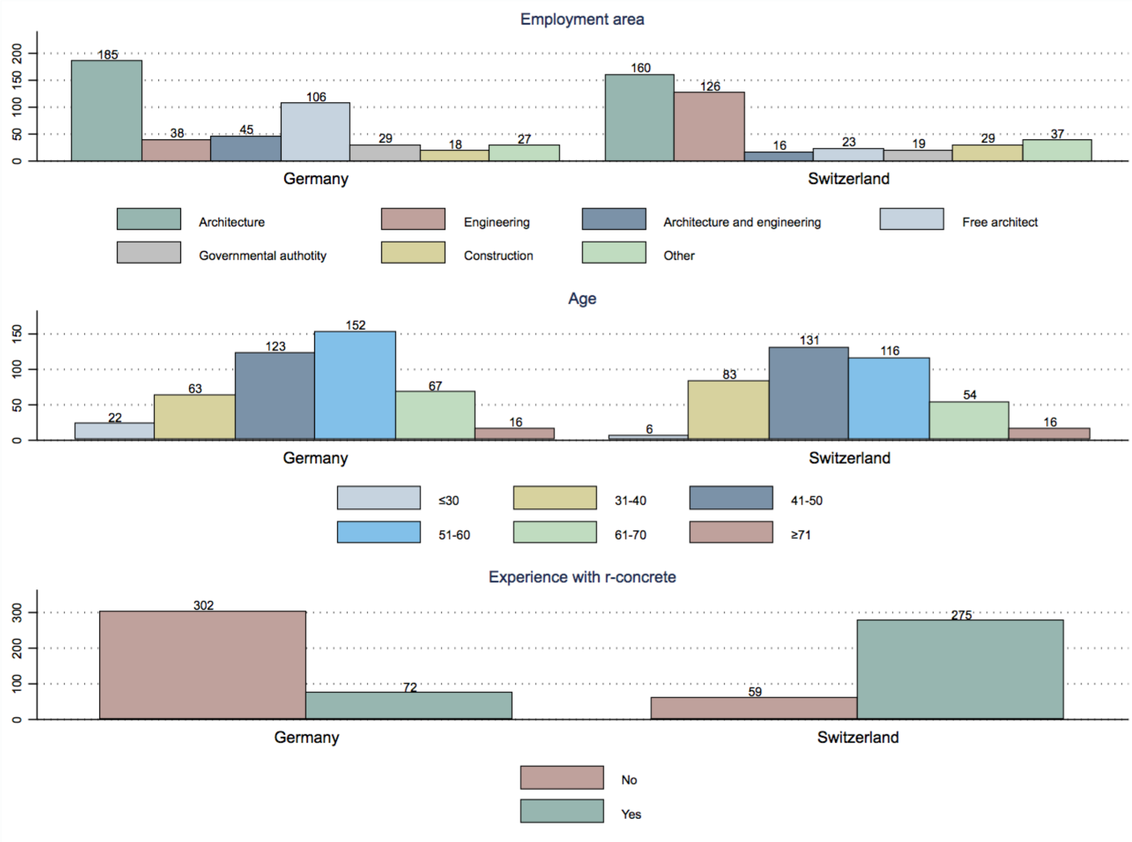
In 2019, 12698 architects, engineers and urban planners were registered at the Swiss Chamber of Engineers and Architects (SIA, 2020) and 135111 at the German Federal Chamber of Architects (BAK, 2020). Due to the limited public availability of e-mail addresses, a total of 35919 architects and engineers in Germany and Switzerland could be invited to participate in the study - 1362 of them accepted the invitation and took part in the survey.[39] These are questionnaires that have been started. Since it was possible to skip questions during the survey, the response rate cannot be reported - the number of responses varies across respective questions.

The question on geographical affiliation was answered by a total of 860 study participants - 449 of whom are active in Germany and 411 in Switzerland. The educational background of the respondents is very similar in both countries. The majority have a master's degree or diploma in civil engineering or architecture - 387 in Germany and 318 in Switzerland. The distribution of further variables by country is illustrated in Figure 18. Most of the respondents are employed in an architectural, an engineering or an integrated architectural and engineering office - 266 in Germany and 302 in Switzerland. The rest of the participants is distributed among freelance architects, government institutions, construction companies and other occupational groups. The age structure is very homogeneous in both countries - most of the respondents are between 41 and 60 years old. Regarding the existing experience with r-concrete, there is a strong difference between the two countries. 81 % of the architects and engineers in Germany stated to have no previous experience with recycled concrete - in Switzerland, by contrast, about 18 %. The differences were tested with the two-sample t-test and proved to be significant ($p = 0.000$). Already in Chapter 1 of this work the geographical distribution of the already existing experience with recycled concrete was illustrated in Figure 3. There it is clearly evident that while in most cantons in Switzerland the percentage of architects and engineers who have experience with r-concrete is between 80 and 100 %, in most German federal states it is between 10 and 30 %. In Germany, the federal states of Rhineland-Palatinate, Bremen, Lower Saxony and Hamburg stand out particularly negatively. There, the proportion of architects who have experience with r-concrete is at most 10 %. The "pioneers" in Germany are the federal states of Hesse and

[39] The number refers to the respondents who stated that they know what r-concrete is about.

Brandenburg, where between 40 and 50 % of the architects and engineers surveyed stated to have experience with recycled concrete.

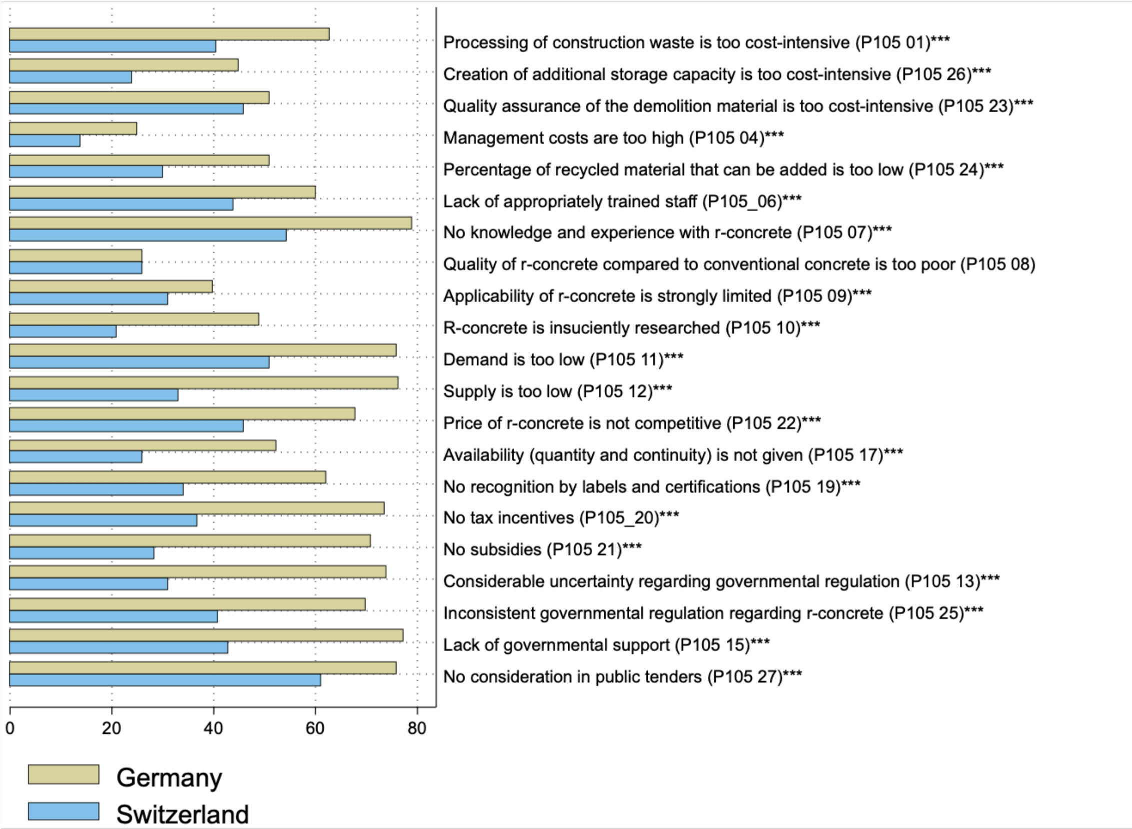
Figure 18: Experience with r-concrete, employment area and age distribution across countries



Within the scope of the survey, the participants were asked to evaluate the obstacles to the use of recycled concrete in building construction. The scale chosen was a controller that could take the values from 1 (*not relevant at all*) to 100 (*very relevant*). The evaluation results of the barriers to the use of r-concrete in construction for Germany and Switzerland are shown in Figure 19. The main obstacles from the point of view of architects and engineers in Germany are the lack of knowledge and experience with recycled concrete, no tax incentives, no consideration in public tenders, absence of governmental support, inconsistent and uncertain governmental regulation as well as low supply and demand.

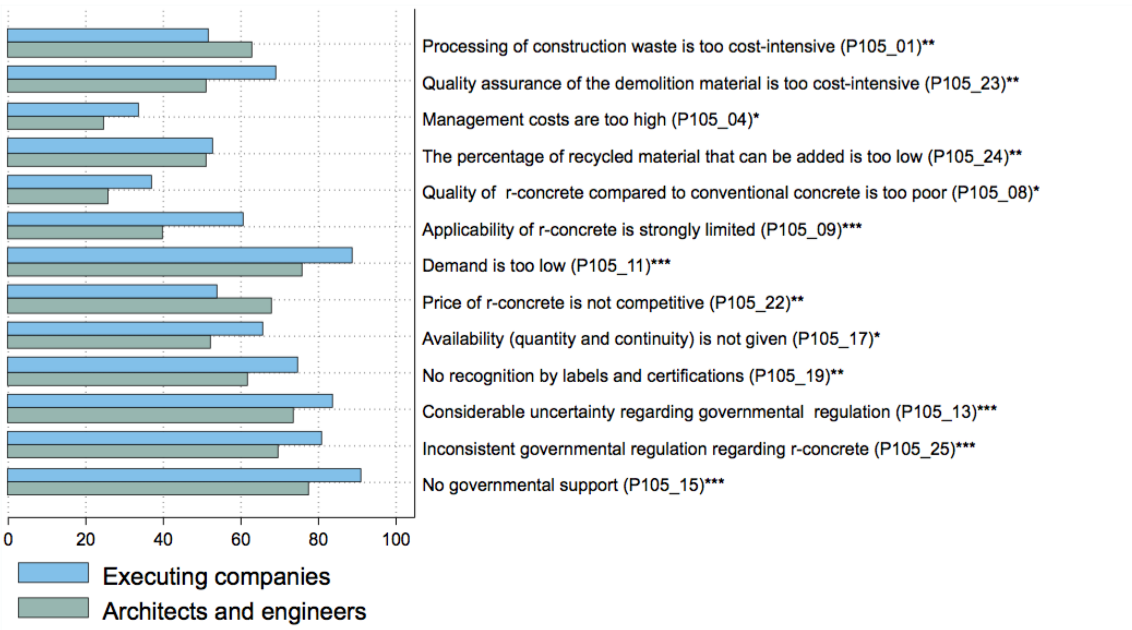
It is striking that the obstacles to the use of r-concrete are systematically assessed differently in Germany and Switzerland. Firstly, the differences are highly significant in most cases. Secondly, in Germany, the relevance of all barriers has been systematically rated higher. Thus, the hypothesis (H_1) that obstacles to the use r-concrete are perceived differently in Germany and Switzerland can be confirmed. The greatest differences in the perception of potential barriers to the use of r-concrete in construction are mainly policy-related factors such as inconsistent and uncertain regulation, lack of government support, absence of tax incentives and subsidies as

Figure 19: Median comparison of barriers to the use of recycled concrete from the perspective of architects and engineers in Germany and Switzerland



Non-parametric equality of medians test.
**p<0.05, **p <0.01, ***p <0.001.*
The results of the survey presented in Chapter 2 have been used here.

Figure 20: Median comparison of barriers to the use of recycled concrete from the perspective of executing companies and architects or engineers



Non-parametric equality of medians test.
**p <0.05, **p<0.01, ***p <0.001; only significant results are shown.*
The results of the survey presented in Chapter 2 have been used her.
Refers to data for Germany and Switzerland.

Table 19: Main barriers to the use of recycled concrete from the perspective of architects, engineers and executing companies in Germany

	Architects and engineers		**Executing companies**	
Rank	**Barriers**	**Median**	**Barriers**	**Median**
1.	No knowledge and experience with r-concrete (P105_07)	79	Lack of governmental support (t202_15)	91
2.	Lack of governmental support (P105_15)	77.5	Demand is too low (t202_11)	89
3.	Supply is too low (P105_12)	76.5	Considerable uncertainty regarding governmental regulation (t202_13)	84
4.	Demand is too low (P105_11)	76	No subsidies (t202_21)	81
5.	No consideration in public tenders (P105_27)	76	Inconsistent governmental regulation regarding r-concrete (t202_25)	81
6.	Considerable uncertainty regarding governmental regulation (P105_13)	74	Supply is too low (t202_12)	81
7.	No tax incentives (P105_20)	73.5	No tax incentives (t202_20)	76,5
8.	No subsidies (P105_21)	71	No knowledge and experience with r-concrete (t202_07)	76
9.	Inconsistent governmental regulation regarding r-concrete (P105_25)	70	No recognition by labels and certifications (t202_19)	75
10.	Price of r-concrete is not competitive (P105_22)	68	Quality assurance of the demolition material is too cost-intensive (t202_23)	69

Ranked by medians.
The results of the survey presented in Chapter 2 have been used here.

well as lacking recognition of r-concrete by labels and certificates.

The perceived relevance of the obstacles to the use of r-concrete in building construction was evaluated both in the survey of architects and engineers as well as in the survey of the executing companies presented in Chapter 2. Therefore, the assessment of individual obstacles can be compared. The evaluation of individual obstacles by architects and engineers and executing companies can be illustrated by Figure 20. It is clearly evident that in most cases the obstacles to the use of recycled concrete are rated more negatively by the executing companies - differences are mostly statistically significant. In Table 19 the obstacles to the use of recycled concrete are ordered by median and presented separately for architects and engineers as well as executing companies in Germany. It is observable that most of the obstacles were rated similarly in terms of their relevance and the 10 highest rated obstacles are in most cases same for both groups.[40]

4.3 Marginal willingness to pay for sustainability-related attributes by architects and engineers

The aim of the present section is to test the hypothesis whether architects and engineers in Switzerland are characterised by a higher willingness to pay for

[40] A complete comparison of the assessment of obstacles to the use of r-concrete between architects, engineers and contractors in Germany is presented in Table A7 in Appendix. The comparison of obstacles to the use of r-concrete and other variables of the survey for architects and engineers in Germany and Switzerland is shown in Table A6 in Appendix.

sustainability-related attributes than architects and engineers in Germany. In addition, it will be examined whether there are differences between current and future architects and engineers. In particular, the hypothesis H_2 and H_3 will be investigated. The data basis for the following empirical model is the discrete choice experiment, which was carried out within the framework of the survey of architects and engineers in Germany and Switzerland. In addition, the data from the discrete choice experiment from previous chapter will be used to compare willingness to pay of actual and future architects and engineers.

4.3.1. Empirical model

Discrete choice experiment, which was carried out as part of the survey of architects and engineers in Germany and Switzerland, is identical to the experiment conducted in the student survey. For this reason, the same empirical strategy is chosen for estimating the marginal willingness to pay for sustainability-related attributes among architects and engineers. Thus, the model is estimated as classical logistic regression, logistic regression with a fixed effects at the individual level and as a multi-level model with random effects at the higher levels. A detailed description of the empirical procedure for discrete choice experiment can be found in Chapter 3. Analogous to the previous chapter, the structural model for the fixed effects regression can be presented as follows:

$$y^*_{csi} = \beta_1 \times costs_{csi} + \beta_2 \times dismantling\ costs_{csi} + \beta_3 \times efficiency_{csi} + \beta_4 \times recyclability_{csi} + a_i + \epsilon_{csi} \quad (15)$$

where y^*_{csi} is latent continuous variable underlying the choice of the product alternative c in the choice set s by the individual i. a_i denotes individual fixed effect; ϵ_{csi} indicates an error term of individual i for choice set s and choice c. The structural model for the multilevel mixed effects regression can be presented as follows:

$$y^*_{csi} = \beta_0 + \beta_1 \times costs_{csi} + \beta_2 \times dismantling\ costs_{csi} + \beta_3 \times efficiency_{csi} + \beta_4 \times recyclability_{csi} + v^{(2)}_{si} + u^{(3)}_{i} + \epsilon_{csi} \quad (16)$$

where y^*_{csi} is latent continuous variable underlying the choice of the product alternative c (level 1) in the choice set s (level 2) by the individual i (level 3). β_n indicates the vector of regression parameters for the choice specific covariates. $v^{(2)}_{si}$ denotes the random effect of choice set s by individual i. $u^{(3)}_{i}$ marks a random effect at individual level.

4.3.2. Results

Table 20: Regressions results: choice of thermal insulation system (architects and engineers)

Variables	**Odds ratios**							
	DEU	CHE	DEU	CHE	DEU	CHE	DEU	CHE
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Logit	Logit	FE	FE	2-Lvl.-ME	2-lvl-ME	3-lvl-ME	3-lvl-ME
Costs (PPP-adj.)	0.996***	0.995***	0.996***	0.995***	0.996***	0.995***	0.996***	0.995***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.002)	(0.000)	(0.000)	(0.000)
Dismantling costs (PPP-adj.)	0.997***	0.997***	0.998***	0.997***	0.997***	0.997***	0.997***	0.997***
	(0.000)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Recyclability	1.031***	1.031***	1.036***	1.032***	1.031***	1.031***	1.031***	1.031***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Efficiency								
C	1.988***	2.043	2.074***	2.116***	1.989***	2.043***	1.989***	2.043***
	(0.251)	(0.260)	(0.268)	(0.280)	(0.244)	(0.261)	(0.244)	(0.261)
B	3.862***	4.474***	4.305***	4.943***	3.862***	4.474***	3.862***	4.473***
	(0.487)	(0.592)	(0.542)	(0.643)	(0.455)	(0.550)	(0.455)	(0.550)
A	5.832***	7.211***	7.244***	8.60***	5.833***	7.212***	5.833***	7.212***
	(0.759)	(0.945)	(0.939)	(1.131)	(0.670)	(0.893)	(0.697)	(0.893)
Clustered SE (individual level)	Yes	Yes	.	.	.	.	.	.
Individual FE	.	.	Yes	Yes	.	.	.	.
Individual RE (var.)	.	.	.	.	3.54e-34	5.04e-34	3.92e-34	2.66e-39
					(1.76e-18)	(2.42e-18)	(4.46e-18)	(1.67e-21)
Choice set RE (var.)	.	.	.	.			9.58e-35	1.58e-34
							(6.08e-18)	(2.76e-18)
Observations	4023	3699	3690	3519	4023	3699	4023	3699
P> χ^2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Pseudo -R^2	0.185	0.193	.	.	.			
AIC	4040.032	3730.939	2648.190	2532.529	4040.032	3730.939	4040.032	3730.939
BIC	4084.13	3774.450	2685.470	2569.524	4084.13	3774.45	4084.13	3774.45
Pregibon-Tukey	0.112	0.981	0.309	0.800	.	.	.	.
Hosmer-Lemeshow	0.4216	0.4564	.	.	.	.	.	.

*Standard errors in parentheses; *p<0.05, **p<0.01, ***p<0.001.*
Random effects are indicated as variance.
Dependent variable is a choice; $y = 1$ if the alternative n has been choosen; otherwise $y = 0$.

The empirical model is applied to test the hypothesis whether the respondents in Switzerland are characterised by more pronounced attitude towards sustainability and thus higher willingness to pay for sustainability-related attributes (H_2). The regression results are shown in Table 20. The models have been estimated separately for Germany and Switzerland. In order to ensure comparability, the cost-related parameters were converted into purchasing power-adjusted (international) Dollars before the estimate was calculated. Models (1) and (2) are conventional logistic regressions with cluster robust standard errors at the individual level. In models (3) and (4) the fixed effect at the individual level was introduced. Models (5) and

(6) are 2-level mixed effects models with random effects at the individual level. (7) and (8) are 3-level-mixed effects models with random effects on the choice set and individual level. There are no indications of possible misspecification in the estimated models. As argued in previous chapter, the standard logistic regression with clustered standard errors on the individual level can be considered as a starting point for further analysis. Thus, fixed and multi-level mixed effects models serve as a robustness check.

As expected, the cost-related attributes have a negative and the sustainability-related attributes have a positive influence on the selection probability of an alternative. The estimates turn out to be highly significant for all experimental parameters and are robust against changes in the model specification. The odds ratios shown in the models (1) and (2) can be converted into predictive margins for each dependent variable. In a discrete choice model the predictive margins correspond to the marginal utility of the respective attributes. The results of the conversion are shown in Table 21. The ratio of the marginal utility between a sustainability-related attribute and a cost-related attribute corresponds to the marginal willingness to pay for the sustainability-related attribute. Thus, the willingness to pay for an increase in the recyclability of the thermal insulation composite system by 1 % for architects and engineers ($MWTP_{recyclability/costs}$) is 8.056 PPP-adjusted Dollars in Germany and 6.544 in Switzerland. To increase recyclability by 1 %, architects and engineers in Germany are willing to spend 12,208 PPP-adjusted Dollars on future dismantling ($MWTP_{recyclability/dis.costs}$); in Switzerland, however, 11.090 international Dollars. In view of the present findings, the H_2 can be rejected - architects in Switzerland are characterised by a lower marginal willingness to pay for sustainability-related attributes. The decision to reject the hypothesis H_2 is based on an estimate of the marginal willingness to pay for sustainability-related attributes in terms of current costs. The two-sided hypothesis (H_3) that current and future architects and engineers are characterised by different willingness to pay for sustainability-related attributes can be confirmed. The willingness to pay for increasing recyclability ($MWTP_{recyclability/costs}$) is higher for architects and engineers than for students in both Germany and Switzerland. The willingness to pay for the energy efficiency class A of the building ($MWTP^{A}_{efficiency/costs}$) is lower by architects and engineers in Germany than for students, but higher among architects and engineers in Switzerland.

