Development of a Methodology for Deriving Fine Processing Steps with the Focus on Preparation of Aged Reinforced Concrete

Alexander Grosse-Kreul[1*], Tobias Drees[1†], David Sanio[2†], Iurie Curoșu[3†], Bernd Kuhlenkötter[1†]

[1*]Chair of Production Systems, Ruhr University Bochum, Industriestr. 38c, Bochum, 44894, Germany.
[2]Institute of Concrete Structures, Ruhr University Bochum, Universitätsstr. 150, Bochum, 44801, Germany.
[3]Chair of Construction Materials, Ruhr University Bochum, Universitätsstr. 150, Bochum, 44801, Germany.

*Corresponding author(s). E-mail(s): grosse-kreul@lps.ruhr-uni-bochum.de;
Contributing authors: drees@lps.ruhr-uni-bochum.de; massivbau@ruhr-uni-bochum.de; baustoffe@ruhr-uni-bochum.de; kuhlenkoetter@lps.ruhr-uni-bochum.de;
†These authors contributed equally to this work.

Abstract

Upon reaching their planned service life most aging buildings are demolished to make room for new constructions. Current demolition practices for reinforced concrete structures often result in low-grade recycling or waste. A more sustainable approach would imply the holistic reuse of the aged reinforced concrete elements for structural purposes. In this context, automated production processes (also called fine processing) are required to ensure industrial scalability and enable a customized refurbishment after the extraction of elements from the donor buildings. This paper develops a systematic methodology that enables the derivation of the respective preparation processes based on the element-specific condition. Eight typical degradation and damage conditions of aged reinforced concrete elements are identified and systematically matched with ten preparation processes. The core result is a three-stage methodology: (1) selection of eight typical damage conditions, (2) derivation of preparation processes for the identified damage conditions, and (3) matching of most suitable concrete processing methods to the preparation processes. Limitations of the proposed methodology are the survey bias due to the participation of individuals with varying levels of expertise, the limited expert participation and the application based on a single example. The proposed systematic approach provides the foundation for automated fine processing for circular construction.

Keywords: cradle to cradle, sustainable manufacturing, reuse, recycling, fine processing, automation

1 Introduction

The buildings sector is the main contributor to global CO_2 emissions, thereby presenting a considerable opportunity for mitigation [1]. The energy-intensive nature of cement production [2] and the amount of waste generated by construction debris [3] can be classified as unsustainable. Construction site waste constitutes approximately 55% of total waste in Germany [3] and 36% at the European level [4]. Reinforced concrete construction has been identified as a major contributor to it, as it comprises approximately 60-90% of all load-bearing structures in Germany [5, 6]. Concurrently, the building stock is vast, as evidenced by the 19 million residential buildings in Germany alone [7]. Given the scarcity of resources in the construction industry and the vast existing building stock, the implementation of various reuse concepts is imperative for a sustainable construction sector [8]. Currently, the recycling of reinforced concrete elements (RCEs) is predominantly characterized by downcycling, resulting in a loss of material quality and functional value relative to its original application [3]. Whereas 88% of the steel from demolished building and civil engineering structures is recycled through energy-intensive thermal processing [8], only 2% of the demolished concrete is reused as recycled aggregates in new concrete [9]. Despite the scarcity of resources, the reuse of RCEs by using an automated production system has not been researched yet. A promising solution for this problem is outlined in [10, 11, 12], which address the modular reuse of aged RCEs. For this purpose, the aged RCEs are first dismantled from the old structures in a controlled manner and under consideration of a digital ecosystem that enables matchmaking between available RCEs and the demand of the target building [13]. The extracted elements are initially investigated according to their general condition by applying experimental, numerical, and data-driven methods and strategies for comprehensive non-destructive characterization [14]. Subsequently, these elements undergo individual fine processing steps for refurbishment, preferably in an automated production system [10]. The aim of this publication is to develop a fundamental methodology for deriving fine processing steps for an automated production system focusing on the preparation of aged RCE. The focus is exclusively on deriving fine processing steps rather than identifying damages, which is examined in more detail in [14]. Compared to [10, 11], which presents the processing of RCEs in a production system at a conceptual level, this publication serves as a foundation for the development of a production system for fine processing, as the preparation processes developed here are to be transferred into an automated production system in the long term. This publication will adress the following research questions:

- Based on what degradation and damage conditions can fine processing steps be derived for the preparation of aged RCEs?
- Which element-specific preparation processes for fine processing are required to address various typical element conditions?
- Which established concrete processing methods are most suitable for identified preparation processes?