Table 21: Marginal utilities and willingness to pay for sustainability-related attributes

Variables	$\partial y/\partial x$			
	Architects and engineers		**Students**	
	Germany	Switzerland	Germany	Switzerland
Costs (PPP-adjusted)	-0.0005961***	-0.0007669***	-0.0006023***	-0.0008969***
	(0.0000425)	(0.0000628)	(0.0000373)	(0.000208)
Dismantling costs (PPP-adjusted)	-0.0004182***	-0.0004525***	-0.0004035***	-0.0004075
	(0.0000803)	(0.0001246)	(0.000716)	(0.0003293)
Recyclability	0.0051032***	0.0050183***	0.0037346***	0.0039597***
	(0.0002196)	(0.0002212)	(0.0001908)	(0.0007426)
Efficiency				
C	0.0939198***	0.0972453***	0.0835471***	0.0762478
	(0.0169493)	(0.0169185)	(0.0133878)	(0.0543788)
B	0.2094744***	0.2370827***	0.2552609***	0.1823693***
	(0.0184037)	(0.0192862)	(0.0163403)	(0.0572433)
A	0.2895805***	0.3326564***	0.3108617***	0.3110089***
	(0.0199619)	(0.0198315)	(0.0168739)	(0.0691737)
Observations	4023	3669	5535	297
$MWTP_{recyclability/costs}$	8.0561	6.544	6.201	4.415
$MWTP^{A}_{efficiency/costs}$	485.792	433.768	516,124	346.760
$MWTP^{B}_{efficiency/costs}$	351,408	309.144	423.810	203.333
$MWTP^{C}_{efficiency/costs}$	157.557	126.803	138.713	85.012
$MWTP_{recyclability/dis.costs}$	12.208	11.090	9.266	9.717
$MWTP^{A}_{efficiency/dis.costs}$	692.445	735.152	770.413	763.212
$MWTP^{B}_{efficiency/dis.costs}$	500.895	523.940	632.617	447.532
$MWTP^{C}_{efficiency/dis.costs}$	224.581	214.907	207.057	187.111

*Standard errors in parentheses; *p<0.05, **p<0.01, ***p<0.001.*
Dependent variable is a choice; $y = 1$ if the alternative n has been chosen; otherwise $y = 0$.
The estimates for students refer to the results from Chapter 3.

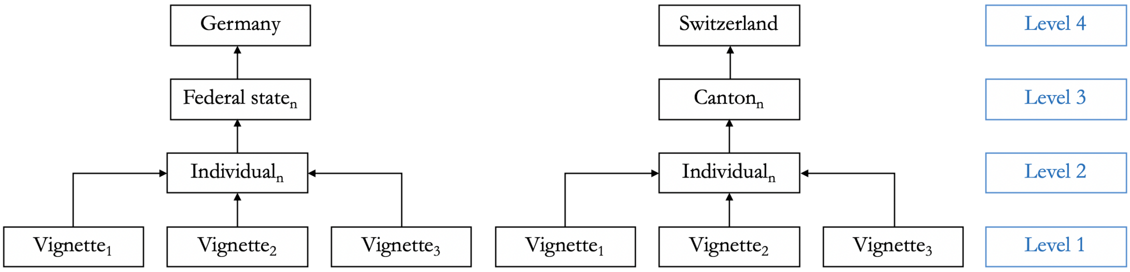
4.4 Economic policy measures to increase the use of recycled concrete in building construction

Within the framework of the following empirical model, the effectiveness of possible economic policy measures to increase the use of recycled concrete in building construction will be examined. In particular, the hypotheses H_5, H_6, H_7, H_8 and H_9 will be tested empirically. The data basis for the empirical model is the factorial survey, which was carried out within the framework of the survey of architects and engineers in Germany and Switzerland.

4.4.1. Empirical model

Since the likelihood of considering recycled concrete when planning a construction project is an ordinal scaled variable, the ordinal logistic regression can be considered as a starting point for further considerations. The structure of the data can be illustrated in Figure 21. The data is organised hierarchically since vignettes are nested in individuals; individuals are nested in federal states and federal states are nested in countries. Thus, the present data consists of 4 levels - since there could be unobserved heterogeneity at each level, the hierarchical nature of the data must

Figure 21: Structure of the data: survey of architects and engineers in Germany and Switzerland



Each individual was presented with 3 vignettes for evaluation.
The numbering of the vignettes refers to the placement of the vignette in the questionnaire.

necessarily be incorporated in the model.

For the analysis of hierarchically organised data, multilevel mixed effects models are particularly suitable (Searle et al., 1992; Agresti, 2010). The advantage of this approach is that the influence of individual invariant explanatory variables can be estimated, which would not be possible with a fixed effect estimator. In this context, the mixed effects model can be considered as a more efficient estimator, as covariates that vary both within and between groups can be estimated (Raudenbush & Bryk, 2002). Furthermore, in a hierarchical mixed effects model with random effects at the higher levels, the unobserved characteristics of all levels can be incorporated (Snijders & Bosker, 2012). In a fixed effects model, the results could be omitted if, for example, both the countries and the federal states were included in the model, since the federal states are nested in countries. Therefore, to account for the potential lack of independence within different levels and to estimate within and between group effects, the basic structural model for the ordinal logistic multilevel mixed effects regression can be specified and presented in the linear notation as follows:

$$y^*_{visc} = \mathbf{x}'_{visc}\boldsymbol{\beta} + \mathbf{z}'_{isc}\boldsymbol{\beta} + u^{(2)}_{isc} + v^{(3)}_{sc} + r^{(4)}_{c} + \epsilon_{visc} \tag{17}$$

where y^*_{visc} denotes the latent continuous variable underlying the willingness to plan the construction project using recycled concrete, given the vectors of the vignette specific (x_{visc}) and individual specific (z_{isc}) covariates. $u^{(2)}_{isc}$ indicates a random effect of an individual i in the federal state s and the country c. $v^{(3)}_{sc}$ denotes the random effect of federal state s nested in country c. $r^{(4)}_{c}$ marks a random effect at country level. The full structural model for the multilevel mixed effects ordinal logistic regression can be presented as follows:

$$\begin{split} y^*_{visc} = \beta_0 + \beta_1 \times label + \beta_2 \times tender + \beta_3 \times recyclate\ proportion + \beta_4 \times costs \\ + \beta_5 \times city\ size + \beta_{6 \ldots n} z_{isc} + u^{(2)}_{isc} + v^{(3)}_{sc} + r^{(4)}_{c} + \epsilon_{visc} \end{split} \tag{18}$$

The independent variable is the willingness to plan the construction project using recycled concrete. The main covariates are the recognition of the use of recycled materials by DGNB-label, consideration of recycled materials as a further award criterion in the public tender, maximum permissible proportion of recycled aggregates that can be added into concrete, additional costs arising from the use of r-concrete and the city size. Besides the presented experimental parameters, further individual-specific covariates z_{isc} will be added into the model.

4.4.2. Results

The estimation results are shown in Table 22. Five regression models with different specifications were estimated. In order to investigate whether a 4-level mixed effects model is a suitable estimation technique, an empty model was specified in (1). The empty model consists only of the dependent variable and random effects for each level. The reported likelihood-ratio test (LR test) shows that there is enough variability between individuals, federal states and countries to favour a mixed-effects ordered logistic regression over a standard ordered logistic regression. The second model is a reduced design that contains only experimental covariates, without any additional controls. In the third model the estimates were extended by other control variables that could influence the results and further covariates of interest. Regressions (1) to (3) are common pool models - the effects of the countries were taken into account, but the coefficients of the dependent variables are the same for both countries. Since it may be interesting to consider experimental parameters in the respective countries, model (3) was estimated separately for Germany (4) and Switzerland (5). Accordingly, models (4) and (5) are 3-level models, since country no longer needs to be incorporated as a level.

In the first model, variance of the random intercept has been estimated at the level of the countries, federal states and individuals. The highest variance is found at the individual level $(1,399)$; the lowest is observed at the state level (0.008). In all estimated models, the recognition of recycled materials through a label, consideration of sustainability in public tender and costs are significant. The size of the city as a decision parameter does not seem to matter, since no significant effect can be proven on the basis of the available data. Thus, in all estimated models the hypotheses H_4, H_5 and H_7 can be confirmed; H_8 cannot be confirmed in any of the estimated models. The hypothesis (H_6), that the maximum amount of recyclates that can be added to the concrete increases the willingness to plan a construction project using r-concrete cannot be confirmed in a model for Switzerland (5). This observation is not surprising, since in Switzerland concrete of lower exposure classes (up to XF1) may contain 100 % of recycled aggregate, whereas in these classes the maximum proportion in Germany is between 25 and 45 % (Hoffmann & Jakobs, 2010). However, in a common pool model (3) and the model for Germany (4) the hypothesis H_6

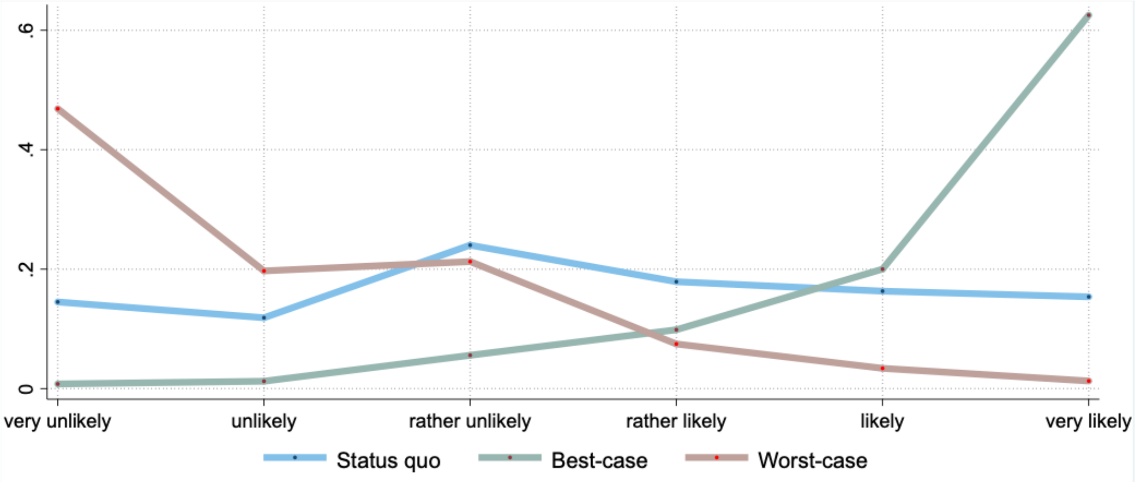
Table 22: Regression results: willingness to plan the construction project using r-concrete

Independent variables		**Odds ratios**			
		Common pool		**Germany**	**Switzerland**
	(1) 4-lvl.-ME	(2) 4-lvl.-ME	(3) 4-lvl.-ME	(4) 3-lvl.-ME	(5) 3-lvl.-ME
Label	.	1.967***	1.971***	2.242***	1.731***
		(0.186)	(0.207)	(0.345)	(0.250)
Sustainability in public tender	.	4.392***	4.576***	4.279***	4.835***
		(0.437)	(0.507)	(0.689)	(0.744)
Max. proportion of recyclates	.	1.006**	1.006*	1.009*	1.003
		(0.00213)	(0.00235)	(0.00347)	(0.003)
Costs	.	0.971***	0.970***	0.969***	0.971***
		(0.002)	(0.002)	(0.003)	(0.003)
City cize					
Middle-sized town	.	0.898	0.919	1.077	0.792
		(0.103)	(0.117)	(0.202)	(0.137)
Big city	.	0.907	0.907	0.950	0.866
		(0.102)	(0.114)	(0.175)	(0.150)
Age	.	.	1.006	1.009	1.005
			(0.007)	(0.012)	(0.010)
Activity					
Free architect	.	.	0.906	1.271	0.355*
			(0.225)	(0.391)	(0.185)
Construction	.	.	0.407**	0.473	0.376*
			(0.138)	(0.278)	(0.157)
Education					
Advanced technical college entrance qualification	.	.	12.64*	17.57	6.585
			(13.58)	(33.14)	(9.389)
General qualification for university entrance	.	.	20.86**	22.54*	27.39
			(23.82)	(34.65)	(58.70)
Bachelor	.	.	15.86**	25.82*	8.246
			(15.62)	(39.04)	(11.20)
Master	.	.	10.24*	15.83*	5.366
			(9.575)	(21.94)	(7.018)
Diploma	.	.	7.839*	9.823	4.691
			(7.232)	(13.17)	(6.149)
PhD	.	.	11.54*	14.22	7.285
			(11.24)	(20.90)	(9.786)
Sustainability in private					
rather not important	.	.	36.11*	35.71	.
			(63.36)	(65.39)	.
rather important	.	.	116.5**	110.2**	3.106
			(197.6)	(191.8)	(2.637)
very important	.	.	194.6**	175.1**	5.377*
			(329.8)	(305.0)	(4.569)
Substitutability of r-concrete (building constr.)					
rather disagree	.	.	2.525	1.998	3.822
	.	.	(1.258)	(1.460)	(2.658)
rather agree	.	.	3.214*	2.930	3.935*
			(1.567)	(2.109)	(2.651)
strongly agree	.	.	5.356**	4.986*	6.422**
			(2.740)	(3.834)	(4.495)
Experience with r-concrete	.	.	1.393*	1.198	1.270
			(0.225)	(0.323)	(0.341)
Country random effect (var.)	0.034	0.057	1.30e-34	.	.
	(0.044)	(0.071)	(8.88e-19)	.	.
State random effect (var.)	0.008	0.12	2.37e-35	3.04e-34	3.40e-32
	(0.213)	(0.294)	(3.99e-19)	(2.72e-18)	(2.29e-17)
Individual random effect (var.)	1.399	2.392	1.856	2.036	1.582
	(0.181)	(0.265)	(0.251)	(0.391)	(0.312)
Observations	2113	2113	1690	822	868
LR test vs. ologit model	0.0000***	0.0000***	0.0000***	0.0000***	0.0000***
$P>\chi^2$	0.0000***	0.0000***	0.0000***	0.0000***	0.0000***

*Standard errors in parentheses; *p<0.05, **p<0.01, ***p<0.001.*
Random effects are indicated as variance.
Age was rescaled to a continuous variable.
All categories of education and activities have been incorporated; non-significant categories are not shown.

can be confirmed. Of the examined experimental variables, the greatest influence is exerted by the recognition of sustainability in the public tender - if sustainability is taken into account as a further criterion in the public tender, the odds of high willingness to plan the construction project with r-concrete versus the combined lower categories are 4,576 times greater, given the other variables are held constant

Figure 22: Predicted probability estimates: best- and worst-case scenarios for Germany



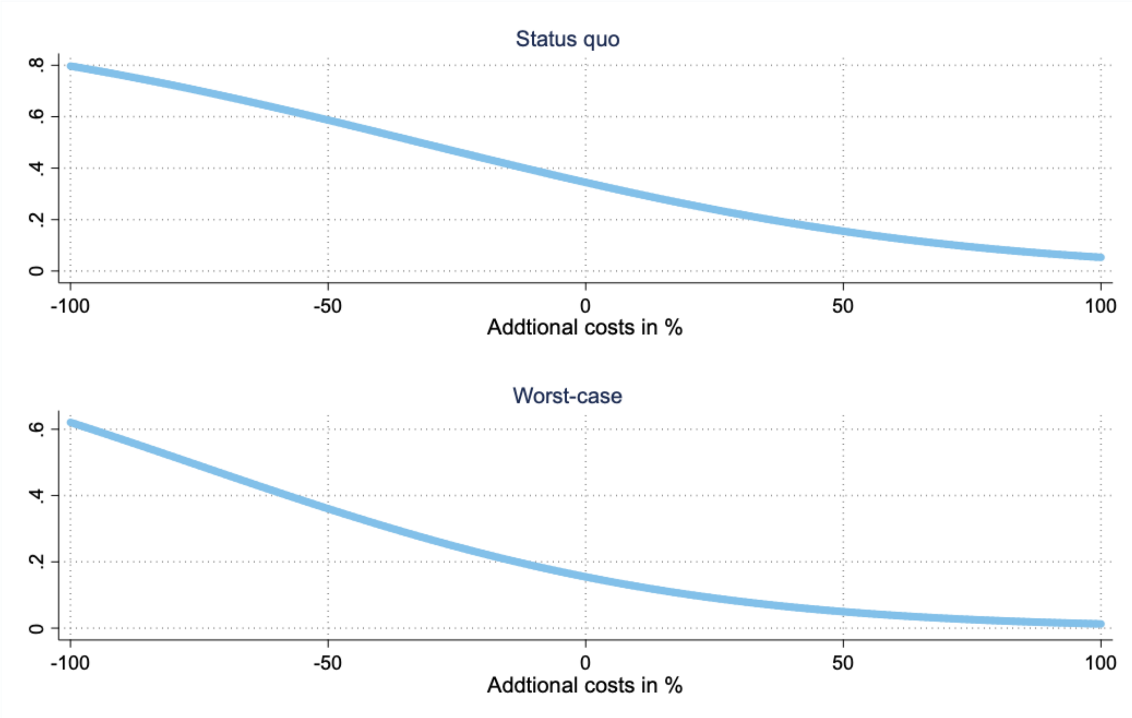
Best-case scenario: sustainability as further award criteria in public tender, recognition of recyclates by a label, no additional costs, maximal permissible proportion of recyclates 100 %, experience with r-concrete.
Worst-case scenario: price as sole award criteria in public tender, no recognition of recyclates by a label, additional costs 100 %, maximal permissible proportion of recyclates 20 %, no experience with r-concrete.
Status quo refers to the estimation where the predictors are set to their mean values.
The presentation refers to the column 4 in Table 22.

in the model (3). The additional costs resulting from the use of r-concrete have a negative effect - for 1 % increase in costs the odds of high willingness to plan the construction project with r-concrete versus the combined lower categories are 0.97 times lower, given the other variables are held constant in the model.

Models (3), (4) and (5) contain additional control variables and covariates of interest such as age, educational background, personal attitude towards sustainability, perception of substitutability of r-concrete in building construction and experience with recycled concrete. In a common pool model (3) it can be stated that the perception of substitutability of r-concrete, attitude towards sustainability in private life as well as experience with r-concrete has a significant positive impact on the probability of planning a construction project using r-concrete. In addition, the dependent variable is influenced to varying degrees by different education levels. In the models for Germany and Switzerland, the perception of substitutability of r-concrete in building construction and sustainability in private life have a significant influence on the willingness to plan the construction project using r-concrete. The multi-level structure was incorporated in all models. The reported likelihood-ratio test (LR test) shows that there is enough variability between countries, states and individuals to favour a mixed-effects ordered logistic regression over a standard ordered logistic regression. $P> \chi^2$ values are significant in all models - there is no evidence that the considered models are misspecified or do not fit the data.

In order to make economic policy recommendations for increasing the use of recycled concrete in building construction in Germany, the model (4) is to be emphasised. From the odds ratios, predicted probabilities can be calculated for each

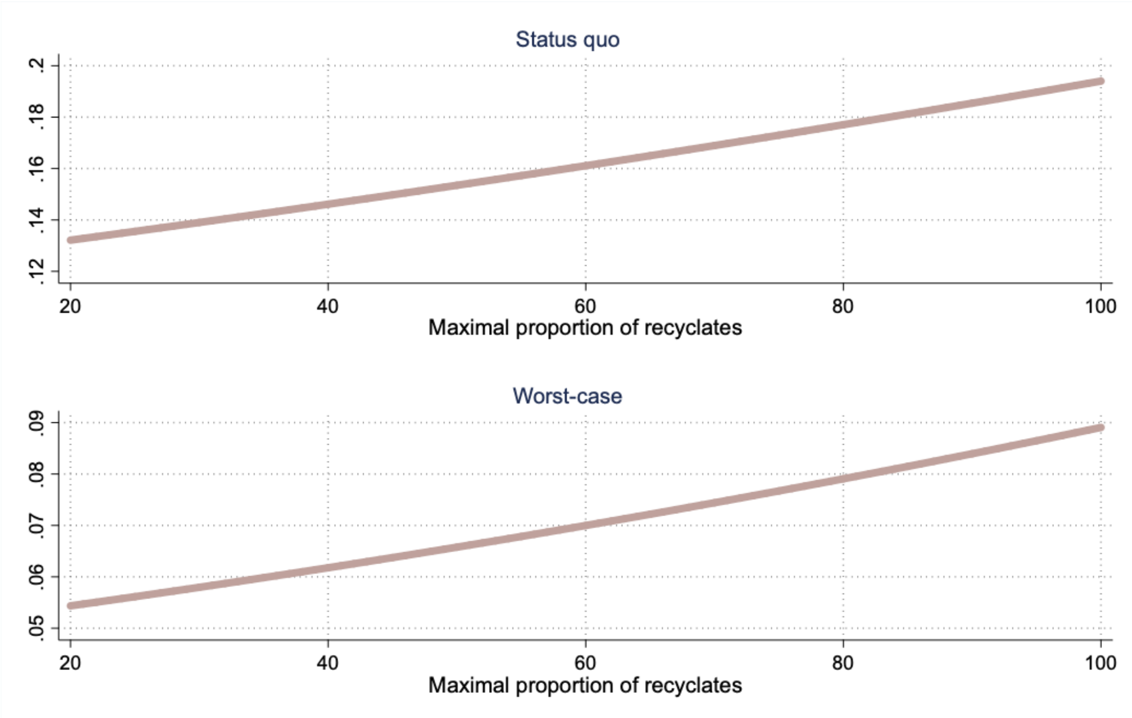
Figure 23: Predictive margins estimates for different scenarios in Germany: the impact of additional costs on the probability of planning the construction project using recycled concrete



Worst-case: price as sole award criteria in public tender, no recognition of recyclates by a label, additional costs 100 %, maximal permissible proportion of recyclates 20 %, no experience with r-concrete.
Status quo: covariates are set to their mean values.
Plots refer to the response category 6 = very likely to plan construction project using recycled concrete.
The presentation refers to the column 4 in Table 22.

response category. Three scenarios were estimated for Germany: status quo, best- and worst-case scenario. The status quo scenario refers to the estimation where the predictors are set to their mean values. The best-case scenario used to model a (relatively realistic) situation, in which the probability of planning the construction project using r-concrete is maximised. It was assumed that sustainability is taken into account as a further award criterion in the public tender, the use of recycled materials is recognised in the DGNB-label, no additional costs occur through the use of r-concrete, the maximum amount of recycled materials that can be added is 100 %. Furthermore, it is assumed that the respective architects and engineers already have experience with recycled concrete. In the worst-case scenario, the respondents are assumed to have no experience with r-concrete, the use of recycled materials is neither recognised in a label nor considered in the public tender; the maximum amount of recyclates that can be added is 20 % and additional costs of 100 % arise. The predicted probabilities across response categories for different scenarios are shown in Figure 22. When comparing scenario estimates, the positive influence of the considered economic policy measures on the willingness to plan the construction project using r-concrete can be clearly observed. On the basis of the available results, the recognition of the recycled materials by a label, an increase in

Figure 24: Predictive margins estimates for different scenarios in Germany: the impact of maximal permissible proportion of recyclates in concrete on the probability of planing the construction project using recycled concrete



Worst-case: price as sole award criteria in public tender, no recognition of recyclates by a label, additional costs 100 %, maximal permissible pronportion of recyclates 20 %, no experience with r-concrete.
Status quo: covariates are set to their mean values.
Plots refer to the response category 6 = very likely to plan construction project using recycled concrete.
The presentation refers to the column 4 in Table 22.

the maximum amount of recycled aggregates that can be added and the consideration of sustainability as a further criterion in the public tender can be recommended as possible policy measures to increase the use of recycled concrete in building construction. Furthermore, it is recommended that pilot projects using recycled concrete should be organised and promoted by the state. Through information and creation of experience, prejudices against r-concrete can be reduced, which could have a positive effect on the use of r-concrete in the construction.

By comparing the negative and positive scenario as a function of additional costs through the usage of recycled concrete, the role of additional costs in the use of r-concrete can be clarified (Figure 23). If no additional costs are incurred, the probability that the most positive category of the dependent variable (*very likely*) is selected is almost 40 %. To obtain the same effect on the probability in the negative scenario, the 50 % subsidy on possible additional costs resulting from the use of r-concrete would be necessary. The effect of the maximum amount of recyclates that can be added on the selection probability of the highest response category (*very likely*) of the dependent variable can be illustrated by Figure 24. It can be observed that, irrespective of the level of the maximum permissible proportion of recycled aggregate, the probability of choosing the highest response category in a status quo scenario is more than twice as high as in the worst-case scenario.

4.4.3. Robustness

The regressions results for the robustness check are shown in Table 23. In estimated models presented in Table 22, random components for the country and state level in the model (3) converge towards 0, indicating that corresponding random effects may be negligible. In order to check the robustness, the common pool model was estimated as a 2-level mixed effects model with random effect at the individual level in (1). (2) is a 2-level mixed effect model with random effect at individual level for Germany. To check the robustness of the experimental parameters, the common pool model with experimental parameters only (from column 2 in Table 22) was estimated as an ordinal regression model with fixed effects at the individual level and cluster robust standard errors at country or federal state level. The model was estimated for common pool data in (3) and for Germany only in (4). The main effects such as recognition by the label, additional costs, consideration of r-concrete in public tenders and maximal permissible proportion of recyclates have proven to be robust and are still significant even if the model specification is changed. The direction of the effects has not changed and only minor changes in the coefficients can be observed. The effects of further covariates, such as experience with r-concrete, perceived substitutability of r-concrete and personal attitudes towards sustainability appears to be robust to changes in the model specification and are also significant in a 2-level common pool model. Overall, there is no evidence that the initial empirical model does not fit the data or is sensitive to changes in the model specification.

Table 23: Robustness check: willingness to plan the construction project using r-concrete

Independent variables	**Odds ratios**			
	Common pool 2-lvl.-ME (1)	Germany 2-lvl.-ME (2)	Common pool FE (3)	Germany FE (4)
Label	1.983***	2.242***	2.409***	2.653***
	(0.204)	(0.345)	(0.221)	(0.412)
Sustainability in public tender	4.485***	4.279***	6.522***	5.797***
	(0.485)	(0.689)	(0.791)	(1.136)
Max. proportion of recyclates	1.006*	1.009*	1.007	1.012***
	(0.00230)	(0.00347)		
Costs	0.971***	0.969***	0.959***	0.957***
	(0.00182)	(0.00265)	(0.00206)	(0.00333)
City cize				
Middle-sized town	0.932	1.077	0.877	0.786
	(0.115)	(0.202)	(0.0836)	(0.160)
Big city	0.912	0.950	0.846**	0.793
	(0.112)	(0.175)	(0.0508)	(0.0977)
Age	1.008	1.009	.	.
	(0.00707)	(0.0118)		
Activity				
Free architect	0.852	1.271	.	.
	(0.208)	(0.391)		
Construction	0.382**	0.473	.	.
	(0.128)	(0.278)		
Education				
Advanced technical college entrance qualification	15.50**	17.57	.	.
	(16.46)	(33.14)		
General qualification for university entrance	19.61**	22.54*	.	.
	(22.31)	(34.65)		
Bachelor	14.69**	25.82*	.	.
	(14.40)	(39.04)		
Master	10.49*	15.83*	.	.
	-9.776	(21.94)		
Diploma	7.743*	9.823	.	.
	-7.121	(13.17)		
PhD	10.05*	14.22	.	.
	-9.735	(20.90)		
Sustainability in private				
Rather not important	47.73*	35.71	.	.
	(82.66)	(65.39)		
Rather important	126.9**	110.2**	.	.
	(213.1)	(191.8)		
Very important	199.6**	175.1**	.	.
	(335.1)	(305.0)		
Substitute				
Rather disagree	2.161	1.998	.	.
	(1.042)	(1.460)		
Rather agree	2.669*	2.930	.	.
	(1.258)	(2.109)		
Strongly agree	4.785**	4.986*	.	.
	(2.369)	(3.834)		
Experience with r-concrete	1.392*	1.198	.	.
	(0.220)	(0.323)		
Individual RE (var.)	1.840	2.036	.	.
	(0.244)	(0.391)		
Individual FE	.	.	Yes	Yes
Cluster robust SE (country)	.	.	Yes	.
Cluster robust SE (federal state)	.	.	.	Yes
Observations	1759	822	2113	1086
LR test vs. ordered model	0.000	0.000	.	.
P> χ^2	0.000	0.000	.	.
Pseudo - R^2	.	.	0.334	0.353

*Standard errors in parentheses; *p<0.05, **p<0.01, ***p<0.001.*
All categories of education and activities have been incorporated; non-significant categories are not shown.

4.5 Conclusion

In this chapter, the obstacles to the use of recycled concrete, marginal willingness to pay for sustainability-related attributes and possible economic policy measures to increase the use of r-concrete in the construction have been empirically investigated. For this purpose, combined item-based, factorial and discrete choice survey of the architects and engineers in Germany and Switzerland has been carried out. Based on the data from the discrete choice experiment, the marginal willingness to pay for sustainability-related attributes was estimated. The effectiveness of possible economic policy measures was examined using the data from the factorial survey.

The main obstacles to the use recycled-concrete from the point of view of architects and engineers in Germany are the lack of knowledge and experience with recycled concrete, absence of governmental support, no consideration of recycled concrete in public tenders or labels and certifications, inconsistent and uncertain governmental regulation as well as low supply and demand. The relevance of possible barriers to the use of r-concrete was systematically rated higher by architects and engineers in Germany than is the case of Switzerland. The evaluation of individual obstacles in Germany is in most cases very similar for architects and engineers as well as for the executing companies. The results of the logistic regression based on the discrete choice experiment indicate that architects and engineers in Germany are characterised by a higher willingness to pay for sustainability-related attributes. Within the framework of the ordered logistic multilevel mixed effects model based on the factorial survey, it was demonstrated that the consideration of recycled materials as a further award criterion in the public tender, recognition of recycled materials in the DGNB-label and an increase in the maximum proportion of recyclates that can be added into concrete increase the likelihood of planning the construction project using recycled concrete.

The study contributes on the one hand to the understanding of the reasons why r-concrete is used to a limited extent in building construction in Germany and on the other to the development of economic policy measures to increase the sustainability in building construction. In context of promoting sustainable construction, the results point to the need to consider recycled materials in the public tender and DGNB-label, stronger governmental support and increase in the maximum permissible proportion of recyclates that can be added to the concrete.

5 Willingness to produce recycled concrete

(Co-authored with Philipp Dräger[41])

In the course of previous work, various research questions have been investigated regarding the obstacles to the use of recycled concrete and possible economic policy measures to increase the use of r-concrete. The perspectives of contractors, architects and engineers as well as students of architecture, civil and environmental engineering have been taken into account. However, one of the groups of actors relevant for the use of recycled concrete in construction has not yet been addressed in detail - the producers of ready-mix concrete. In the studies presented in previous chapters, low supply[42] of r-concrete was identified as one of the main obstacles to the use of r-concrete in building construction. Ultimately, the decision as to whether to offer r-concrete is taken 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. Thus, this chapter 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 then combined with regional economic and geographical data and applied to an empirical model to test the formulated research hypotheses.

The study presented in this chapter begins with the derivation of 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 analysed 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 the chapter the research questions, methodologies and central results are briefly summarised.

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[42]On a scale of 1 to 100 (*not relevant at all* to *very relevant*), the median in Germany is 81 for executing companies and 76.5 for architects and engineers. For a more detailed comparison between executing companies of construction value chain, architects and engineers the reader is referred to Table A7 in Appendix.

5.1 Theoretical background and hypotheses

5.1.1. 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. In contrast to conventional concrete, whose production is highly technically standardised, the production of r-concrete requires development and adaptation of the special concrete recipe. It depends on the one hand on the composition of the recycled granulate and on the other hand on the desired concrete properties (Stürmer & 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. 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 & 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.[43]

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. 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 & Puga, 2001), which requires additional spending on research and development. Since the monopolies generally generate higher profits in a non-regulated market, it can be assumed that the monopolies are potentially in a better position to provide financial resources for the necessary research, development and production as well as testing of prototypes than would be the case in a competitive market (Rosenberg, 1981). As the market position of the monopolies can be strengthened by innovation and the monopolies can bear the associated costs, there would be incentives to promote innovation in

[43] 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.

a monopoly market (Schumpeter, 1942). The results of technical literature on the relationship between market concentration and innovation also suggest that higher market concentration can lead to higher R&D spending and consequently to higher innovation (Dasgupta & Stiglitz, 1980; Gayle, 2002; Smith et al., 2002; Weiss, 2005). Subsequently, it can be argued that monopolies could have fewer incentives for product innovation as they would replace existing products on which the monopoly position is based (Tirole, 1988). Companies that already generate monopoly profits have a strong incentive to maintain the status quo in order to generate the highest possible level of profits with existing products (Usher, 1964; Arrow, 1962; Arrow, 1962a). The empirical literature also achieve different results - Scherer (1965) and Hamberg (1966) state a positive relationship between market concentration and innovation activities. In contrast, Williamson (1965) and Bozeman & Link (1983) identify a negative relationship. However, the results of the previous research 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 to be expected. The change does not directly affect the product, but only the production process - recycled concrete as a product has largely the same physical, chemical and mechanical properties as conventional concrete. Thus, it can be assumed that no negative relationship is to be expected between the willingness to produce recycled concrete and the market concentration. On the contrary, due to the lower intensity of competition, market power and incentives to maintain the monopoly position through innovation, it can be assumed that the willingness to produce recycled concrete will increase with rising regional market concentration.

Similar argumentation can be applied to 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 & 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:

- H_1: The willingness to produce recycled concrete increases with rising regional market concentration.
- H_2: The willingness to produce recycled concrete increases with rising firm size.

5.1.2. Vertical integration

In addition to horizontal integration (market concentration), vertical integration is also considered in the present study. Vertical integration describes a situation in which the company takes over or integrates the activities of the upstream and downstream value chain. 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. 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. 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:

- H_3: The willingness to produce recycled concrete decreases if the concrete producer also manufactures or mines natural stone, sand and gravel.
- H_4: The willingness to produce recycled concrete increases if the concrete producer also undertakes the demolition work at the construction site.
- H_5: The willingness to produce recycled concrete increases if the concrete producer also undertakes the waste collection.
- H_6: The willingness to produce recycled concrete increases if the concrete producer also undertakes the waste recycling.

5.1.3. 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. Construction and demolition waste occur more likely in regions, which are characterised by a higher economic activity - it is plausible to assume that highly industrialised 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:

- H_7: The willingness to produce recycled concrete increases with rising economic activity of the region.

5.1.4. 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 organisation of the value chain can influence the willingness to produce recycled concrete. In principle, 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 - these 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. The further away the input supplier, the greater the incentive for the concrete producer to replace the primary inputs such as gravel, sand and stone with (regional) secondary aggregates.

When deconstructing a building, a decision must be made - to recycle or landfill the demolition waste. 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. It would be expected that the increasing distance from the supply area of the ready-mix concrete producer to the landfill would increase the willingness to produce recycled concrete. Thus, regarding the geographical distances, the following hypotheses can be formulated:

- H_8: The willingness to produce recycled concrete increases with rising distance from the supply area of the concrete production plant to the disposal site.
- H_9: The willingness to produce recycled concrete increases with rising distance from the concrete production plant to the sand, gravel and stone supplier.

5.2 Research design and data collection

The defined hypotheses are to be tested by means of a logistic regression model. The dependent variable is the willingness to produce recycled concrete. The independent variables are the parameters formulated in the hypotheses. In order to enable the estimation, the empirical data must be compiled and calculated for both the dependent and the independent variables. In the present subsection, the procedure for data collection and parameterisation will be described in detail.

5.2.1. Willingness to produce recycled concrete

As there is no functioning market for recycled concrete in Germany yet and empirical observations on the actual production are not available, only the potential willingness to produce the recycled concrete can be recorded. The willingness to produce recycled concrete is investigated by means of a survey. For this purpose, a telephone survey of 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 organised 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. The telephone survey was carried out by an employee of the institute in October 2018 during regular working hours. During the telephone survey, a question was asked about the potential willingness to produce recycled concrete in a fictive situation. The situation and the following question are defined as follows:

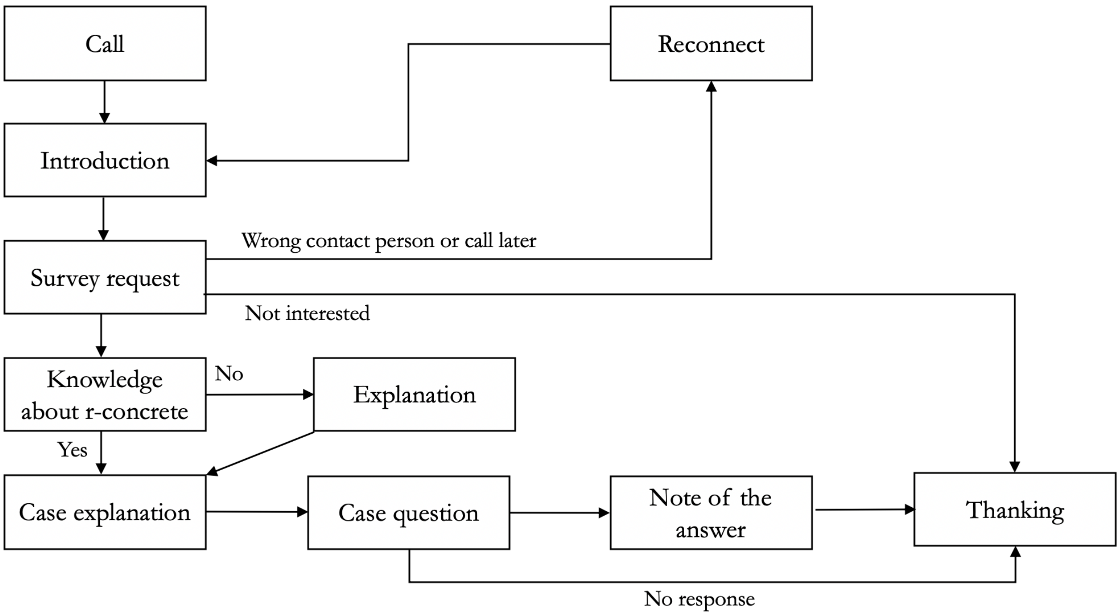
> *Imagine that a customer contacts you to order recycled concrete. You would be willing to accept such an order with a comparable quantity of conventional ready-mixed concrete.*
>
> ***How likely would it be - on a scale of 1, definitely not, to 5, definitely - that you would accept this order?***

The answers are recorded on a 5-level scale of the Likert-type. 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%.

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

As one enterprise 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 standardised, as shown in Figure 25. During each interview a short introduction

Figure 25: Protocol of the telephone interview



was carried out before the presentation of a fictive situation. If the interviewee had not yet heard about recycled concrete, it was briefly explained. If the interviewee was unable to give a statement, he or she was asked to be forwarded to the appropriate person. To increase the response rate, the companies that could not be reached were called again two weeks after initial call.

5.2.2. 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. Classifications 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.

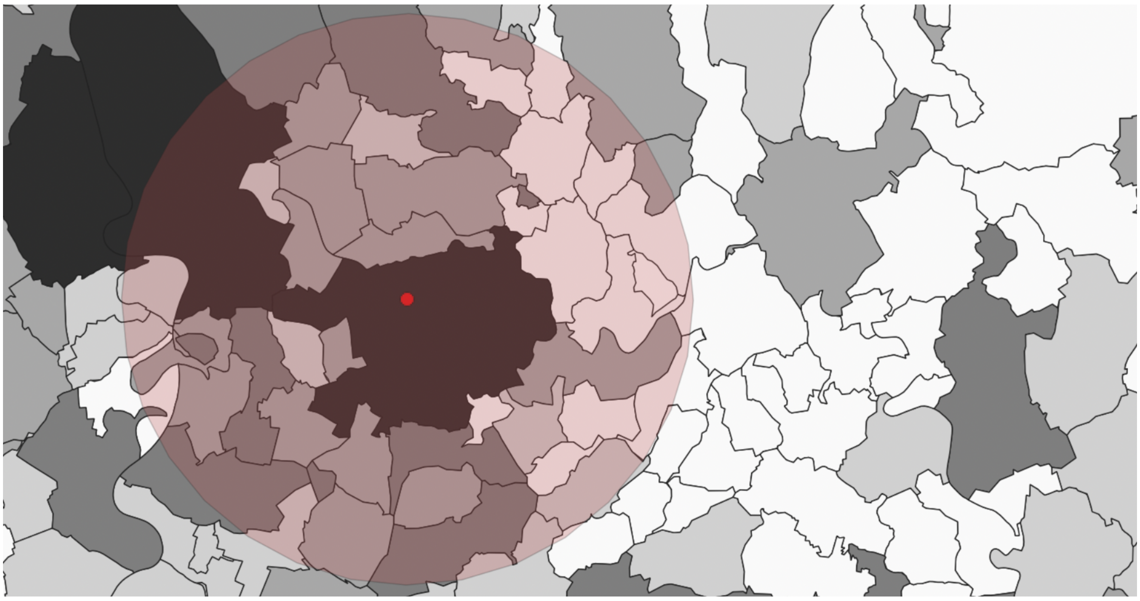
Since many companies have several establishments, the addresses of the establishments had to be entered manually. By using open source geoinformation system Quantum GIS (QGIS) version 3.6, geographical coordinates were assigned to the addresses and then transferred to the projecting coordinates reference 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 - the location information is thus accurate to within 1 meter. 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 kilometres. In addition, distances from the ready-mix concrete manufacturers to the next landfill of class[44] 1 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.

5.2.3. 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 kilometres was drawn around each establishment. The populations of the municipalities located within or intersecting these districts were summed and act as a proxy variable for the economic activity of the region in which the ready-mixed concrete site is located. Higher quantity of inhabitants 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) was used and processed as a shape file at QGIS.

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

Figure 26: Exemplary supply zone of the ready-mix concrete production site



5.2.4. 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 kilometres 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. This, very restrictive assumption was chosen, because the turnover and employment data are not available at the establishment level. The calculation of population-weighted turnover of the permanent establishment represents a better alternative than an entry as missing values.

5.2.5. 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). By otherwise constant conditions it can be assumed that ready-mixed concrete can be transported an average of 30 kilometres within one hour. The measure of horizontal market concentration often used in the economic literature, such as CR_1, CR_4, CR_8, etc., which represents the sum of the market shares of the 1, 4 and respectively 8 largest companies, are not suitable since the relative sizes of the companies are not taken into account. The Herfindahl-Hirschman Index (HHI), which takes into account both the distribution of turnover and the number of companies, represents a more appropriate tool for measuring market concentration. HHI[45] 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 (Hirschman, 1945; Hirschman, 1964; Herfindahl, 1950). In contrast to the CR_n, the larger companies are given a higher weight, which eliminates the distortion resulting from relative size of the company.

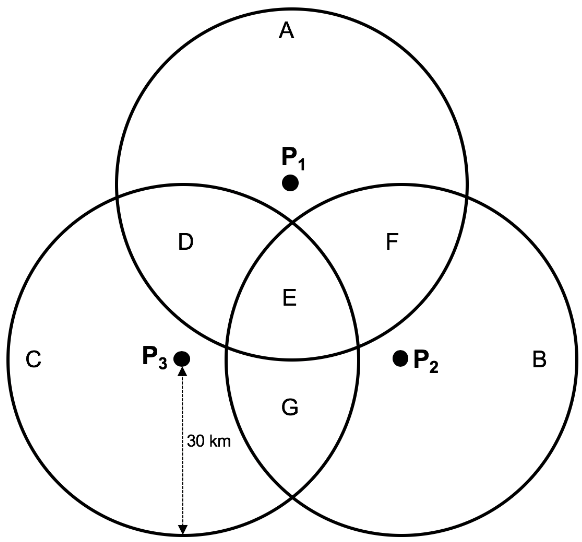
In the present study, the Herfindahl-Hirschman Index is calculated as a fixed radius method, similar to the approach used to examine the regional market concentration of hospitals by Gaynor & Vogt (2000) and Wright et al. (2019).[46] It is assumed that if the supply zones of several concrete production 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. The calculation procedure can be illustrated by Figure 27.

Around three production sites P_1, P_2 and P_3 circles with the radius equivalent of 30 kilometres have been drawn. These circles indicate the respective supply zones of P_n. When the supply zones of the production sites intersect, they form a competition zone - in area A, site P_1 has sole supply sovereignty, in area F sites P_1 and P_2 compete with each other, and in area E all three production sites compete with each other. HHI is calculated based on the intersections of the individual supply zones

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

[46] 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 specialised hospital service - in certain cases the markets may be both national and international.

Figure 27: Exemplary calculation of Herfindahl-Hirschman Index: fixed radius method



and is generalised as:

$$HHI = \sum_{i=1}^{n} s^2 \tag{19}$$

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:

$$s = \frac{x_i}{\sum_{i=1}^{n} x_i} \tag{20}$$

where x_i indicates a turnover of the respective establishment. The denominator represents the total turnover of all operating units within the regional market. The HHI for competition zone A can is calculated as:

$$HHI_A = (\frac{x_1}{x_1})^2 \tag{21}$$

In competition zone A, the production site P_1 has the monopoly position with the highest market concentration of HHI_A=1 - zone A can only be supplied by the site P_1 due to limited transportability of ready-mix concrete. Zone E is supplied by all three companies and the HHI for this zone is calculated as:

$$HHI_E = (\frac{x_1}{x_1 + x_2 + x_3})^2 + (\frac{x_2}{x_1 + x_2 + x_3})^2 + (\frac{x_3}{x_1 + x_2 + x_3})^2 \tag{22}$$

Analogous to equations 21 and 22, the HHI is calculated for other surfaces. After calculating the HHI for individual competition zones, an area-weighted HHI is calculated for the supply zone of each production facility. The weighted supply zone

HHI for the production site P_1 is calculated as:

$$HHI_1 = a_A \times HHI_A + a_F \times HHI_F + a_E \times HHI_E + a_D \times HHI_D \qquad (23)$$

where a denotes the proportion of respective competition zone in the total area of supply zone. As illustrated by the above example, the HHI was calculated for the supply zones of all ready-mixed concrete plants in Germany.

5.2.6. 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 characterise 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.

5.3 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 summarised in Table 24.

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. The regional distribution of the concrete production sites is shown in Table 25.