To derive the proposed methodology, various tasks are performed. Chapter 2 gives a short overview of the background of the fine processing. In Chapter 3 the state of the art of methodologies for the derivation of fine processing steps is presented and briefly discussed. Chapter 4 covers systematic literature reviews, expert interviews and a quantitative survey to identify concrete processing methods for RCEs, to analyze damage conditions and associated preparation processes and to match the concrete processing methods with preparation processes using a suitability assessment. Chapter 5 provides a specific description of the methodology for deriving an individual fine processing with focus on preparation, which is applied to a sample RCE in Chapter 6.

2 Background of fine processing

The fine processing of aged RCEs encompasses multiple subprocesses from four different areas: preparation, module segmentation, connection attachment and quality assurance. The preparation includes all processes that address damage-specific repairs to individual RCEs. The module segmentation involves producing a target geometry required for the new building. The connection

attachment enables the creation of connections for joining RCEs to a new structure. Quality assurance ensures compliance with the specified target properties and national standards to be achieved at the end of the fine processing. These four areas guarantee that the reclaimed concrete components can be safely reused. [10]
To ensure structural safety, durability, and code compliance, fine processing operates within a clear process chain. It relies on a prior damage assessment (e.g., non-destructive testing during donor building audits to determine residual structural capacity) and an engineering repair design (defining required structural and protective measures). Fine processing itself represents the execution layer that physically implements these engineering requirements in an automated environment. Interfaces with structural requalification and code compliance are an important part and will be addressed in the future. In this context, the terms *damage condition*, *preparation process* and *concrete processing method* must be defined.

- *Damage conditions* refer to structural and material defects that arise due to degradation, previous use or the use of demolition methods during dismantling of the RCE. Defects, caused by degradation mechanisms [15] or mechanical damage during element dismantling, range from minor concrete spalling to severe damage to the reinforcement.
- The implementation of *preparation processes* is directly associated with the extent of the degradation or damage, as they constitute specific interventions designed to facilitate the refurbishment of the affected RCEs. The preparation processes are individualized and adapted to the specific damage condition being addressed [10] and are already being applied, as a preventive measure to ensure safe reuse. To conclude, the term describes what needs to be done.
- A *concrete processing method* is defined as a set of tools detailing the processes that can be utilized to manufacture the reusable concrete element and aims to produce a geometrically defined, solid body [16]. In summary, this term describes how it should be done.

Figure 1 shows the components of fine processing. The aged RCE functions as the input and the reusable RCE serves as the output. The present publication focuses on the preparation, which is the first part of fine processing. A methodology will be derived for the purpose of this study and is based on three pillars that allow the derivation of an individual refurbishment. This foundation for developing the methodology for deriving fine processing steps with the focus on preparation, enables the creation of initial production cells for fine processing.