Table 24: Descriptive statistics for 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	13971	50601	72	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

Table 25: Ready-mixed concrete plants by federal states in Germany

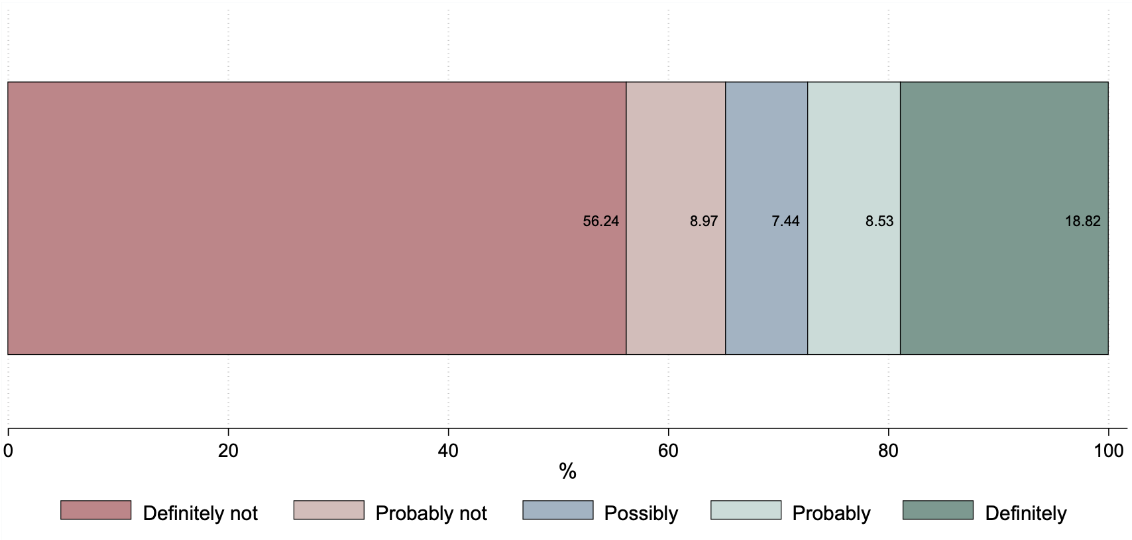
Federal state	Frequency	%
Baden-Würtemberg	222	17.52
Bavaria	262	20.68
Berlin	11	0.87
Brandenburg	57	4.50
Bremen	7	0.55
Hamburg	12	0.95
Hesse	124	9.79
Mecklenburg-Vorpommern	6	0.47
Lower Saxony	118	9.31
North Rhine-Westphalia	139	10.97
Rhineland-Palatinate	78	6.16
Saaarland	4	0.32
Saxony	96	7.58
Saxony-Anhalt	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 28 - 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 characterised by the fact that they would definitely or probably accept the order to produce recycled concrete.[47] In contrast, 56.24 % of the plants would probably or definitely not accept the order to produce recycled concrete.

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

[47]This is a very important result in terms of increasing the use of r-concrete in the construction sector. 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. However, the results of this study indicate that the supply of recycled concrete is potentially available. In view of this finding, the question arises as to why construction industry actors perceive the supply of r-concrete as low. A possible explanation would be the incomplete information on the part of architects, engineers and contractors.

Figure 28: Willingness to produce recycled concrete across response categories



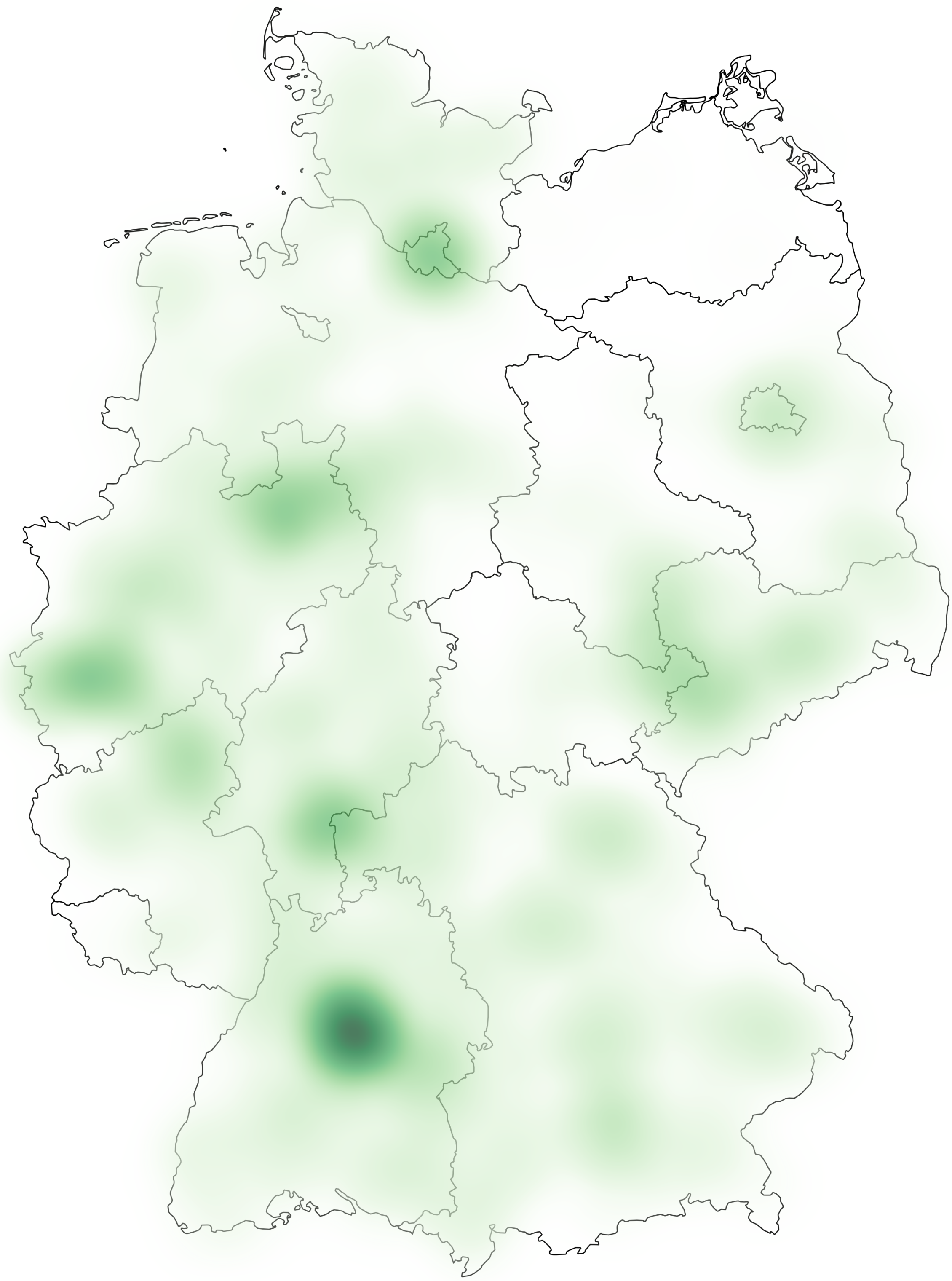
N=457; refers to the production plants.

made visible. The higher the number of sites in the certain area and the higher the (numerical) willingness to produce recycled concrete, the more colourful the area appears. The radius has been defined as 50 km. By extending the perimeter, the outer borders of the coloured marking shift and the colour 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 29. 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 colour 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.

The vertical integration of the companies was measured by whether the company undertakes the 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 30. 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.

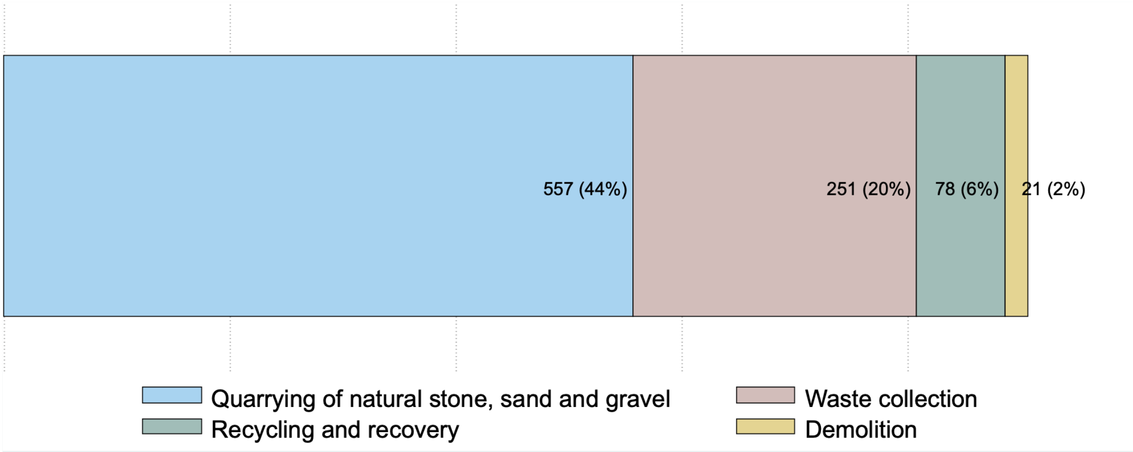
The distribution of companies' activities by response categories is shown in Figure 31. 57 % of the companies that have indicated that they would probably or definitely not accept the order are involved in the production or distribution sand, gravel and stone. In contrast, 46 % of the companies involved in the production or distribution of sand, gravel and stone would probably or definitely accept the

Figure 29: Willingness to produce recycled concrete by location: heat map



order to produce recycled concrete. 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

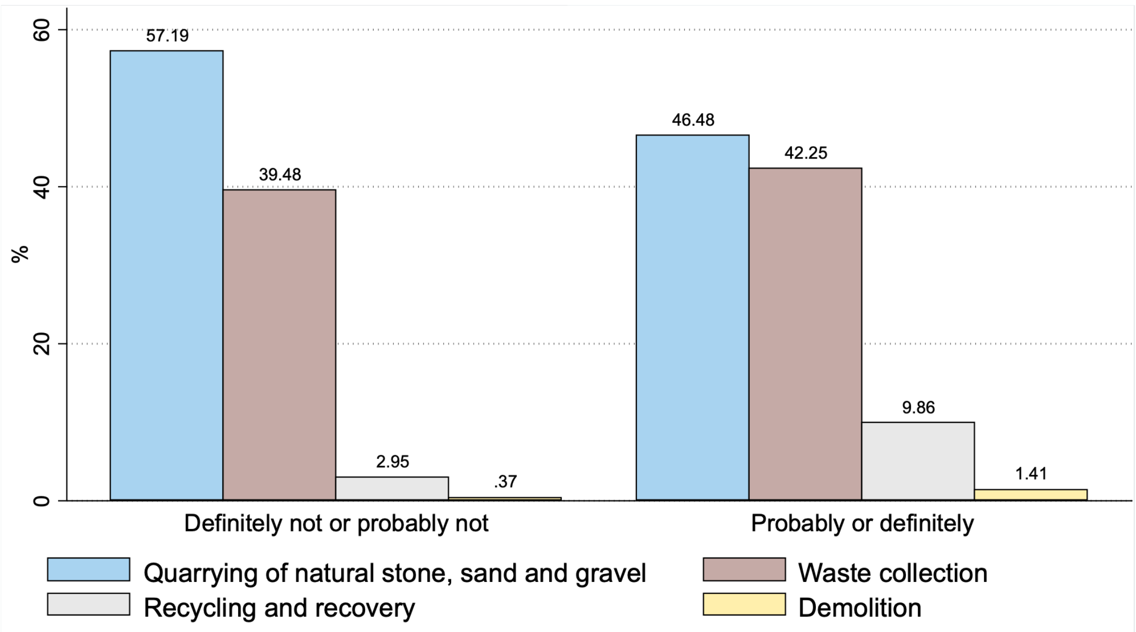
Figure 30: Vertical integration of ready-mixed concrete production sites



Percentages refer to N=1267 concrete production plants.
Refers to the activities that companies carry out alongside concrete production.
Vertical integration encoded as dummy; multiple affiliation possible.

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 H_5 and H_3 can be preliminary confirmed. The willingness to produce recycled concrete increases if the production site also undertakes the waste collection (H_5) and decreases if it manufactures natural stone, sand and gravel (H_3). On the basis of the preliminary descriptive results, the hypotheses H_4 and H_6 cannot be confirmed, since the two-sample t-tests and equality of medians tests do not indicate significant results.

Figure 31: Vertical integration of ready-mixed concrete production sites and willingness to produce recycled concrete



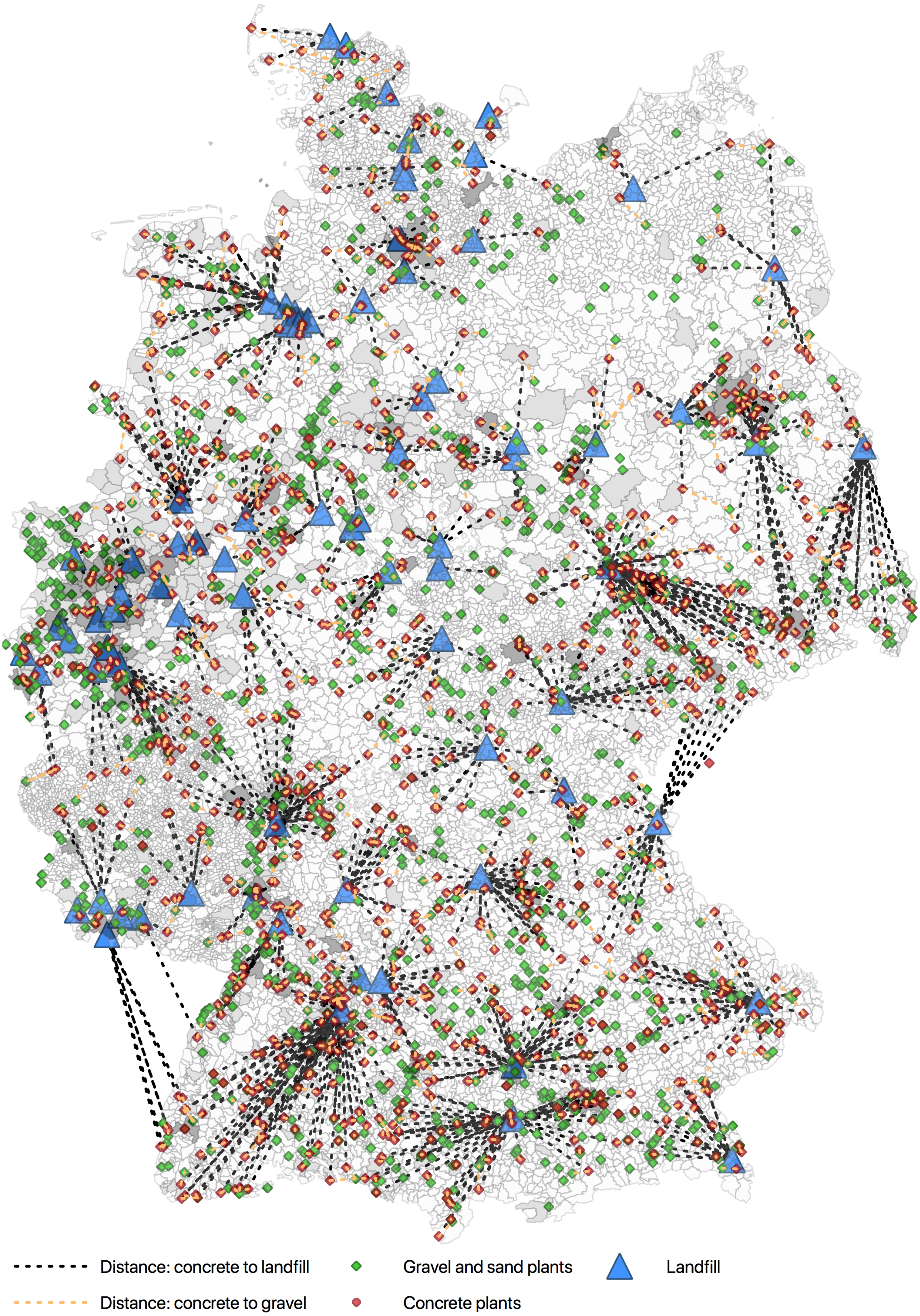
Distances between the production sites of the ready-mixed concrete manufacturer and the respective sand, stone and gravel pits or suppliers as well as landfill sites are shown in Figure 32. A large number of gravel suppliers around the ready-mixed concrete sites is observable. A total of 1565 suppliers 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. Based on the findings above, the hypotheses H_8 and H_9 cannot be confirmed at this stage.

The numerical distribution of regional market concentration can be illustrated by Figure A2 in Appendix. 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 kilometres 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 (H_1). Two-sample t-test indicates that the hypothesis H_1 can be preliminary confirmed - there are significant differences in the means between groups with positive and negative answers ($p = 0.064$). The hypothesis (H_2) 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 (H_7) 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.

Figure 32: Locations and distances



5.4 Empirical analysis

Within the framework of the present subsection, the willingness to produce r-concrete will by investigated by means of an ordinal logistic regression model. The aim of the model is to test the hypotheses formulated at the beginning of the chapter.

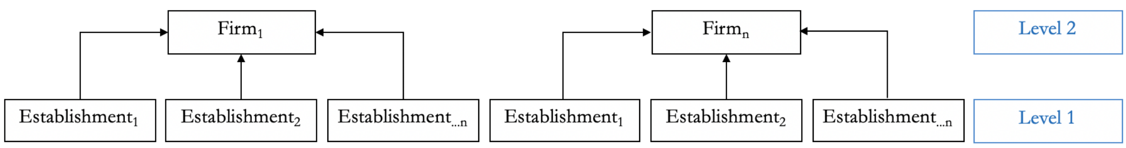
5.4.1. Empirical model

As mentioned in the previous course of work, ready-mix concrete producers are organised as enterprises and one enterprise may have several production sites. Thus, the variables are structured in two levels - the group specific variables (level 2)[48], which record the characteristics of the companies, and individual specific variables (level1)[49], which trace the characteristics of the individual production facilities. The multilevel structure of the data can be illustrated by Figure 33.

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[50], all enterprises surveyed stated that the response[51] 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.

Willingness to produce recycled concrete is an ordinal scaled variable. Thus, the ordinal logistic regression can be considered as the starting point for further considerations. Ordinal logistic regression describes the causal relationship between the ordinal response variable and one or more independent variables (Fagerland & Hosmer, 2016). Since the permanent establishments are organised 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 & Pischke, 2009). By introducing a company-specific dummy variable, group-specific differences

Figure 33: Structure of the data on willingness to produce recycled concrete



[48] Vertical integration dummies.

[49] HHI, firm size, economic activity of the region, distances.

[50] Not mentioned for reasons of data protection.

[51] Response to the question "How likely would it be - on a scale of 1, *definitely not*, to 5, *definitely* - that you would accept this order?". The question refers to the inquiry concerning the production of recycled concrete.

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 2003, Wooldridge 2010). 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 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 & Frees, 2007). Due to the fact that there is no (or only minor) variation in the dependent variable within the companies and that the company affiliation accounts for a large part of the variation of the response variable, causal relationships between the potential willingness to produce recycled concrete and the dependent variables can only be determined and interpreted to a limited extent. The dependency of responses within the companies indicate that the fixed effects approach is a less appropriate instrument in a given case.

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:

$$y_e^* = \mathbf{x}_e' \boldsymbol{\beta} + \varepsilon_e \tag{24}$$

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:

$$\begin{aligned} y_e^* = \beta_0 + \beta_1 \times market\ concentration \\ + \beta_2 \times quarrying\ of\ natural\ stone, sand\ and\ gravel \\ + \beta_3 \times waste\ collection + \beta_4 \times recycling\ and\ recovery + \beta_5 \times demolition \\ + \beta_6 \times firm\ size + \beta_7 \times regional\ economic\ activity \\ + \beta_8 \times distance\ \ to\ input\ supplier \\ + \beta_9 \times distance\ to\ waste\ disposal + \varepsilon_e \end{aligned} \tag{25}$$

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.

5.4.2. Results

The regression results are shown in Table 26.[52] 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 the 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 & Harrel, 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

[52]In contrast to the empirical models analysed 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 26: Ordinal logistic regression model on potential willingness to produce r- concrete.

Variables	**Odds ratios**	
	(1)	(2)
	5-level-reponse	3-level-reponse
Employees	1.061**	1.081**
	(0.030)	(0.036)
Population (30km)	1.061**	1.064**
	(0.026)	(0.030)
HHI (30km)	1.037***	1.042***
	(0.014)	(0.017)
Quarrying of stone	0.331**	0.201**
	(0.179)	(0.136)
Waste collection	3.934**	2.361
	(2.283)	(1.845)
Recycling	0.564	0.436
	(0.533)	(0.511)
Demolition work	1.367	2.427
	(1.998)	(5.064)
Distance to supplier	1.031	1.054
	(0.045)	(0.056)
Distance to disposal	1.007	1.008
	(0.008)	(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.

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. 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 regression 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. The parallel regression assumption is to be considered as fulfilled. On the one hand, the disadvantage of this method is the fact that the decoding from 5-level-response to 3-level-response is accompanied by loss of information. On the other hand, the information is unevenly condensed - category 1 and 3 of the 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. For the reasons mentioned above, it makes sense to consider both models in the further analysis.

The ordinal version of the Hosmer-Lemeshow test (Fagerland & Hosmer, 2013; Fagerland & Hosmer, 2016), Lipsitz test (Lipsitz et al., 1996) and Pulkstenis-Robinson test (Pulkstenis & Robinson, 2004) were used to measure the goodness of fit. The null hypothesis for the goodness of fit tests is that the model fits well the data. A small p-value is therefore an indication that the model is misspecified (Fagerland & Hosmer, 2016). The test results presented in Table 26 give no indication that the models (1) and (2) are misspecified. The specification link test for single equation models (Pregibon, 1979) is not significant, indicating an appropriate model specification for (1) and (2). Table 26 also presents pseudo-R^2 (McFadden, 1974), which, by analogy with the coefficient of determination (R^2) in linear regression, 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 (Norušis, 2005), so that pseudo-R^2 values between 0.2 and 0.4 are regarded as very successful (Tabachnik & 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:

- H_1: The willingness to produce recycled concrete increases with rising regional market concentration.
- H_2: The willingness to produce recycled concrete increases with rising firm size.
- H_3: The willingness to produce recycled concrete decreases if the concrete producer also manufactures or mines natural stone, sand and gravel.
- H_5: The willingness to produce recycled concrete increases if the concrete

producer also undertakes the waste collection.