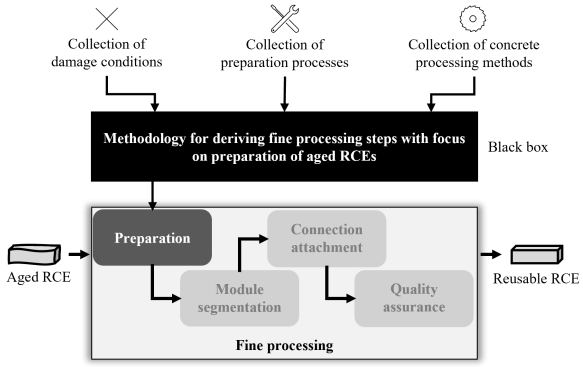


Fig. 1 Overview of the fine processing of aged RCEs

3 Existing methodologies for the derivation of component-specific fine processing steps

As the available sources on fine processing steps are limited, the search strategy has been expanded to include general processing steps in the field of concrete processing and production systems. Therefore, multiple methodologies for the derivation of component-specific processing steps are already established in construction and automation technology and will be presented and analyzed in the following section.
Morgenstern et al. describe a digital workflow that addresses the maintenance and repair of RCE by evaluating enriched Building Information Modeling (BIM) data [17]. Specifically, the as-is state of RCEs is assessed to derive maintenance and repair

measures. This approach requires both comprehensive data on the RCE and the availability of BIM data. However, in the context of reusing aged RCE, the existence of extensive element data cannot be assumed. Furthermore, specific preparation steps are not mapped to the as-is states, which is essential for the actual preparation. Building on the maintenance of RCE, Benitez et al. present a dynamic decision model (DDM) for maintenance planning of corrosion-vulnerable reinforced concrete structures [18]. Their method determines the most suitable inspection and repair method for the structure under consideration, which must be executed within a specific timeframe. The primary focus of this publication is the development of a methodology based on the Analytic Hierarchy Process, rather than providing detailed output on preparation steps. Nepal et al. provide another approach for the optimal repair planning of damaged reinforced concrete structures [19]. They present a method that evaluates the probability of structural load-bearing failure over the entire service life and proposes an optimal repair and maintenance strategy. The latter accounts for both maintenance costs and the risk of structural failure. Similar to the aforementioned work, this publication does not focus on deriving preparation steps based on damage conditions, but rather on predicting the failure of a reinforced concrete structure and the associated costs for damage remediation. Önalan et al. introduce a digital workflow for concrete reuse [20]. It begins with robotic surveying and inventorying of the material stock after deconstruction. Based on the available material, an algorithm matches the RCEs to a new building design. Finally, the manual assembly of the components is carried out with extended reality (XR) support. However, the constructed structures are limited to simple masonry assemblies produced from the original geometries without prior reconditioning. Similarly, component-specific preparation based on damage conditions is not addressed, as the elements are processed in their as-is state. Babic et al. [21] outline a range of methodologies that facilitate automated feature recognition based on Computer-Aided Design (CAD) models, thereby enabling the autonomous planning of manufacturing processes for a specific product. The geometric properties of the component are determined through the extraction process and assigned to the manufacturing processes that facilitate the production. The approach presented herein addresses the manufacturing of new components based on a three-dimensional representation. However, this sole focus on new components means that the automated feature recognition is not well-suited for the reuse of existing components.

Bhatia et al. delineate the methodology of Computer-Aided Process Planning (CAPP) [22]. These CAPP systems initially analyze the surfaces of the digital representations of a selected component to be manufactured and derive the necessary manufacturing processes from it. The manufacturing process is defined by the specific operations involved, the requisite machinery, the necessary tools, and the machine parameters. As stated in Yusof et al. [23], CAPP systems are utilized in a variety of forms. These approaches differ in terms of the underlying process derivation algorithm. CAPP systems are particularly relevant to the manufacturing industry and do not address the derivation of preparation steps for aged RCEs, which might not even possess a digital representation.

In addition, Brinkhoff et al. [24] delineates the derivation of process steps based on BIM. It is employed to derive pertinent information for task planning in the context of robotic operations like specific movements for placing bricks on a wall. Brinkhoff et al. [24] exclusively addresses task derivation for a robot for the construction of brick walls and not the automated processing (e.g., by robots) of RCEs with varying weights and geometries. Additionally, in certain instances, data from BIM is not available for existing RCEs. The derivation of assembly tasks (for construction, electrical, and plumbing systems) for a robotic system using a large language model (LLM) is presented in You et al. [25]. In accordance with the stipulated task parameters, the blueprints, and the inventory of available resources, a meticulous, step-by-step solution is formulated, delineating precise instructions for the robot. These instructions encompass the sequence of actions, the designated resource, and the optimal trajectory of movement. [25] is constrained to the derivation of assembly sequences for the robotic assembly of construction, electrical, and plumbing systems, which means only newly manufactured components with construction specifications, blueprints and a list of available resources are considered.

Case-based reasoning support for the automatic generation of construction schedules based on the reuse of proven project experience is presented in Tauscher et al. [26]. The incorporation of a construction process schedule facilitates the implementation of well-established solutions for common construction site issues. The methodology does not yield specific processing steps for concrete components. Rather, it provides a comprehensive construction plan for a construction project.

In summary, it can be stated that none of the sources address the fine processing of aged RCEs and the associated obstacles. While several of the cited methods generally address reconditioning in the form of maintenance and repair [17, 18, 19], they do not outline a clear relationship between damage conditions and preparation steps. The majority of the aforementioned methodologies prioritize the derivation of process steps from a digital representation of the product ([17, 21, 22, 24]) or adopt a holistic perspective in process derivation, as opposed to a component-level approach ([25], [26]). Table 1 summarizes the findings.

Table 1 Comparison of the existing methodologies for the derivation of component-specific processing steps

Methodology	Main principle	Shortcomings
DDM [18]	• Development of a dynamic decision model for maintenance planning of corrosion-vulnerable reinforced concrete structures • Determination of the most suitable inspection and repair method	• Focus on the development of a methodology based on the Analytic Hierarchy Process • No provision of preparation steps
Stochastic deterioration model [19]	• Evaluation of the probability of structural load-bearing failure • Optimal repair planning of damaged reinforced concrete structures	• Focus on predicting the failure of a reinforced concrete structure and the associated costs for damage remediation

Table 1 Comparison of the existing methodologies for the derivation of component-specific processing steps

Methodology	Main principle	Shortcomings
BIM-based [17]	• Assesment of the as-is state of RCEs to derive maintenance and repair measures	• Centers on the as-is state based on the available data • Requires enriched BIM data
BIM-based [24]	• Derive pertinent information from the BIM-model for task planning • Derivation of robotic operations	• Focus on simple brick wall applications • Requires the existence of a BIM-model
LiDAR, 2D and 3D packing methods, XR [20]	• Digital workflow for concrete reuse • Robotic surveying and inventorying of the material stock, algorithmic matching the RCEs to a new building design, XR support for manual assembly of the components is carried out with	• Limited to simple masonry assemblies • Elements are processed in their as-is state without any preparation
CAD feature recognition [21]	• Autonomous planning of manufacturing processes for a specific product • Based on automated feature recognition of a CAD-model	• Sole consideration of new products
CAPP [22, 23]	• Analysis of the surfaces of the digital representations (CAD-model) and derivation of a manufacturing process	• Focus on products of the manufacturing industry without application for RCEs
LLM [25]	• Deriving precise step-by-step instructions for a robot based on construction specifications and blueprints • Including the sequence of actions, the designated resource, and the optimal trajectory of movement	• Application only for newly manufactured components like construction, electrical, and plumbing systems
Case-based reasoning support [26]	• Provides a construction plan for a construction project • Based on the reuse of proven project experience	• Addresses only comprehensive construction plan for a construction project

4 Analysis of processing methods, concrete damage conditions and preparation processes

4.1 Collection of concrete processing methods

To identify the existing concrete processing methods for RCEs, a systematic literature review has been carried out using the approach by *vom Brocke* [27] and the taxonomy of *Cooper* [28] to define the scope and focus of the literature review. The detailed application of the *vom Brocke* approach is shown in Figure 2. Primarily, the review scope is addressed by defining the focus, the goal, the organization, the perspective, the audience, and the coverage of the literature review. Search terms were derived from the manufacturing process categories of [16] (sawing, jet cutting, milling, grinding, drilling, crushing, cutting, material supplementation, and rebar processing) combined with concrete processing keywords using Boolean operators (e.g., *("concrete processing" OR "concrete removal" OR "refurbishment") AND ("sawing" OR "milling" OR "water jetting")*). Subsequently, the literature is analyzed with regard to the goal defined in step one. To ensure reproducibility, explicit inclusion and exclusion criteria were defined:

- Inclusion criteria: Publications focusing on mechanical, thermal, or chemical concrete processing methods, structural element surface preparation, repair, or rebar exposure; published in English or German.
- Exclusion criteria: Studies focusing purely on primary raw material production, coarse recycling/aggregate crushing without element refurbishment intent, or non-structural concrete applications.