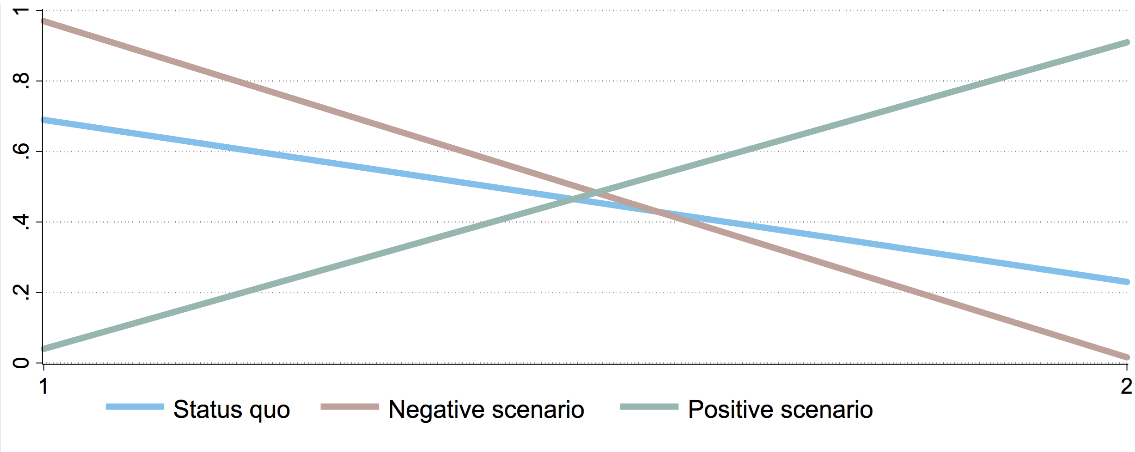
- H_7: The willingness to produce recycled concrete increases with rising economic activity of the region.

However, the following hypotheses cannot be confirmed:

- H_4: The willingness to produce recycled concrete increases if the concrete producer also undertakes the demolition work at the construction site.
- H_6: The willingness to produce recycled concrete increases if the concrete producer also undertakes the waste recycling.
- H_8: The willingness to produce recycled concrete increases with rising distance from the supply area of the concrete production plant to the disposal site.
- H_9: 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 34. To ensure interpretability, the predictive margins were calculated from the 3-lvl.-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 the figure, 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.

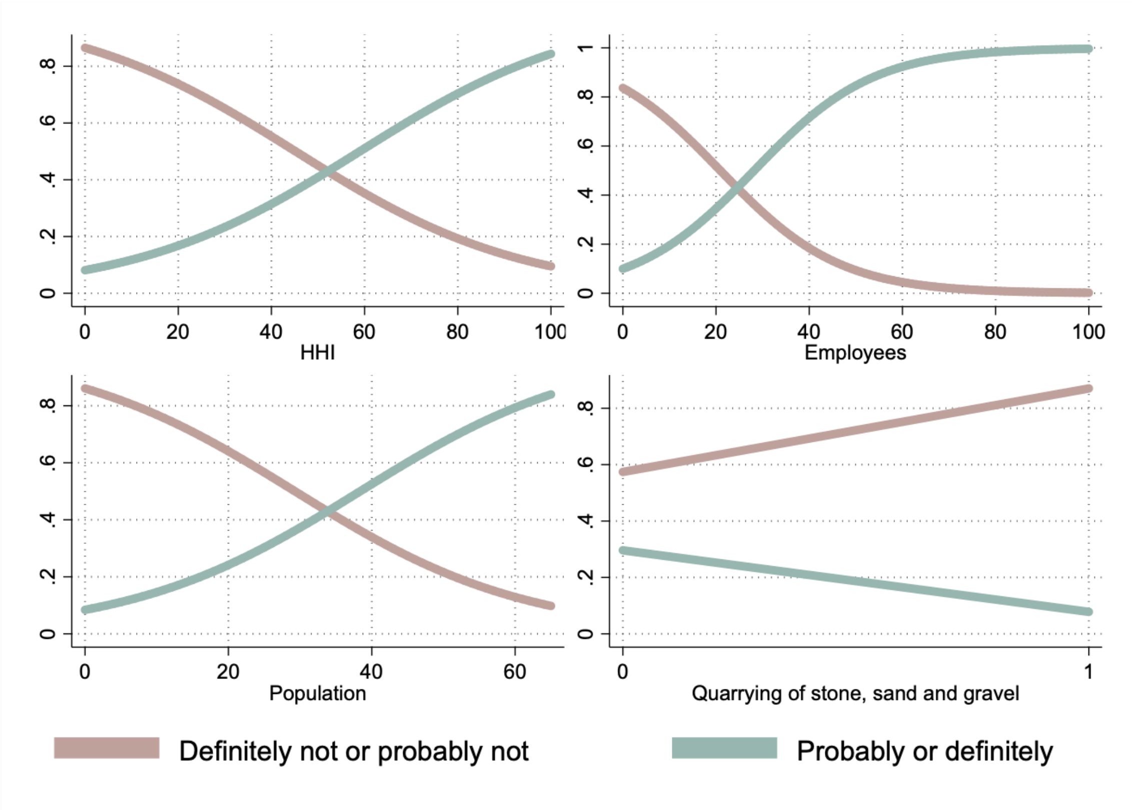
Figure 34: Predicted probabilities across response categories



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 35). 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 millions inhabitants, the market concentration exceeds 50 (HHI=0,5) and more than 25 employees are employed in the plant.

Figure 35: Predictive margins across response categories



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

5.4.3. Robustness

In order to check the robustness, the models have been estimated using different methods. The regression results are shown in Table 27. 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.

5.5 Conclusion

In this chapter the determinants of the willingness to produce r-concrete were investigated empirically. For this purpose, a telephone survey of ready-mixed concrete producers located in Germany was conducted. The answers were combined with geographical data of the regions in which the plants are located and analysed by means of an ordinal logistic regression model.

Table 27: Robustness check: willingness to produce recycled concrete.

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

It was 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 input materials such as sand and gravel in addition to its main activity.

One of the important results of presented research is the finding that the supply of recycled concrete is potentially existing. This study contributes to the understanding of the functioning of the market for recycled concrete. The outcomes of this study are relevant to the objectives of the overall work for several reasons. On the one hand, the results provide valuable information for the identification of target groups for economic policy measures to increase the use of r-concrete. On the other hand, the findings can be used to identify the regions for the purpose of introducing pilot projects to test possible measures to increase the use of recycled concrete in building construction.

6 Discussion

6.1 Methodological limitations

When discussing the results in the context of the targeted increase in the use of recycled concrete in building construction, the methodological limitations of the research must necessarily be taken into account. One of the important limitations is the fact that the empirical data that form the basis of the work were largely obtained through the surveys. Since not every element of the population had the same probability of being selected into the sample, the sampling procedure for all surveys is to be considered as non-random. On the one hand, it can be assumed that the respondents who already have experience with recycled concrete or are basically interested in r-concrete or sustainable construction are more likely to participate in the survey. On the other hand, the enterprises, architects and engineers who have not publicly provided their e-mail addresses could not be invited to participate in the survey at all. Furthermore, in the student survey, the invitation to participate was not sent directly. The professors of architecture, civil and environmental engineering were asked to forward the survey to the students. Thus, the participation of the students depends not only on their personal attitude towards sustainable construction, but also on that of the professors, who had the choice to forward the survey or not. It can be assumed that non-random sampling may affect the accuracy and potential generalisability of the results.

At the same time, it should be noted that in the studies in which different groups of actors in Germany and Switzerland have been compared, the samples were not always balanced between the countries. In the survey of executing companies and students in Germany and Switzerland, less than 10 % of the respondents came from Switzerland. This may limit the meaningfulness of the item-based questions for Switzerland. However, it can be assumed that the impact of the unbalanced samples on the results of the work is largely negligible. The main focus of the work was to identify obstacles to the use of recycled concrete and to test the effectiveness of economic policy measures to increase the use of r-concrete in Germany - Switzerland acted rather as a benchmark and as a tool to make possible obstacles visible by depicting the differences. The unbalanced nature of the sample has only minor consequences for the empirical model for executing companies, as the model was estimated as a common pool regression with control for country affiliation when examining economic policy measures to increase the use of r-concrete. However, the estimate of the willingness to pay for sustainability-related attributes among students in Switzerland should be viewed with caution, as it is based on 297 observations of only 33 participants.

A further possible limitation of the results may arise from the fact that the effectiveness of possible economic policy measures as well as the estimation of the willingness to pay for sustainability-related attributes were examined in the course of economic experiments. In the factorial surveys and the discrete choice experiments, complex decision situations were largely reduced to a few decision parameters. Although the reduction in complexity has the advantage that the relevant decision parameters can be measured in a controlled manner, it distorts reality and leads to the generation of the decision environment, that is not representative of "real life" situations. Thus, the factorial survey and discrete choice are based on the "ceteris paribus" assumption. In this context, Levitt & List (2007) point out that, due to the accompanying reduction in reality, economic experiments provide little information on whether and to what extent experimental observations also apply to the real world; rather, the experiments make clear what can happen and provides an underlying mechanism that might be at work when certain data patterns are observed in the field. Thus, the experiments carried out do not claim to be an exact representation of reality, but provide us with valuable information on how the investigated measures for the promotion of recycled concrete might work.

The obstacles in the use of recycled concrete were investigated by means of itembased questions, which may result in several methodological limitations. On the one hand, interpretation-related biases may arise in the assessment of possible obstacles - different actors, located at different stages of the construction value chain, may interpret the items differently. On the other hand, the item-based questions do not allow any conclusion about the causal relationship between the specific obstacles and the use of recycled concrete. The meaningfulness of the assessment of relevance may also be limited by the fact that individual items do not differ clearly enough from each other.

Another limitation that can potentially influence the interpretability of the results is the fact that the study participants had no financial incentive to fill out the questionnaire truthfully and to make a well thought-out decision in experimental situations.[53] Wilcox (1993) and Harrison (1994) point out that if the participants in the experiments are not compensated for their effort, they often do not make sufficient efforts to achieve the best possible performance. A lack of financial incentives could potentially distort the results of the study - on the one hand, it can be assumed that respondents participated in the study out of intrinsic motivation or individual interest in the topic; on the other hand, untrue or illogical answers could neither

[53] An exception is the survey of students of architecture, civil and environmental engineering in Germany and Switzerland, where 30 x 10 Euro vouchers were raffled randomly among study participants. Although this increased the incentives to participate in the study, the incentives to answer the questions truthfully and to make well-thought-out decisions in factorial survey and discrete choice experiment were not provided.

be identified nor sanctioned. Both factors could potentially impair the quality and interpretability of the responses.

In the context of the use of economic experiments, it is important to point out that the parameterisation of the experimental variables exerts a decisive influence on the estimation results. However, parameterisation as a methodological limitation plays a minor role in the present work. In the examination of economic policy measures for to increase the use of recycled concrete, the emphasis was mainly on the direction and existence of the effect and not on the quantitative expression of coefficients. In estimating the willingness to pay, the change in the experimental parameters could indeed change the coefficients and the resulting marginal rate of substitution - however, a different parameterisation would make little sense, since the parameters have been chosen in such a way as to ensure the highest possible approximation to reality.[54]

Further methodological limitations refer explicitly to the investigation of the willingness to produce recycled concrete in Chapter 5, where the readiness for production of r-concrete was determined by means of a telephone interview. There is a distortion in favour of the larger companies in the sample[55]. On the one hand, larger companies were more willing to answer the interview questions. On the other, larger companies were to a greater extent available by telephone and more often had an accessible contact person who had the expertise to answer the question. The empirical model used to investigate the willingness to produce recycled concrete is a strongly reduced representation of reality - so that only selected determinants of readiness to produce r-concrete could be considered in the model. In an optimal case, additional geographical and socio-political variables should be included in the model for control purposes, which may be problematic in view of the relatively small sample size and the resulting broad confidence intervals and high standard errors.[56]

Finally, it should be noted that although the limitations described in this section may influence the research results, it cannot be conclusively assessed to what extent and whether the results are distorted at all. Although the results of the surveys and the empirical models based on them provide indications of possible trends and causal relationships, they should not be generalised. Nevertheless, considering the

[54] In this context, further research to investigate the willingness to pay for sustainability-related attributes under different parameterisations and experimental conditions would be conceivable.

[55] The mean annual turnover for the companies that answered the question is 1.39e+07 Euros, for the companies that were unreachable or did not want or could not answer the question the mean annual turnover is 6630510 Euros ($p<0.001$ for two-sample t-test).

[56] In the telephone survey, 117 of 412 identified ready-mixed concrete companies participated, which corresponds to a response rate of 28.39 %. Despite the excellent response rate, the receptivity of the empirical model is severely limited due to the small sample size. In an optimal case, at least 200 observations (Green, 1991) or 10 observations per variable (Harrel, 2001) would be necessary for consistent estimation.

methodological limitations, the results of the presented studies are an appropriate starting point for developing empirically based measures to increase the use of recycled concrete in building construction.

6.2 Measures to increase the use of r-concrete in building construction

Before the research results and possible measures to increase the use of recycled concrete in construction can be discussed in detail, it is essential to address the fundamental question that has been raised in the course of present work. Is it possible that recycled concrete is more widespread in Switzerland because decision makers there generally have a more pronounced attitude towards sustainability? The results of the work strongly suggest that this is not the case. Firstly, there are no significant differences between Germany and Switzerland in the average and median responses on the individual attitude towards sustainability, neither among students of architecture, civil and environmental engineering nor among architects and engineers. Secondly, both students and architects and engineers in Switzerland have a lower willingness to pay for sustainability-related attributes. Assuming that a more pronounced positive attitude towards sustainability would be associated with a higher willingness to pay for sustainability-related attributes in an experimental situation, it can be concluded that students, architects and engineers in Switzerland, compared to Germany, do not have a more pronounced positive attitude towards sustainability. In the context of promoting the use of r-concrete in building construction, the above results indicate that in Switzerland the actors considered are not per se more sustainable in their self-perception and behaviour - the observed differences in the use of r-concrete between Germany and Switzerland are most likely due to other (external) factors that can be directly or indirectly influenced by political, economic and regulatory measures.

6.2.1. Public tenders

Both the executing companies and the architects and engineers identified the non-recognition of recycled materials in public tenders as one of the main reasons why recycled concrete is only used to a limited extent in building construction in Germany. Empirical models based on factorial surveys have shown that the inclusion of recycled materials as a further award criterion in public tendering has a significant positive influence on the likelihood of planning a construction project with r-concrete (for architects and engineers) and on the probability of applying for public tendering using recycled concrete (for contractors). In light of these results, it is recommended to consider the aspect of sustainability (as the use of recycled materials) as a further award criterion in public tenders. The use of recycled building materials as an award criterion should be appropriately weighted, considering all regulation-specific aspects at communal and federal state level. The wording “appropriately” is intentionally chosen because, in the absence of experience, the reaction of the actors to different weightings is not predictable. Too high a weighting of the sustainability criterion could lead to severe price increases and reduce the supply diversity in public tender; too low a weighting has only limited effect on promotion of sustainable construction.[57] Therefore, the optimal weighting should be determined over time by "trial and error" - up to the point where the highest possible weighting of the use of recycled materials, by a simultaneously tolerable additional price, is achieved.[58] In this context, Dageförde (2017) recommends weighting the price criterion with at least 30 %. However, the following aspect should be taken into account - in principle, different proportions of recycled aggregates can be used in the building materials. The aim is to provide incentives to ensure that the maximum permissible proportion of recycled aggregates is used. For this reason, it is recommended that the points awarded for the sustainability criterion (use of recycled materials) be weighted according to the proportion of recycled aggregates used in the respective building component, taking into account the intended application. The point weighting for the use of recycled materials in the public tender can be formulated as follows:

$$Points_{Sust} = Points_{Basis} \times \frac{Share^{Used}_{Recyclates}}{Share^{Max}_{Recyclates}} \tag{26}$$

Where $Points_{Basis}$ denotes the maximum number of points to be awarded for the use of recycled materials. $Share^{Used}_{Recyclates}$ indicates the actual amount of recycled aggregate used, where $Share^{Max}_{Recyclates}$marks the highest permissible amount of recycled aggregate in the corresponding component under intended use. The overall rating of the offer in a public tender with two criteria is then:

$$Score = W_{Price} \times Points_{Price} + W_{Sust} \times Points_{Sust} \tag{27}$$

and thus:

$$Score = W_{Price} \times Points_{Price} + W_{Sust} \times Points_{Basis} \times \frac{Share^{Used}_{Recyclates}}{Share^{Max}_{Recyclates}} \tag{28}$$

[57] In general, higher prices usually lead to more supply. However, it is to be expected that this law is only partially applicable to public tenders, as higher prices reduce the likelihood that the participant will win the public tender. Too high a weighting of the sustainability criterion could lead to a sharp increase in the bid price and consequently to participants assessing their chances of success as low and thus foregoing participation in the public tender.

[58] In this context it is not yet clear whether the higher weighting of the sustainability criterion would lead to higher prices. Price increases are conceivable, but the actual reaction of the market participants will depend on the respective cost structure of the company, technical capabilities and regional geographical as well as economical characteristics. The research project outlined in Chapter 1 indicate that the use of recycled concrete results in minimal additional costs, which are expected to decrease with increasing use of r-concrete and resulting experience.

Taking into account the use of recycled materials as an additional criterion in the public tender as a system of double weighting[59] as shown in equation (28) has several advantages. On the one hand, the participants of the public tender are generally given incentives to use recycled materials. On the other hand, incentives are provided to use the highest possible proportion of recycled aggregates.

Regarding the public tendering, another simple measure to increase the use of recycled concrete could be considered, although this is less realistic due to methodological and legal constraints. The extraction of the gravel and sand necessary for the production of concrete leads to the use of natural resources, which may entail additional costs due to the destruction of natural habitats of flora and fauna, emissions as well as changes in soil and water. In this context, it can be assumed that the extraction of sand and gravel is associated with an external effect - the price of gravel and sand takes into account the private, but not the external costs. Therefore, it might be appropriate that in a public tender, the decision is based on the price at which the external costs resulting from the extraction of sand and gravel are added. The public authority would pay the price indicated in the tender application, but the decision to award the contract would base on the price that takes account of the externalities. Thus, suppliers using recycled aggregates may have a higher actual price but a lower effective price. As long as the total additional costs due to the price difference corresponds to the share of external costs borne by the state, the welfare effect can be considered as neutral. In terms of welfare, it should make no difference whether public funds are spent on eliminating the negative effects of sand and gravel extraction or on a possible price mark-up of a supplier, which uses recycled aggregates and thus prevents the generation of external costs. However, a practical implementation of such a measure is currently not possible, as further research is needed to quantify the external effects of sand and gravel extraction. In particular, it is necessary to determine which external costs are associated with the extraction of sand and gravel and what proportion of these is borne by the public sector in the long term. In addition, further welfare and legal aspects of such a measure should be investigated.

Regarding the public tender procedure, a further measure would be advisable. In the context of the present work, inconsistent and uncertain regulation was identified

[59] A simple example of a fictitious public tender with two bidders who differ only in the proportion of recycled aggregates used: maximum of 100 points is awarded for both the price and sustainability criteria; price is weighted at 70 % and sustainability at 30 %; company A would use 25 % recycled aggregate, company B, on the other hand, would use 10 %. The maximum permissible proportion of recycled aggregates in respective application is assumed to be 25 %. The total number of points is respectively: $Score_A = 0.7 \times 100 + 0.3 \times 100 \times \frac{0.25}{0.25} = 100$ for company A and $Score_B = 0.7 \times 100 + 0.3 \times 100 \times \frac{0.1}{0.25} = 82$ for company B. Company A would win the contract in this public tender.

as one of the obstacles why recycled concrete is used to a limited extent in the building construction in Germany. The practice of public tendering is determined by several federal state- and community-specific laws and regulations, which are partially highly different. In this context, the standardisation and nationwide harmonisation of public tender-related governmental regulation is recommended. The use of recycled materials should be taken into account as a further criterion in public tendering - the award procedure, weighting of the criteria and the evaluation process should be communicated publicly and transparently to the bidders and handled in the same way in all federal states and communities.

6.2.2. Label

The non-recognition of the recycled materials usage by a label was identified as one of the main reasons for the limited use of recycled concrete in building construction in Germany, both by contractors and by architects and engineers. The experimental evidence is ambiguous - for architects and engineers, the probability of planning a building project using r-concrete increases when the use of recycled materials is recognised by a label; for contractors, however, the likelihood of applying for a public tender using r-concrete decreases when the use of recycled materials is recognised by a label. For architects and engineers, the responses given in the survey are consistent with the experimental results. In contrast, the contractors see the non-recognition by a label as one of the main obstacles to the use of r-concrete, but are less likely to participate in public tendering if the recycled building materials are recognised by a label. A possible explanation for this observation is the fact that the use of recycled materials has different consequences for the respective actors. A particularly sustainable construction project can improve the image and prestige of architects and engineers and can be used for marketing purposes. For contractors, the use of recycled building materials has rather negative practical implications, as recognition through a label is inevitably linked to the fulfilment of additional regulation standards, which can cause additional costs and affect the price competitiveness in public tender. Against this background, the question arises whether the recognition of recycled materials in a label can be recommended as a measure to increase the use of recycled concrete in building construction. This question is to be answered in the affirmative. Empirical and experimental evidence regarding planning actors is considered sufficient to recommend such a measure. Experimentally, although there is evidence of aversion on the part of the executing companies to the obligation to comply with additional standards, it can be assumed that this is an initial phenomenon, given the undeveloped market and the limited spread of recycled concrete. Once recycled materials have been recognised by a label, companies would, over time, increasingly acquire both technical and regulatory expertise and experience so that the use of recycled materials would no longer involve significant efforts and additional adjustments in the value chain.

6.2.3. Knowledge and information

Both, a lack of knowledge and experience with recycled concrete and a shortage of adequately trained employees were identified as further major obstacles to the use of r-concrete in building construction. There are significant differences between Germany and Switzerland, whereby the relevance of these aspects[60] is systematically perceived as higher in Germany. For the lack of knowledge and experience with recycled concrete, from the perspective of executing companies the median for Germany is 76 and for Switzerland it is 3; for the lack of appropriately trained employees, the median for Germany is 51, while in Switzerland it is 10.5. For the lack of knowledge and experience with recycled concrete, from the perspective of architects and engineers the median for Germany is 79 and for Switzerland 54; for the lack of appropriately trained employees, the median for Germany is 60, while in Switzerland it is 44. 19 % of respondents in Germany stated to have previous experience with r-concrete, compared to 82 % in Switzerland.

The above considerations refer to the obstacles from the point of view of contractors, architects and engineers. However, when comparing the results of the survey of the executing and planning actors with those of the students, there are indications that the identified lack of adequately trained employees and knowledge may be related to university education. Firstly, a significantly higher proportion of students in Switzerland have already heard of recycled concrete during their studies - 74 % in Switzerland and 52 % in Germany. Secondly, there are significant differences in the perceived coverage of the regulatory and technical properties of r-concrete in study contents - in both cases, on a scale of 1 to 4, the median is 3 for Switzerland and 2 for Germany.[61] Thirdly, when comparing the perception of the depth of treatment of sustainability-related contents between countries, students in Switzerland gave in median significantly higher values in most of the dimensions considered. Fourthly, students in Switzerland perceive the sustainability-relatedness of the practical elements of their studies as significantly higher - the median for Switzerland is 3 and for Germany 2.[62]. On the basis of the available data, the causal relationship between recycled concrete- and sustainability-related theoretical and practical contents in

[60] Items were coded from *1=not relevant at all* to *100=very relevant*.

[61] Respective items: "Technical and chemical properties of r-concrete were covered extensively within the course of study" (sr03; from *1=strongly disagree* to *4=strongly agree*) and "Regulatory aspects of r-concrete were covered extensively within the course of study" (sr04; from *1=strongly disagree* to 4=*strongly agree*).

[62] Respective item: "Practical elements of the studies have a strong connection to circular economy" (sn06; from *1=strongly disagree* to *4=strongly agree*).

the study on the one side and lack of knowledge as an obstacle perceived by architects, engineers and executing companies on the other side, cannot be conclusively determined. However, empirical observations may indicate that a lower coverage of r-concrete- and sustainability-related contents in studies in Germany could lead to a lower level of knowledge among professionals and correspondingly to a lower use of recycled concrete. The tendency is clear from observed data - lack of knowledge and experience in the field of r-concrete is perceived as an obstacle to a higher degree in Germany; at the same time, sustainability and recycled concrete-related theoretical and practical contents seem to be treated to a lower degree in Germany during the studies of architecture, civil and environmental engineering.

Both a lack of knowledge and experience with r-concrete and a shortage of adequately trained employees have been identified as direct obstacles to the use of r-concrete. In addition, the relevance of other obstacles has been assessed as high, which, although not directly related to knowledge, point to the lack of information and knowledge. These include the perceived relevance of obstacles such as insufficient research on recycled concrete and limited application possibilities. Summing-up, in view of the discussed results, it is recommended to intensify existing measures for information and knowledge transfer, for students, as well as for executing and planning actors. Above all, sustainability- and r-concrete-related contents should be addressed to a greater extent in the course of studies of architecture, civil and environmental engineering.

The above recommendation can also be supported by the empirical model presented in Chapter 2. It was found that the professional training measures on the subject of recycled concrete increase the likelihood that the executing companies apply for the public tender using r-concrete. In addition, it has been shown that there is potentially a positive relationship between the perceived substitutability of concrete and the depth of coverage of sustainability-related contents in the studies. In view of the results observed in the student survey, it would be plausible to assume that the more comprehensive discussion of sustainability-related contents within the framework of the study could result in a higher perceived substitutability of r-concrete and consequently, in a wider use of recycled concrete.

In view of the recommendation made, the question arises as to how the measures for information and knowledge transfer in the field of recycled concrete can be organised and implemented in practice. In order to be admitted to the Chamber of Architects in Germany, proof must be provided that a certain amount of professional trainings have been attended after the university graduation. In addition, the laws of the federal states lay down the obligation to undergo further annual trainings - specific provisions are described comprehensively in the advanced training regulations of the respective architectural chambers. Even though the details of these regulations vary between federal states, a certain number of advanced training hours must be attended each year - the topics of the further training courses can be chosen freely and should only be based on the focus of the architect's or engineer's work. In the context of promoting the use of recycled concrete in the building construction, two specific measures are recommended regarding architects and engineers. Firstly, a mandatory module on sustainability[63] should be introduced, both for the admission into the Chamber of Architects and for the annual advanced training - the architects and engineers should be obliged to attend a certain proportion of the advanced training courses from this module. This measure requires changes to the advanced training regulations of the federal chambers of architects, which should be implemented uniformly nationwide. Secondly, the range of events offered and acknowledged by the federal chambers of architects on sustainable building and r-concrete must be significantly extended. On 5th May 2020, all publicly listed professional training events of the federal chambers of architects were reviewed and analysed in terms of their thematic emphasis. As shown in Table 28[64], out of a total of 1420 courses offered for 2020, only 3 deal with the topics of sustainable construction or recycled concrete. The necessity of expanding the range courses in the field of sustainable construction and r-concrete is obvious.

Architects and engineers are organised in chambers of architects and are characterised by a relatively homogeneous occupational profile - accordingly, measures for information and knowledge transfer can be implemented and coordinated with relatively little effort. By contrast, the companies and the skilled workers involved in carrying out building construction work are a highly heterogeneous group that includes many different professions and activities. These are organised in chambers of crafts or industry and commerce. Due to the heterogeneity of the members, the central obligation for further training as for architects and engineers is neither desirable nor enforceable. In the context of the promotion of sustainable construction, the chambers of crafts, industry and commerce should rather act as mediation platforms to draw attention to the events on sustainable construction and r-concrete that are

[63]The thematic focus of the courses in this module should be as diverse as possible so that architects and engineers of all disciplines can acquire additional expertise in all facets of sustainability. For example, recycled concrete and sustainable building is of little relevance to interior architects. Nevertheless, courses on sustainable material selection or recycling-friendly interior design could be useful in promoting sustainable construction.

[64]The present observation is only a reference and is intended to provide only a rough indication of possible tendencies. It should be noted that the range of events offered may overlap between the federal states. Only the events from 5th May to 31th December 2020 were taken into account. Whether the topics of sustainable construction or r-concrete are addressed in the offered training was determined subjectively on the basis of the description of the event - it is however both conceivable and possible that the topics will be dealt with in further courses, even if the course description does not indicate a direct reference. It should be noted that currently numerous events have been cancelled or postponed due to the lock-down resulting from SARS-CoV-2 spread.

Table 28: Training courses offered or acknowledged by federal chambers of architects on the subject of sustainable construction or r-concrete

Federal state	Total	Sustainability
Baden-Würtemberg	161	2
Bavaria	175	0
Brandenburg, Berlin	135	0
Hamburg	112	1
Hesse	148	0
Mecklenburg-Vorpommern	98	0
Lower Saxony, Bremen	123	0
North Rhine-Westphalia	186	0
Rhineland-Palatinate	50	0
Saaarland	11	0
Saxony	34	0
Saxony-Anhalt	10	0
Schleswig-Holstein	99	0
Thuringia	78	0

Status: 5 May 2020.

organised by external actors.

Whether and to what extent r-concrete is used in building construction depends on a multitude of different actors. These are enterprises and specialists in the construction, concrete and raw materials value chain, representatives of regional administration and politics, but also scientists and research institutions. In order to promote the inter- and transdisciplinary networking of the actors, it is recommended that regular events are organised and carried out by the federal states and local authorities in which different actors can exchange knowledge and experience in the field of circular economy, sustainable construction and r-concrete.[65] Such events should inevitably include blocks at which the technical and regulatory possibilities of using recycled building materials in construction are demonstrated on the basis of successfully implemented projects. In order to create and canalise the incentives for further professional development, it is recommended that such events be recognised as further training by the chambers of architects and engineers.

6.2.4. Governmental support

On the basis of conducted research, the lack of governmental support was identified as one of the central obstacles to the use of recycled concrete in Germany - the

[65]In the context of this recommendation, the current development provides an optimistic view of the future. In recent years, numerous events on the subject of circular economy and the use of recycled materials in building construction have already been organised and carried out by various players. Particularly worth mentioning are the event activities of the federal states of Baden-Württemberg and Rhineland-Palatinate, Network Circular Value Creation :metabolon, Resource Foundation, Federal Ministry of Education and Research (HighTechMatBau), IRR - Innovation Region Rheinisches Revier GmbH and many others.

relevance[66] was evaluated by executing companies with 91 and by architects and engineers with 77.5 in median. Furthermore, the relevance of the lack of tax incentives and subsidies was rated 73.5 and 71 by architects and engineers and 76.5 and 81 by contractors. The empirical results point to the need for governmental support measures to increase the use of r-concrete in building construction. In the following, it will be discussed how such support measures can be designed and whether these are legally feasible.

In the factorial survey of the executing companies presented in Chapter 2, it was found that, in the case of reimbursement of additional costs resulting from the use of recycled materials of at least 50 %, the estimated probability of participating in the public tender using recycled concrete exceeds the likelihood of non-participation. If, however, a negative scenario is assumed, a reimbursement of 120 % would be necessary, which means that not only the additional costs resulting from the use of recycled building materials must be reimbursed, but also their use should be subsidised with 20 %. This implies that the executing companies would have to be compensated for the use of r-concrete with 20 % of the possible cost difference in addition to the reimbursement of the total cost difference. At this point it should be made clear that r-concrete can generally be produced without additional costs. However, if additional costs are incurred through the use of r-concrete, it can be expected that the final price differences between recycled and conventional concrete are marginal. The potential need for subsidies can be illustrated by a highly simplified example.[67] If the price of conventional concrete is 100 Euros per cubic metre and 60 cubic metres of concrete are used in a single-family house, the total cost of concrete for the construction is 6000 Euros. Assuming that recycled concrete is offered for 105 Euros per cubic metre, the use of r-concrete results in additional costs of 300 Euros per single-family house. If the empirically estimated reimbursement rate of 120 % is taken as a basis, the total amount of the required governmental support is 360 Euros - 300 euros direct reimbursement of additional costs resulting from the use of r-concrete and 60 Euros subsidy. In view of the fact that this is a negligible amount compared to the total costs of the construction project, it can be assumed that these costs are bearable in terms of fiscal policy. Despite the fact that the above example is based on estimates of a very restrictive empirical model, the reimbursement of costs can be proposed as an economic policy recommendation, not least due to the relatively low financial burden on the public sector and the empirically proven

[66]Mentioned items were coded from *1=not relevant at all* to *100=very relevant*.

[67]For illustrative purposes, it was assumed in this example that the entire house can be built with a homogeneous type of concrete whose production and use is also possible as recycled concrete. In reality, different concrete types must be used for different building components, applications and external influences. Furthermore it is important to note that the use of r-concrete is not permitted in all applications.

positive impact on the participation in the public tender using r-concrete.

Therefore, it is recommended to introduce a publicly financed aid to increase the use of r-concrete in building construction. The aid should consist of the reimbursement of additional costs resulting from the use of r-concrete weighted by the coefficient of the actually used and the maximum permissible percentage of recycled aggregates in a respective application. All companies that substitute concrete required for building construction with recycled concrete can apply for cost reimbursement if additional costs are incurred due to the use of r-concrete. The reference value for the reimbursement should be the average regional price for standard concrete in a respective application. In order to prevent adverse adjustment effects on the part of market participants and to ensure cost efficiency, the reimbursement amount per cubic meter of concrete is to be capped.[68]

$$Refund_{Weighted} = Refund_{Basis} \times \frac{Share^{Used}_{Recyclates}}{Share^{Max}_{Recyclates}} \tag{29}$$

The cap on the amount of the refund is at the discretion of the respective decision-makers in public administration and politics - it would be conceivable to limit the refund scheme only to the situation where the price difference between r-concrete and conventional concrete does not exceed 30 %. Thus, for example, 100 % of the costs resulting from the use of r-concrete can be reimbursed, as long as they do not exceed the costs that would result from the use of standard concrete by 30 %. As can be seen from equation (29), the reimbursement amount is linked to the proportion of recycled aggregates used. This is intended to provide incentives to use the maximum permissible amount of recycled aggregates. $Refund_{Basis}$ indicates the maximum reimbursement rate of the costs resulting from the use of recycled concrete. Due to the lack of experience with such measures, the reaction and behaviour of market participants is uncertain - for example, in a component with 1 % recycled aggregate, but where 25 % would be the maximum allowed, the reimbursement of additional costs would be 4 % when the $Refund_{Basis}$ is set to 100 %. In such a situation, however, it is questionable whether the company would choose to substitute standard concrete with recycled concrete. Depending on the actual behaviour of the actors, it is quite conceivable to set $Refund_{Basis}$>100% in the introductory phase of the measure and gradually reduce it over time, depending on the results achieved. In the example above, an increase of $Refund_{Basis}$ to 250 % would imply the potential additional costs reimbursement of 10 %. In this situation, assuming that the company uses the maximum permissible proportion of recycled aggregates in the building

[68]The aim is to increase the sustainability in construction. Therefore, costs and benefits must be in an appropriate relationship to each other.

component, the reimbursement of the additional costs would be 250 %. This means on the one hand that the cost difference between conventional and recycled concrete is reimbursed at 100 % and on the other hand that companies are rewarded for the use of r-concrete with 150 % of the price difference. Given a price difference of approximately 5 Euros per cubic metre, as was observed during the construction of a university building in Berlin (Mettke et al., 2015), the reimbursement rate of 250 % would mean that, on the one hand, the cost difference of 5 Euros would be reimbursed and, on the other, the company would be granted 7.5 Euros per cubic metre of recycled concrete. Concrete for interior construction elements and foundation elements of exposure class XC1 is listed by Heidelberger Beton at 151 Euros per cubic metre (Heidelberger Beton, 2020), which indicates that the relative financial burden of the proposed measure is quite moderate from a fiscal policy perspective. At present, however, no statements can be made about the practical effectiveness of the cost reimbursement, not least because the willingness to substitute conventional concrete with recycled concrete may depend to a large extent on further accompanying measures to increase the use of r-concrete in building construction. However, the empirical results of the factorial survey of executing companies indicate that cost reimbursement could potentially increase the use of r-concrete in building construction.

In order to increase the use of r-concrete in building construction, the introduction of a tax reduction on turnover tax for ready-mix concrete is also conceivable. Similar to the cost reimbursement, this measure should be linked to the proportion of recycled aggregates used, as shown in equation (30). $Tax^{Final}_{Turnover}$ denotes the final turnover tax which is levied on concrete. $Tax^{Basis}_{Turnover}$ marks a regular turnover tax on concrete. $Reduction_{Basis}$ indicates the highest possible percentage reduction of the turnover tax. If the turnover tax is 19 % and the highest possible tax reduction for ready-mixed concrete is defined as 50 %, a company that has used 25 % of r-concrete in a component with maximal permissible proportion of recycled granulate of 25 % would have to pay a turnover tax of 9.5 % ($0.19 - 0.19 \times 0.5 \times \frac{0.25}{0.25} = 0.095$). In contrast, if in the equivalent situation the company would use only 1 % of recycled granulates, the turnover tax on concrete would be 18.62 % ($0.19 - 0.19 \times 0.5 \times \frac{0.01}{0.25} = 0.1862$).

$$Tax^{Final}_{Turnover} = Tax^{Basis}_{Turnover} - Tax^{Basis}_{Turnover} \times Reduction_{Basis} \times \frac{Share^{Used}_{Recyclates}}{Share^{Max}_{Recyclates}} \quad (30)$$

The tax relief as an instrument to promote the use of r-concrete in building construction can be characterised by a considerable degree of flexibility. On the one hand, the basis reduction rate ($Reduction_{Basis}$) can be set in such a manner that only the price competitiveness of r-concrete is ensured. On the other hand, if the basis reduction rate is further increased, r-concrete becomes increasingly cheaper than conventional concrete. In both cases, incentives are provided to exploit the maximum permissible proportion of recycled aggregates. This measure inevitably raises the question of how high the tax reduction rate should be set. As the reaction of the market participants cannot be predicted, it is advisable to set the initial tax reduction rate at a relatively low value of 20 %. The measure should be evaluated on a regular basis - it may be necessary to increase the original 20 % rate until the desired effect is achieved. The desired effect is the use of r -concrete in all building construction applications permitted by the regulations with a maximum permissible proportion of recycled aggregates.

Apart from the practical implementation of the proposed measures, the question arises whether such measures are legally permissible. According to the Treaty on the Functioning of the European Union (TFEU), any aid granted by a state or through state resources in any form which distorts or threatens to distort competition by favouring certain enterprises or the production of certain goods is incompatible with the common market and therefore in principle not permissible (TFEU Article 107 §1). However, exceptions to the above principle are also foreseen. §3 (b) and (c) of Article 107 of the Treaty on the Functioning of the European Union are particularly relevant to the possible support for the use of r-concrete in building construction and the production of recycled aggregates or recycled concrete. These regulate aid that can be considered compatible with the internal market and therefore may be permissible. Accordingly, aid to promote the execution of important projects of common European interest and aid to facilitate the development of certain economic activities or of certain economic areas, if such aid does not adversely affect trading conditions to an extent contrary to the common interest, may be permissible. Member States intending to grant aid are obliged to notify their intentions to the European Commission before implementing the measure (TFEU Art. 108 §3). State aid can therefore only be granted after a decision in the course of which the European Commission examines whether the conditions of Article 107 are met. Regarding the formulation of Article 107 §3 of the Treaty on the Functioning of the European Union, the European Commission has significant discretion in determining permissible aids. According to Article 107, aid may be permissible if it is intended to promote important projects of common European interest. The provisions of Directive 2008/98/EC of the European Parliament and of the Council of 2008 on waste management and recycling can be interpreted as an expression of the common European interest. Accordingly, waste is to be avoided in the first instance (Article 4) and measures are to be taken by member states to promote high-quality recycling (Article 11). As the use of r-concrete on the one hand avoids construction waste and on the other hand ensures high-quality recycling in similar applications, it can be assumed that the proposed measures aiming to increase the use of recycled concrete in building construction could be permissible.[69]

6.2.5. Proportion of recycled aggregates in concrete

A further possible obstacle to the use of r-concrete in building construction is a relatively low maximum permissible proportion of recycled aggregates in the concrete. For architects and engineers in Switzerland, this obstacle seems to play a rather minor role as it is rated in median at 30 for its relevance[70] - in Germany it is rated significantly higher at 51. Among executing companies, the relevance of the maximum permissible proportion of recycled aggregates as obstacle is rated at 53 in Germany and 55.5 in Switzerland. Despite the relatively low perception as an obstacle, in the factorial survey of architects and engineers in Germany was found that the increase of the maximal permissible proportion of recycled aggregate in concrete significantly increases the probability of planning a construction project using recycled concrete.

Within the framework of comprehensive research projects, it was proven that quality requirements for concrete are also met if the proportion of recycled aggregates is increased (Stürmer & Kulle, 2017; Nobis & Vollpracht, 2015). In view of the fact that technical equivalence is ensured in most applications and the experimental evidence from the factorial survey, it is recommended to increase the maximum permissible percentage of recycled aggregate in concrete. This would result in the advantage of exploiting economies of scale in the production of concrete. A higher proportion of recycled aggregates could reduce average costs - on the one hand, because the initial adjustment costs are spread over larger quantities and, on the other hand, because price discounts are granted in many cases for larger quantities of secondary aggregates purchased. Increasing the maximum amount of secondary aggregates that can be mixed in could thus increase the price competitiveness of recycled concrete against conventional concrete. In view of this recommendation, the question arises to what extent and for which application classes the maximum permissible proportion of recycled aggregates should be increased. Since numerous factors such as the chemical and physical properties of concrete, future application purposes and long-term material behaviour must be taken into account, this question cannot be answered conclusively within the framework of an economically oriented

[69] Only the rough competition law principles of the possible measures to increase the use of r-concrete in building construction have been outlined here. It should be borne in mind that the competition law regulations of the European Union are not limited to the Treaty on the Functioning of the European Union. At this point, there is a need for further research regarding the feasibility of the proposed measures under competition law. Despite the fact that this topic is more far-reaching than has been presented, the provisions of Article 107 paragraph 3 (b) and (c) of the Treaty on the Functioning of the European Union may indicate that aid to promote the use of r-concrete could be permissible.

[70] Mentioned items were coded from *1=not relevant at all.* to *100=very relevant.*

work. It would be conceivable to follow international practice, such as in Switzerland, i. e. to increase the maximum permissible proportion of recycled aggregates to 100 % for concrete exposure classes XC0, XC1, XC1-3 and XC4 of type 1 (type C in Switzerland). Precise specifications regarding the possible increase in the maximum proportion of recycled aggregates in concrete should be developed within the framework of an independent research project. Subsequently, the results should be discussed in expert circles, consisting of representatives of politics and administration, concrete manufacturers, executing and planning companies of the construction value chain, and implemented in regulatory practice.

6.3 Practical implementation

An important aspect must be taken into account when implementing proposed economic policy measures. In particular, the reimbursement of additional costs resulting from the use of r-concrete, the reduction of turnover tax and the inclusion of recycled materials in the public tender are relatively new measures, for which the environmental effectiveness and the reaction of the market participants are uncertain. On the one hand, it may be necessary to adjust the measures, for example by changing the weighting of the sustainability criterion in the public tender or by changing the highest possible tax reduction rate. On the other hand, implemented measures may lead to undesired adjustment effects which, although they achieve the desired goal, lead to significant distortions in the market. Uncertainty thus creates a risk for all actors involved. For this reason, the immediate nationwide imposition of all proposed and homogeneous designed measures is not recommended. Rather, the practical implementation of the measures should take place in 4 phases. In the first phase, different implementation variants of a measure are to be tested against the background of the environmental policy objective and the behaviour of the market actors at local regional level. Each region selected for the project pilot should test a differently designed measure. In Berlin and Cologne, for example, different refund rates of turnover tax could be tested, while in Aachen the consideration of recycled building materials in public tenders would be examined. In the second phase the local measures are to be evaluated and adjusted by an independent inter- and transdisciplinary commission. In the third phase, a nationwide commission should be set up to evaluate the experience of all regional measures and develop a concept for nationwide implementation of the entire measures package. In the fourth phase, the developed measures are to be implemented throughout Germany.[71] In this context,

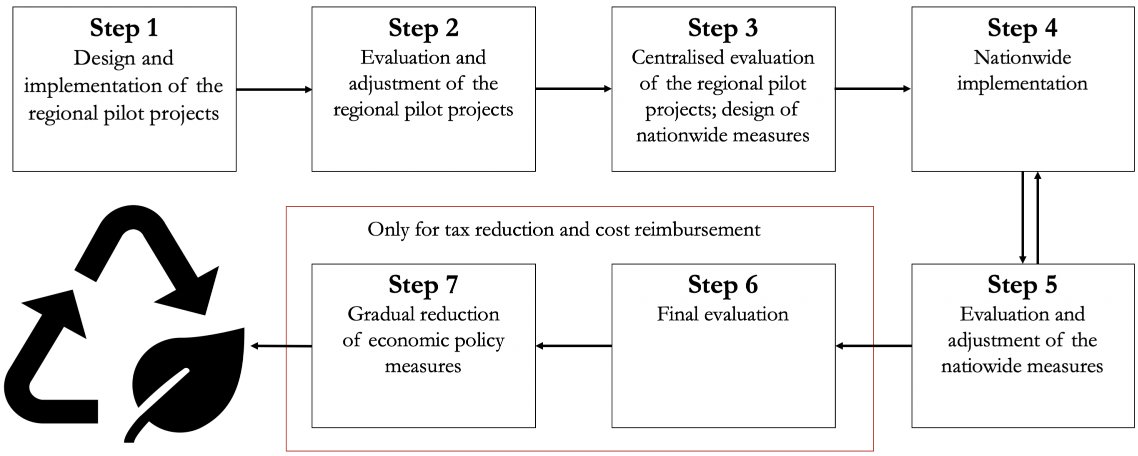
[71]An example of a similar multi-stage approach is the implementation of the emissions trading system in China. Starting in 2013, differently designed emissions trading systems were introduced and tested in 7 Chinese provinces. After the evaluation of each of the 7 pilot projects, a nationwide emissions trading system was introduced in 2017. (Goulder et al., 2017; ICAP, 2020)

the practical examination of the effectiveness of a single measure to increase the use of r-concrete would be conceivable within the framework of a natural experiment in a regionally restricted pilot project. This would involve introducing a measure in selected conurbations and scientifically observing the reaction of market participants and, above all, the use of r-concrete in building construction. After a certain period of time, the results of this measure in the pilot regions would be compared with those of comparable regions where a respective measure have not been carried out. The results with regard to the use of r-concrete would thus be compared both over time, i.e. before and after the introduction of the measure, and between the regions where the measure was and was not introduced.

As already mentioned above, the measures in the pilot projects should be tested individually. However, the Germany-wide introduction is to take place as a concentrated action in the entirety of the designed measures. In order to determine the causal effect throughout Germany, it would be conceivable to introduce each individual measure in turn. Since in this case each individual measure should be implemented, evaluated and reintroduced after adaptation, the process from initial nationwide implementation of a single measure to nationwide introduction of the overall measures package could take decades. As primary resources are further depleted during this time and potentially avoidable construction waste is produced, such an approach is not recommended. The measures are to be introduced within the framework of a simultaneous concentrated action and should be gradually reduced after nationwide implementation once recycled concrete has established itself as a building material. In order to ensure regulatory certainty and consistency, the measures are to be designed as homogeneously and transparently as possible nationwide. Nevertheless, local economic, geographical and legal characteristics of the regions should inevitably be taken into account.

An important indication for the design of the pilot projects is provided by the results of the investigation on the willingness to produce recycled concrete, which was presented in Chapter 5. It was found that company size, local concrete market concentration and economic activity of the region have a significantly positive impact on the willingness to produce recycled concrete. In view of this finding, it is advisable to implement the pilot projects in the first phase primarily in the conurbations, which are characterised by large population and high regional concrete market concentration. The advantage lies in the fact that potentially shorter transport distances are realisable there, which allows the ecological and economic advantage of r-concrete over conventional concrete to be exploited. In addition, it is expected that urban areas in particular are potentially characterised by higher demand and supply of recycled aggregates. Larger companies in highly concentrated markets are potentially able to meet the demand for r-concrete from a single source. Since the production of recycled concrete involves additional control and adjustment costs, which are incurred individually by each producer, price competitiveness and continuity of supply can be ensured to a greater extent in such circumstances than if many smaller suppliers were to serve the entire regional demand for r-concrete. Another important finding that emerges from the study in Chapter 5 is the fact that, contrary to widespread opinion, the supply of r-concrete is potentially existing. More than 27 % of the companies stated that they would definitely or very probably produce r-concrete in a quantity and quality comparable to other orders with conventional concrete. 117 from 412 companies, operating 457 from 1267 concrete production facilities took part in the survey. Thus, more than 28 % of concrete producing companies, which operate 36 % of concrete producing plants in Germany, participated in the study. Based on the results outlined above, it would be advisable to implement the pilot projects first in those regional hotspots, which are characterised by high potential willingness to produce recycled as shown in Figure 29.

Figure 36: Outline of the practical implementation of measures to increase the use of concrete in building construction



6.4 Qualitative validation of the results

The students could not be invited directly to participate in the survey presented in Chapter 3. Therefore, the professors of architecture, civil and environmental engineering were asked to forward the survey to their students. To enable the professors to participate in the survey and to bring their expertise into the research, it could be chosen at the beginning of the survey whether one belongs to the group of professors or students. If the respondent indicated that he or she belonged to the group of professors, one was asked to answer two open qualitative questions:

- "In your opinion, what is the most important reason why r-concrete is only used restrictively in building construction in Germany?"

- “In your opinion, what would have to happen for r-concrete to be used to a greater extent in building construction?”

Among other items, these two questions have also been asked to architects and engineers. In the context of this chapter, the qualitative answers to the above questions will be discussed in the context of the derived economic policy recommendations. In particular, it will be examined whether the identified obstacles and derived recommendations for increasing the use of r-concrete in building construction correspond to the statements made in the open questions. In contrast to the empirical evaluation of the standardised survey items, as in the course of the previous work, subjective perceptions and impressions of the actors involved will be also addressed.

At least one of the open questions asked was answered by 588 respondents - 32 of whom are professors of architecture, civil or environmental engineering. More than 40 % of the respondents stated that lack of experience, information or knowledge about r-concrete is the most important obstacle for the use of r-concrete in building construction. In some cases, a lack of environmental awareness and a lack of willingness to deviate from existing habits was pointed out. Especially among building contractors, r-concrete seems to be poorly known and appears to face low acceptance. Despite the fact that in most cases the technical and physical properties of recycled concrete are equivalent, recycled building materials are associated with a negative image and poor quality, according to the argumentation. With regard to the lack of experience, information and knowledge, the data of the qualitative questions correspond to the results of the standardised survey items.

A further aspect, which was indicated by the respondents, is the fact that the price of r-concrete is not competitive compared to conventional concrete. In a decision-making situation between two building materials, the argumentation is that in view of the lack of environmental awareness and the pursuit of profit, one always chooses the cheaper alternative. A pronounced perception of the insufficient price competitiveness of recycled concrete compared to conventional concrete can also be observed in the evaluation of the standardised survey items among contractors and architects. In the course of the work, low demand and supply were identified as important obstacles to the use of r-concrete - the importance of these obstacles is also pointed out in many cases in the open questions. Several respondents indicated that they would consider the use of r-concrete, but this is not an option in view of the lack of supply. One of the respondents stated that he had never heard of a concrete manufacturer offering recycled concrete.

An interesting aspect that may provide a stimulus for further research is the fact that five respondents indicated that the lobbying of ready-mixed concrete producers is the most important reason for the limited use of r-concrete in building construction in Germany. This aspect was mentioned both in the group of professors and in the group of architects and engineers. The lobby of the ready-mixed concrete manufacturers influences the legislative process on the one hand, but also the technical regulations regarding r-concrete on the other hand, according to the argumentation. Whether this can actually be one of the reasons why r-concrete is only used cautiously in building construction in Germany remains open in the light of this work, but should be addressed in the context of further research.

Regarding the economic policy measures necessary to increase the use of r-concrete in building construction, the information provided in the open questions corresponds to the economic policy measures discussed in the previous subsection. Most respondents recommend different types of governmental support to ensure price neutrality, revision of the regulatory framework to simplify the use of r-concrete, consideration of recycled materials in public tenders and recognition in a label. In particular, the necessity is emphasised, on the one hand, to communicate more intensively the technical and regulatory information on the application of r-concrete and to disseminate this information through further training seminars and, on the other hand, to publicly promote the use of r-concrete. There appears to be a broad consensus that sustainability and r-concrete-related content should be given greater emphasis in professional training and university curricula.

7 Final conclusion

Mineral construction waste represents the largest waste fraction in Germany. Despite the high recycling rate in building construction, the processed secondary materials are mainly used for non-equivalent applications. The potential for producing high-quality materials from the secondary aggregates is not being exploited - current recycling practice in Germany is mainly characterised by downcycling. In view of the fact that the use of recycled materials in building construction is both technically and regulatively possible, inevitably the question arises as to why r-concrete has so far been used in building construction in Germany to a very limited extent and what measures can be taken in order to increase the use of r-concrete in building construction. For this reason, in the present dissertation the obstacles to the use of recycled concrete and possible measures to increase the use of r-concrete in the construction sector were examined. The aim of the work was to derive an empirically based economic policy recommendation for increasing the use of r-concrete in building construction. For this purpose, four empirical studies were carried out, which shed light on diverse facets of the problem from the perspective of different actors in the construction value chain.

In the study presented in Chapter 2, an item-based and factorial online survey was conducted to investigate the obstacles and possible economic policy measures to increase the use of r-concrete in building construction. The survey was focused on the executing companies of construction value chain in Germany and Switzerland. It was found that the obstacles to the use of r-concrete that are perceived as most relevant from the point of view of executing companies in Germany are the lack of governmental support, low demand and supply, inconsistent and uncertain regulation, absent recognition through labels and certificates, and lack of knowledge and experience with recycled concrete. Compared to Switzerland, the relevance of barriers such as absent recognition through labels and certificates and the lack of knowledge and experience with recycled concrete was rated significantly higher in Germany. Regarding the intended increase in the use of r-concrete in building construction, it was found that the consideration of recycled materials in the public tender, reimbursement of the additional costs resulting from the use of r-concrete and further training measures on the subject of r-concrete significantly increase the willingness to participate in the public tender using recycled concrete. Recognition of the use of recycled materials in a label, on the other hand, reduces the likelihood of applying for the public tender using recycled concrete.

In the study presented in Chapter 3, an online survey was conducted among students of architecture, civil and environmental engineering in Germany and Switzerland. By means of an item-based survey it was examined whether sustainability-related contents were covered to a higher extent during studies in Switzerland than is the case of Germany. The discrete choice experiment was used to test whether students in Switzerland are characterised by a higher willingness to pay for sustainability-related attributes. By directly comparing the perceived extent to which sustainability-related topics were addressed in the course of studies, it was found that topics such as waste treatment, circular economy, resource efficiency, selective deconstruction and environmental protection were treated to a significantly higher degree in Switzerland. Furthermore, it was found that students in Switzerland on average assess the substitutability of r-concrete in building and underground construction as significantly higher than students in Germany. In addition, the results indicate that more intensive treatment of the sustainability-related contents as well as a focus on sustainability in the practical elements of the study may increase the perceived substitutability of recycled concrete. The results of the discrete choice experiment suggest that students in Switzerland are characterised by a lower willingness to pay for sustainability-related attributes.

In the study presented in Chapter 4, the obstacles to the use of r-concrete and the willingness to pay for sustainability-related attributes were examined empirically. For this purpose, an item-based and factorial survey as well as a discrete choice experiment of architects and engineers in Germany and Switzerland were conducted. Factors such as lack of knowledge and experience with r-concrete, low supply and demand, lack of governmental support and the non-consideration of recycled materials in public tenders were identified as central obstacles to the use of r-concrete in building construction. The relevance of the obstacles in the use of r-concrete is systematically perceived as significantly higher in Germany than in Switzerland. At the same time, the relevance of the obstacles in Germany is perceived by the executing companies as systematically significantly higher than by architects and engineers. In context of factorial survey it was found that the recognition of recycled materials in a label and the consideration of recycled materials in the public tender as an additional award criterion significantly increases the willingness to plan a construction project using r-concrete. Furthermore, the results of the discrete choice experiment indicate that architects and engineers in Switzerland are characterised by a lower willingness to pay for sustainability-related attributes.

In the study presented in Chapter 5, economic and geographical determinants of the willingness to produce recycled concrete were investigated empirically. For this purpose, a telephone survey of ready-mixed concrete producers in Germany was conducted. It was found that the economic activity of the region has a significantly positive influence on the willingness to produce recycled concrete. Company size and the concentration of the regional concrete market also have a significantly positive impact on the production readiness of r-concrete. In contrast, the willingness to produce recycled concrete decreases if the respective ready-mixed concrete producers are involved in the extraction and production of sand and gravel in addition to their main activity, but increases if the companies are active in the collection of waste.

Based on the empirical results of the work, policy recommendations can be derived to increase the use of recycled concrete in building construction. The consideration of the use of recycled materials need to be included as a further award criterion in the public tender. The criterion should be weighted appropriately considering the actual proportion of recycled aggregates used. The elements of regulation concerning the criteria for deciding on the award of the contract in public tendering should be harmonised nationwide. The increase of the maximum permissible proportion of recycled aggregates in concrete and the recognition of the use of recycled materials in a label are also recommended as further measures. To increase the use of recycled concrete in building construction, additional cost refunds and tax reductions are advisable. Both the additional cost reimbursement and the tax concession should take into account proportion of the recycled aggregates actually used in the total permissible recycled aggregates in a respective application. In addition, it is recommended to intensify existing measures for information and knowledge dissemination in the field of recycled concrete and sustainable construction. On the one hand, these topics should be addressed to a greater extent within the framework of vocational and university training and, on the other hand, should be included as a compulsory module for professional training and admission to the chambers of architects.

In this dissertation the economic policy measures to increase the use of recycled concrete in building construction have been derived and discussed on the basis of empirical results. However, it should be noted that probably none of the proposed measures alone can increase the use of r-concrete in building construction. Rather, a concentrated action of all societal actors is required, who, in mutual coordination and agreement, simultaneously undertake target-oriented and well-balanced measures regarding the long-term goal of increasing the sustainability in construction. Above all, political and societal will is required to accept short-term adjustments and the inconvenience they may entail in favour of the long-term objective of increasing sustainability in the construction. In the sense that Theodor Herzl once wrote:

> *"If you will it, it's not a fable, but if you don't will it, a fable it is and a fable it will stay"* (Herzl, 1902, p. 138).

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Appendix

Table A1: Transcript of the survey on the barriers to the use of recycled concrete from the perspective of executing companies

Variable	Question or statement	Reply options and coding
	Filter question	
bb00	Do you know what r-concrete (rc-concrete or recycled concrete) is about?[72]	0: No 1: Yes
	Part 1: Company information	
bb07	In which country is your company located? Note: This refers to the location of your working place.	1. Germany 2: Switzerland 3: Other
dz01	Which field of activity does your company belong to? Note: Multiple entries are possible.	1. Construction 2. Recycling 3. Commodities and building materials 4. Other (text)[73]
dz02	How many employees are employed in your company? Note: This item refers to the company as a whole.	Number
	Part 2: General perception of r-concrete	
bb01	Does your company currently produce recycled aggregates, recycled concrete, recycled concrete products or uses recycled concrete in construction or have made it before?	0: No 1: Yes
bb02	On the whole, how is the use of r-concrete in building construction assessed against the background of sustainability in your company?	1: Very negative 2: Negative 3: Positive 4: Very positive
bb03	The role of r-concrete in promoting sustainable construction is perceived as important by your company as a whole.	1: Strongly disagree 2: Disagree 3: Agree 4: Strongly agree
bb04	In your company there is a contact person or a department for r-concrete. Question: Does this statement apply?	1: Does not apply at all 2: Does rather not apply 3: Partially applies 4: Fully applies
bb05	Your company has defined goals, policies or processes regarding r-concrete. Question: Does this statement apply?	1: Does not apply at all 2: Does rather not apply 3: Partially applies 4: Fully applies
bb06	How often did you have training and qualification seminars or events on the subject of recycled concrete in the last two years? Note: Please enter a number.	Number

[72] If the answer was *No*, survey was immediately terminated.

[73] Information in this response category could be partially manually assigned to previous categories.

Table A1 continued from previous page

Variable	Question or statement	Reply options and coding
	Part 3: Factorial survey	
sb20	Note: In the following a hypothetical situation is presented. We are interested in how you would act in light of this constellation. Example situation: *"You are becoming aware of a comprehensive public tender. There, the production of aggregate, ready-mixed concrete and the construction of a building are announced. The tender explicitly mentions that when deciding on the award, the aspect of sustainability (use of recycled materials) is considered as a further criterion in addition to the price. If additional costs arise from the use of recycled materials, you will be reimbursed with 75 % of additional costs. The use of recycled materials is not recognised by any of the well-known labels."* Question: How likely is it that you as a company will apply for this tender using r-concrete?	1: Definitely not 2: Probably not 3: Perhaps 4: Probably 5: Definitely
	Part 4: Advantages and disadvantages of r-concrete	
	How do you perceive the advantages of using r-concrete? Note: Please weight the following reasons for using recycled concrete from the perspective of your company. Please use the regulator. Leave the controller in its initial position if you cannot judge a particular item.	1-100 (from *1=not relevant at all* to *100=very relevant*)
t201_01	Avoidance of new landfill sites	——॥——
t201_02	Avoidance of new mining sites	——॥——
t201_03	Reduction of material costs	——॥——
t201_04	Reduction of transport costs	——॥——
t201_09	Reduction of resource consumption	——॥——
t201_10	Reduction of land use	——॥——
t201_06	Environmental consciousness	——॥——
t201_07	Improvement of competitiveness	——॥——
t201_08	Expansion of sales markets	——॥——
t202	How do you assess the obstacles in the use of r-concrete in building construction? How relevant are these as barriers to the use of r-concrete in building construction? Note: Please weight the following items. Leave the slider in its initial position if you cannot judge the item.	1-100 (from *1=not relevant at all* to *100=very relevant*)
t202_01	Processing of construction waste is too cost-intensive	——॥——
t202_02	Transport is too cost-intensive	——॥——
t202_03	Placement of equipment on the construction site is too cost-intensive.	——॥——
t202_26	Creation of additional storage capacity too cost-intensive	——॥——
t202_23	Quality assurance of the demolition material is too cost-intensive	——॥——
t202_04	Management costs are too high	——॥——
t202_05	Time expenditure is too high	——॥——
t202_22	Price of r-concrete is not competitive	——॥——
t202_16	Cost difference of r-material compared to normal grain is too high	——॥——
t202_24	The percentage of recycled material that can be added is too low	——॥——
t202_06	Lack of a sufficient number of appropriately trained staff	——॥——

Table A1 continued from previous page

Variable	Question or statement	Reply options and coding
t202_07	No knowledge and experience with r-concrete	—〃—
t202_08	Quality of r-concrete compared to conventional concrete is too poor	—〃—
t202_09	Applicability of r-concrete is strongly limited	—〃—
t202_10	R-concrete is insufficiently researched	—〃—
t202_11	Demand is too low	—〃—
t202_12	Supply is too low	—〃—
t202_17	Availability (quantity and continuity) is not given	—〃—
t202_19	No recognition by labels and certifications	—〃—
t202_20	No tax incentives	—〃—
t202_21	No subsidies	—〃—
t202_13	Considerable uncertainty regarding governmental regulation	—〃—
t202_25	Inconsistent governmental regulation regarding r-concrete	—〃—
t202_15	Lack of governmental support	—〃—
	Part 5: Competition	
b101	The market of your industry is highly concentrated and dominated by one or few companies. Question: Do you agree with this statement?	1: Strongly disagree 2: Disagree 3: Agree 4: Strongly agree
b102	Please estimate the market share of your company in your industry. Note: Specify the interval which applies for your company.	1: <10 % 2: 10-20 % 3: 20-30 % 4: 30-40 % 5: 40-50 % 6: 50-60 % 7: 60-70 % 8: 70-80 % 9: 80-90 % 10: >90 %
b104	How often are cooperation agreements entered into with other companies for the production, delivery or provision of goods or services?	1: Never 2: Rarely 3: Sometimes 4: Frequently 5: Very frequently
b105	Competition in the market in which your company operates is driven by price. Question: Do you agree with this statement?	1: Strongly disagree 2: Disagree 3: Agree 4: Strongly agree
b106	Competition in the market in which your company operates is driven by quality. Question: Do you agree with this statement?	1: Strongly disagree 2: Disagree 3: Agree 4: Strongly agree
b201	The distance from your establishment to your customers plays an important role in business decisions. Question: Does this statement apply?	1: Does not apply at all 2: Does rather not apply 3: Partially applies 4: Fully applies

Table A1 continued from previous page

Variable	Question or statement	Reply options and coding
b202	The distance from your establishment to the suppliers plays an important role in business decisions. Question: Does this statement apply?	1: Does not apply at all 2: Does rather not apply 3: Partially applies 4: Fully applies
b203	Please estimate the average geographical distance to your main customers (in kilometers).	1: <20 2: 20-40 3: 40-60 4: 60-80 5: 80-100 6: >100
b204	Please estimate the average geographical distance to your main suppliers (in kilometers).	1: <20 2: 20-40 3: 40-60 4: 60-80 5: 80-100 6: >100

Table A2: Ranked descriptive statistics: survey of the execution companies in Germany and Switzerland

		Germany		Switzerland			
Rank	**Variable**	**Median**	**N**	**Median**	**N**	**Pearson chi2(1)**	**Rel. diff.**
1	t202_19	75	203	3	29	24.142***	0,727273
2	bb05	1	386	3	35	31.602***	0,666667
3	bb04	1	408	3	34	17.737***	0,666667
4	t202_07	76	252	11	31	22.053***	0,656566
5	t202_11	89	241	26	30	24.698***	0,636364
6	t202_22	54	189	7	30	17.118***	0,474747
7	t202_23	69	245	22	30	21.356***	0,474747
8	t202_16	53,5	186	8	30	14.641***	0,459596
9	t202_01	52	247	7	30	12.659***	0,454545
10	t202_06	51	216	10,5	30	18.374***	0,409091
11	t202_26	48	221	11	27	9.351***	0,373737
12	t201_01	84	304	48	30	6.995***	0,363636
13	t202_10	47	205	12,5	30	9.627***	0,348485
14	t201_02	81	309	47	30	8.459***	0,343434
15	bb02	3	245	4	35	10.974***	0,333333
16	bb03	3	307	4	35	20.045***	0,333333
17	bb105	3	318	4	31	7.193***	0,333333
18	t202_03	46	221	15	29	14.082***	0,313131
19	t202_13	84	193	56	29	15.022***	0,282828
20	t202_05	46	207	19,5	24	11.750***	0,267677
21	b104	3	310	4	29	29.785***	0,25
22	t202_02	30	229	5,5	28	12.830***	0,247475
23	t202_15	91	211	67	29	16.514***	0,242424
24	t201_03	67	290	87	30	14.713***	0,20202
25	t202_21	81	193	61	29	8.022***	0,20202
26	t201_10	76	288	40,5	28	5.478**	0,358586
27	b201	3	320	2	28	5.903**	0,333333
28	t202_25	81	197	59	29	6.425**	0,222222
29	t202_12	81	228	59,5	28	4.010**	0,217172
30	t202_20	76,5	196	59	28	5.878**	0,176768
31	b102	1	258	2	26	3.718*	0,111111
32	b204	2	301	3	27	1005	0,333333
33	b101	3	281	2	30	0.039	0,333333
34	b202	3	310	2	29	0.652	0,333333
35	b106	3	303	2	30	1912	0,333333
36	t201_04	59	276	48	28	1331	0,111111
37	t201_07	51	275	41	31	0.005	0,10101
38	t202_04	34	213	25	26	1.389	0,090909
39	t201_09	92	314	83,5	32	0.501	0,085859
40	t201_08	44,5	266	37	31	0.863	0,075758
41	t201_06	92	311	99	33	1642	0,070707
42	t202_17	66	216	70,5	30	0.684	0,045455
43	t202_24	53	227	55,5	30	0.025	0,025253
44	t202_09	61	217	63	30	0.001	0,020202
45	t202_08	37	200	37,5	28	0.000	0,005051

**p*<0.05, ***p*<0.01, ****p*<0.001.*

In order to test the differences non-parametric equality of medians test was used.

Table A3: Transcript of the survey on the study contents in Germany and Switzerland

Variable	Question or statement	Reply options and coding
	Filter question	
s09	Which group do you belong to?[74]	1: Student 2: Professor
	Part 0: Questions for professors	
s09	In your opinion, what is the most important reason why r-concrete is only used to a limited extent in building construction in Germany?	Text
s10	In your opinion, what would have to happen for r-concrete to be used to a greater extent in building construction in Germany?	Text
	Part 1: General information	
s102	In which country do you study?	1: Germany 2: Switzerland
s101	At which university do you study? Note: If your university does not appear in the selection, please enter it manually.	List of universities
se07	What do you study?	1: Architecture 2: Civil engineering 3: Environmental engineering 4: Other
s106	What semester are you in? Note: Refers to the total number of semesters, both in the Bachelor and the Master.	Number
s103	How old are you?	Number
s104	Please select your gender.	1: Male 2: Female 3: Other
s105	How much money do you have available each month? Note: In your local currency and less the cost of rent.	1: $<$ 200 2: 200-400 3: 400-600 4: 600-800 5: 800-1000 6: $>$1000
	Part 2: Discrete choice situation	

[74] If the respondent stated that he/she was a student, the survey started with question s102. If the respondent indicated that he/she was a professor, only questions s09 and s10 were asked. For the professors, the entire survey consisted only of these two questions.

Table A3 continued from previous page

Variable	Question or statement	Reply options and coding
	Note: In the following a hypothetical situation is presented. We are interested in how you would act in light of this constellation. Situation: *"As an architect or engineer, you have decided to take over the renovation and insulation of the exterior walls of your detached house by yourself. The house was built in 1973, measures 130 square meters of living space; solid construction with plastered facade. There is a choice of three composite thermal insulation systems with different properties."* *Please take a careful look at all three variants of all sets presented and answer the question below* Question: Which thermal insulation system would you choose? Note: If you do not want to choose any of the above alternatives, leave the selection box in its initial position.	Three choice alternatives with randomly varying parameters: Deconstruction costs: [75] 50, 100, 150, 200 Euros Recyclability:[76] 0, 25, 50, 75 % Energy efficiency:[77] A, B, C, D Costs:[78] 50, 150, 250, 350 Euros
	Part 3: Sustainability in studies contents	
sn01	On the whole, circular economy is an integral part of my studies. Question: Do you agree with this statement?	1: Strongly disagree 2: Disagree 3: Agree 4: Strongly agree
sn02	How high is the proportion of courses that had a clear reference to circular economy in which you had participated? Note: Proportion of courses related to circular economy = number of courses taken with reference to circular economy / total number of courses×100.	1: <10 % 2: 10-20 % 3: 20-30 % 4: 30-40 % 5: 40-50 % 6: 50-60 % 7: 60-70 % 8: 70-80 % 9: 80-90 % 10: >90 %
sn03	On average, how extensively was the circular economy discussed in the 3 courses with the strongest reference to circular economy? Note: The question refers to the courses you have taken.	1: Not extensive at all 2: Rather not extensive 3: Extensive 4: Very extensive
sn04	How large is the proportion of courses that had a clear reference to circular economy that you were able to attend optionally? Note: Proportion of courses related to circular economy = number of optional courses with reference to circular economy / total number of possible optional courses ×100.	1: <10 % 2: 10-20 % 3: 20-30 % 4: 30-40 % 5: 40-50 % 6: 50-60 % 7: 60-70 % 8: 70-80 % 9: 80-90 % 10: >90 %

[75] Per square meter of the thermal insulation composite system.
[76] Proportion of the composite thermal insulation system that can be recycled.
[77] Energy efficiency of the building, which is ensured by the use of the respective thermal insulation composite system.
[78] Per square meter of the thermal insulation composite system.

Table A3 continued from previous page

Variable	Question or statement	Reply options and coding
sn05	How intensively have the following topics been covered in your studies to date? Note: If you cannot judge a particular aspect, leave the slider in its initial position.	1-100 (from *1=not extensive at all* to *100=very extensive*)
sn05_01	Waste prevention	——‖——
sn05_02	Waste recycling	——‖——
sn05_03	Closing the energy and material cycles	——‖——
sn05_04	Resource efficiency	——‖——
sn05_05	Refurbishment	——‖——
sn05_06	Selective deconstruction	——‖——
sn05_07	Environmental protection	——‖——
sn06	Practical elements of the studies have a strong reference to circular economy. Question: Do you agree with this statement?	1: Strongly disagree 2: Disagree 3: Agree 4: Strongly agree
sn07	How important sustainability is to you in your private life?	1: Not important at all 2: Rather not important 3: Rather important 4: Very important
sn08	The previous studies have contributed to the development of a pronounced environmental awareness. Question: Do you agree with this statement?	1: Strongly disagree 2: Disagree 3: Agree 4: Strongly agree
	Part 4: Recycled concrete	
sr01	Have you heard of recycled concrete (r-concrete) during your previous studies?[79]	0: No 1: Yes
sr02	R-concrete was mentioned in the course of the study, but was not considered in detail. Question: Do you agree with this statement?	0: No 1: Yes
sr03	Technical and chemical properties of r-concrete were covered extensively within the course of study. Question: Do you agree with this statement?	1: Strongly disagree 2: Disagree 3: Agree 4: Strongly agree
sr04	Regulatory aspects of r-concrete were covered extensively within the course of study. Question: Do you agree with this statement?	1: Strongly disagree 2: Disagree 3: Agree 4: Strongly agree
sr05	Regarding the application in building construction, I consider r-concrete as a complete substitute for classical ready-mixed concrete. Question: Do you agree with this statement?	1: Strongly disagree 2: Disagree 3: Agree 4: Strongly agree

[79] If the respondent indicated not to have heard about recycled concrete in the course of previous studies, the survey was terminated.

Table A3 continued from previous page

Variable	Question or statement	Reply options and coding
sr06	Regarding the application in underground construction, I consider r-concrete as a complete substitute for classical ready-mixed concrete. Question: Do you agree with this statement?	1: Strongly disagree 2: Disagree 3: Agree 4: Strongly agree

Table A4: Two-sample t-test and equality of medians test for survey variables on study contents, sustainability and perception of r-concrete

Variables	N_{Ger}	N_{Sw}	$Median_{Ger}$	$Median_{Sw}$	χ^2_{median}	$Mean_{Ger}$	$Mean_{Sw}$	$Diff_{mean}$
sn01	476	31	2.000	3.000	8.108***	2.401	2.968	-0.566***
sn02	471	31	35.000	45.000	16.260***	35.000	47.903	-12.903***
sn03	448	28	2.000	3.000	5.126**	2.400	2.679	-0.279
sn04	366	24	3.000	6.000	9.911***	3.137	4.542	-1.405***
sn05_01	476	30	21.000	38.500	1.597	30.861	46.700	-15.839***
sn05_02	473	27	21.000	16.000	0.856	32.827	26.111	6.716
sn05_03	466	26	26.500	45.500	2.599	33.406	47.308	-13.902**
sn05_04	482	28	43.000	75.000	7.407***	47.060	67.464	-20.404***
sn05_05	468	25	34.000	11.000	4.959**	40.154	25.320	14.834**
sn05_06	438	26	16.000	18.500	0.316	25.027	35.000	-9.973*
sn05_07	487	28	44.000	72.000	7.576***	46.856	66.357	-19.501***
sn06	400	26	2.000	3.000	15.877***	2.078	2.692	-0.615***
sn07	490	31	3.000	3.000	3.934**	3.408	3.258	0.150
sn08	477	31	2.000	3.000	7.756***	2.325	2.677	-0.352**
sr01	502	31	1.000	1.000	.	0.522	0.742	-0.220**
sr02	260	23	1.000	0.000	.	0.762	0.348	0.414***
sr03	247	21	2.000	3.000	17.388***	2.008	2.905	-0.897***
sr04	245	21	2.000	3.000	14.893***	1.906	2.905	-0.999***
sr05	170	16	3.000	3.000	8.445***	2.524	3.125	-0.601***
sr06	169	14	3.000	3.500	11.107***	2.722	3.357	-0.635***

**p<0.05, **p<0.01, ***p<0.001.*

Figure A1: Respondents across universities

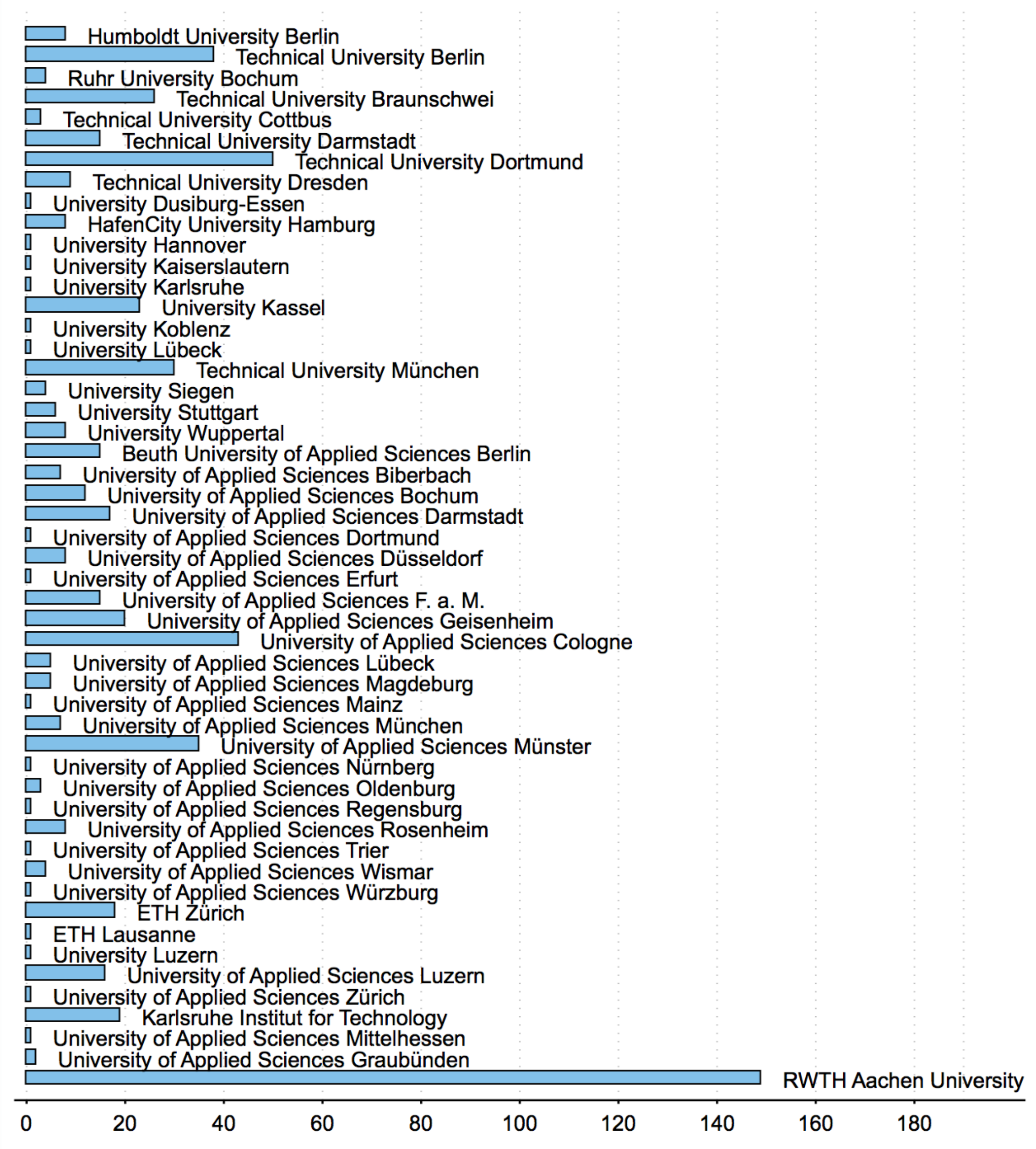

Table A5: Transcript of the survey on the barriers to the use of recycled concrete from the perspective of architects and engineers

Variable	Question or statement	Reply options and coding
	Filter-question	
P152	Do you know what r-concrete (rc-concrete or recycled concrete) is about?[80]	0: No 1: Yes
	Part 1: General information about the person and the company	
P108	Where are you employed?	1: Architectural office 2: Engineering office 3: Architectural and engineering office 4: Freelance 5: Governmental authority 6: Construction company 7: Other
P119	In which federal state or canton are you mainly active?	1-42 (each state or canton as category)
P107	If you are not a freelancer, how many people are employed in the company? Note: Please select the interval.	1: $\leq$ 2 2: 3-5 3: 6-8 4: 9-11 5: 12-15 6: $\geq$ 16
P112	How old are you? Note: Please select the interval.	1: $\leq$ 30 2: 31-40 3: 41-50 4: 51-60 5: 61-70 6: $\geq$ 71
P111	Please indicate your highest educational level.	1-10 (German education system; each educational level as category; high school to PhD)
P103	How important sustainability is to you in your private life?	1: Not important at all 2: Rather not important 3: Rather important 4: Very important
	Part 2: Factorial survey	
	Note: Hypothetical situations are presented below. We are interested in how you would act in view of this constellation. Note: Please read the situation description carefully	1: Very unlikely 2: Unlikely 3: Rather unlikely

[80]If the answer was *0=No*, the survey was immediately terminated.

Table A5 continued from previous page

Variable	Question or statement	Reply options and coding
	Note: In the following a hypothetical situation is presented. We are interested in how you would act in light of this constellation. Exemplary situation: *"You are becoming aware of a comprehensive public tender for the construction of a student housing complex in a rural community. The tender explicitly mentions that when deciding on the award, the aspect of sustainability (use of recycled materials) is considered as a further criterion in addition to the price. The use of recycled aggregates is not recognised in the DGNB-label. The maximum permissible proportion of recycled aggregates in concrete is 20 %. Compared to conventional concrete, the use of recycled concrete results in additional costs of 100 %."* Question: How likely is it that you plan to use recycled concrete for this construction project?	4: Rather likely 5: Likely 6: Very likely
	Part 3: Discrete choice	
	Note: In the following a hypothetical situation is presented. We are interested in how you would act in light of this constellation. Situation: *"As an architect or engineer, you have decided to take over the renovation and insulation of the exterior walls of your detached house by yourself. The house was built in 1973, measures 130 square meters of living space; solid construction with plastered facade. There is a choice of three composite thermal insulation systems with different properties."* *Please take a careful look at all three variants of all sets presented and answer the question below* Question: Which thermal insulation system would you choose? Note: If you do not want to choose any of the above alternatives, leave the selection box in its initial position.	Three choice alternatives with randomly varying parameters: Deconstruction costs:[81] 50, 100, 150, 200 Euros Recyclability:[82] 0, 25, 50, 75 % Energy efficiency:[83] A, B, C, D Costs:[84] 50, 150, 250, 350 Euros
P113	Have you already worked with r-concrete?	0: No 1: Yes
P120	How many training and qualification events on r-concrete have you attended in the last two years? Note: Please choose an interval.	1: 0 2: 1-2 3: 3-4 4: 5-6 5: ≥ 7
P121	Regarding the application in underground construction, I consider r-concrete as a complete substitute for classical ready-mixed concrete. Question: Do you agree with this statement?	1: Strongly disagree 2: Disagree 3: Agree 4: Strongly agree
P122	Regarding the application in building construction, I consider r-concrete as a complete substitute for classical ready-mixed concrete. Question: Do you agree with this statement?	1: Strongly disagree 2: Disagree 3: Agree 4: Strongly agree

[81] Per square meter of the thermal insulation composite system.
[82] 8Proportion of the composite thermal insulation system that can be recycled.
[83] Energy effciency of the building, which is ensured by the use of the respective thermal insulation composite system.
[84] Per square meter of the thermal insulation composite system.

Table A5 continued from previous page

Variable	Question or statement	Reply options and coding
P115	In your opinion, what is the most important reason why r-concrete is only used to a limited extent in building construction in Germany?	Text
P116	In your opinion, what would have to happen for r-concrete to be used to a greater extent in building construction in Germany?	Text
P105	Question: How do you assess the obstacles in the use of r-concrete in building construction? How relevant are these as barriers to the use of r-concrete in building construction? Note: Please weight the following items. Leave the slider in its initial position if you cannot judge the item.	1-100 (from *1=not relevant at all”* to *100=very relevant*)
P105_01	Processing of construction waste is too cost-intensive	——‖——
P105_26	Creation of additional storage capacity is too cost-intensive	——‖——
P105_23	Quality assurance of the demolition material is too cost-intensive	——‖——
P105_04	Management costs are too high	——‖——
P105_06	Lack of a sufficient number of appropriately trained staff	——‖——
P105_07	No knowledge and experience with r-concrete	——‖——
P105_08	Quality of r-concrete compared to conventional concrete is too poor	——‖——
P105_09	Applicability of r-concrete is strongly limited	——‖——
P105_10	R-concrete is insufficiently researched	——‖——
P105_11	Demand is too low	——‖——
P105_12	Supply is too low	——‖——
P105_22	The price of r-concrete is not competitive	——‖——
P105_17	Availability (quantity and continuity) is not given	——‖——
P105_20	No tax incentives	——‖——
P105_19	No recognition by labels and certifications	——‖——
P105_21	No subsidies	——‖——
P105_13	Considerable uncertainty regarding governmental,regulation	——‖——
P105_25	Inconsistent governmental regulation regarding r-concrete	——‖——
P105_15	Lack of governmental support	——‖——
P105_27	No consideration in public tenders	——‖——

Table A6: Perception of the barriers to the use of recycled concrete by architects and engineers and further survey variables: Germany and Switzerland

Variables	N_{Ger}	N_{Sw}	$Median_{Ger}$	$Median_{Sw}$	p_{test}^{median}	$Mean_{Ger}$	$Mean_{Sw}$	p_{test}^{mean}
Processing of construction waste is too cost-intensive (P105_01)	272	280	63.000	40.500	0.000***	57.305	45.232	0.000***
Creation of additional storage capacity is too cost-intensive (P105_26)	256	269	45.000	24.000	0.000***	45.172	33.316	0.000***
Quality assurance of the demolition material is too cost-intensive (P105_23)	273	281	51.000	46.000	0.000***	55.330	44.591	0.000***
Management costs are too high (P105_04)	237	261	25.000	14.000	0.000***	35.722	22.383	0.000***
The percentage of recycled material that can be added is too low (P105_24)	253	272	51.000	30.000	0.000***	47.372	37.662	0.000***
Lack of a sufficient number of appropriately trained staff (P105_06)	255	267	60.000	44.000	0.000***	57.733	42.375	0.000***
No knowledge and experience with r-concrete (P105_07)	305	290	79.000	54.500	0.000***	73.052	53.459	0.000***
Quality of r-concrete compared to conventional concrete is too poor (P105_08)	224	279	26.000	26.000	0.582	33.317	33.602	0.839
Applicability of r-concrete is strongly limited (P105_09)	227	284	40.000	31.000	0.000***	44.555	37.310	0.000***
R-concrete is insufficiently researched(P105_10)	226	267	49.000	21.000	0.000***	47.642	29.831	0.000***
Demand is too low (P105_11)	274	277	76.000	51.000	0.000***	70.022	50.155	0.000***
Supply is too low (P105_12)	260	262	76.500	33.000	0.000***	69.758	37.176	0.000***
The price of r-concrete is not competitive (P105_22)	250	281	68.000	46.000	0.000***	63.968	44.594	0.000***
Availability (quantity and continuity) is not given (P105_17)	238	258	52.500	26.000	0.000***	55.164	33.876	0.000***
No tax incentives (P105_20)	238	235	73.500	37.000	0.000***	63.567	40.974	0.000***
No recognition by labels and certifications (P105_19)	233	253	62.000	34.000	0.000***	60.528	39.431	0.000***
No subsidies (P105_21)	233	246	71.000	28.500	0.000***	63.597	39.423	0.000***
Considerable uncertainty regarding governmental regulation (P105_13)	228	214	74.000	31.000	0.000***	67.667	39.051	0.000***
Inconsistent governmental regulation regarding r-concrete (P105_25)	218	219	70.000	41.000	0.000***	65.115	41.607	0.000***
Lack of governmental support (P105_15)	248	237	77.500	43.000	0.000***	71.230	44.945	0.000***
No consideration in public tenders (P105_27)	259	266	76.000	61.000	0.000***	71.757	56.684	0.000***
Substitutability building construction (P122)	313	333	3.000	3.000	0.000***	2.789	2.964	0.000***
Substitutability underground construction (P121)	298	294	3.000	3.000	0.112	3.208	3.034	0.000***
Sustainability in private life (P103)	447	411	4.000	4.000	.	3.541	3.552	0.623

**p<0.05, **p<0.01, ***p<0.001*

In order to test the differences two-sample t-test and non-parametric equality of medians test were used

Table A7: Perception of the barriers to the use of recycled concrete: executing companies and architects in Germany

Variables	N_{Ex}	N_{Arch}	$Median_{Ex}$	$Median_{Arch}$	p_{test}^{median}	$Mean_{Ex}$	$Mean_{Arch}$	p_{test}^{mean}
Processing of construction waste is too cost-intensive (P105_01)	247	272	52.000	63.000	0.015**	53.121	57.305	0.134
Creation of additional storage capacity is too cost-intensive (P105_26)	221	256	48.000	45.000	0.635	48.480	45.172	0.232
Quality assurance of the demolition material is too cost-intensive (P105_23)	245	273	69.000	51.000	0.011**	62.878	55.330	0.005***
Management costs are too high (P105_04)	213	237	34.000	25.000	0.092*	40.423	35.722	0.102
The percentage of recycled material that can be added is too low (P105_24)	227	253	53.000	51.000	0.010**	57.405	47.372	0.000***
Lack of a sufficient number of appropriately trained staff (P105_06)	216	255	51.000	60.000	0.124	52.546	57.733	0.086*
No knowledge and experience with r-concrete (P105_07)	252	305	76.000	79.000	0.857	65.964	73.052	0.007***
Quality of r-concrete compared to conventional concrete is too poor (P105_08)	200	224	37.000	26.000	0.053*	37.760	33.317	0.114
Applicability of r-concrete is strongly limited (P105_09)	217	227	61.000	40.000	0.000***	59.631	44.555	0.000***
R-concrete is insufficiently researched(P105_10)	205	226	47.000	49.000	0.498	46.761	47.642	0.771
Demand is too low (P105_11)	241	274	89.000	76.000	0.000***	72.959	70.022	0.267
Supply is too low (P105_12)	228	260	81.000	76.500	0.213	66.342	69.758	0.237
Price of r-concrete is not competitive (P105_22)	189	250	54.000	68.000	0.018**	56.693	63.968	0.013**
Availability (quantity and continuity) is not given (P105_17)	216	238	66.000	52.500	0.075*	60.153	55.164	0.103
No recognition by labels and certifications (P105_19)	203	233	75.000	62.000	0.048**	65.970	60.528	0.090*
No tax incentives (P105_20)	196	238	76.500	73.500	0.440	64.872	63.567	0.696
No subsidies (P105_21)	193	233	81.000	71.000	0.144	66.259	63.597	0.423
Considerable uncertainty regarding governmental regulation (P105_13)	193	228	84.000	74.000	0.002***	73.451	67.667	0.048**
Inconsistent governmental regulations regarding r-concrete (P105_25)	197	218	81.000	70.000	0.007***	71.061	65.115	0.046**
Lack of governmental support (P105_15)	211	248	91.000	77.500	0.003***	75.886	71.230	0.108

**p<0.05, **p<0.01, ***p<0.001*

In order to test the differences two-sample t-test and non-parametric equality of medians test were used

Figure A2: Regional distribution of market concentration (HHI)