The screening process was conducted in three sequential stages: (1) initial database queries yielding 220307 records, (2) title and abstract screening to exclude irrelevant topics, and (3) full-text evaluation for final eligibility. A total of 58 relevant sources were identified and synthesized. The identified processing methods and their descriptions are summarized in Table 2.

Finally, a research agenda was formulated by synthesizing the results and identifying research gaps. Less researched topics were deliberately identified to serve as a baseline for the subsequent expert interviews in Section 4.3.

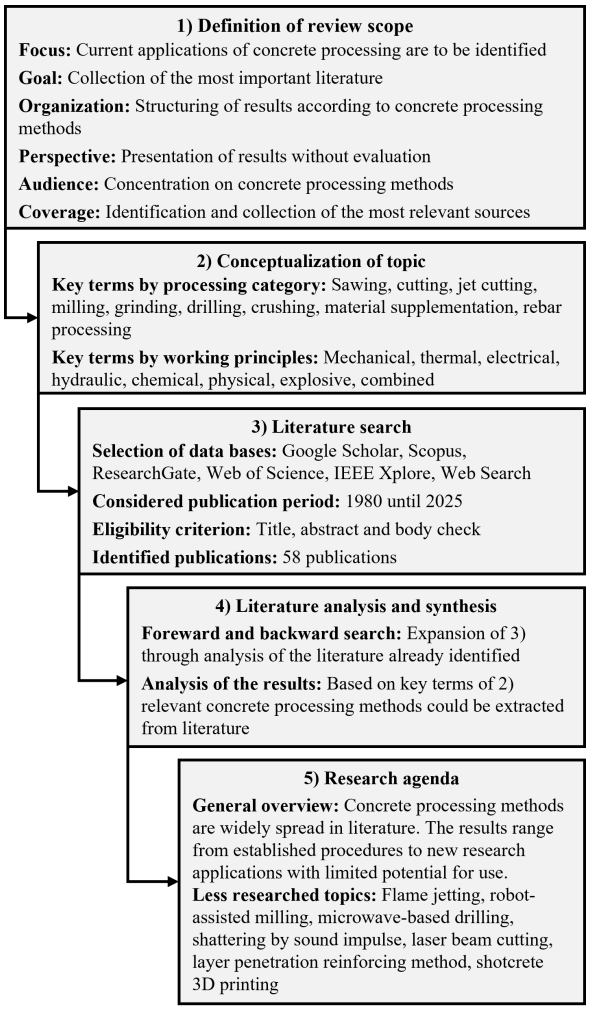


Fig. 2 Methodological approach for collecting concrete processing methods from the literature (Source: Own elaboration based on [27])

Most concrete processing methods are widely spread in literature. Specific methods, like flame jetting, robot-assisted milling, microwave-based drilling, shattering by sound impulse and laser beam cutting reveal limited use in research.

Table 2 List of the identified processing methods for RCEs

Category	Processing method	Description
Sawing	Chainsaw [29, 30, 31]	A motor-driven saw equipped with a chain blade, which can be used for cutting through (reinforced) concrete structures.
	Wire saw [29, 32, 30, 31, 33, 34, 35, 36]	Concrete is cut using a wire embedded with industrial diamonds, suitable for precise cuts in thick concrete, bridges, and tunnels.
	Band saw [37, 38]	Uses a continuous steel band with cutting teeth (often diamond-coated) for straight or curved cuts in concrete slabs, beams, and walls. Ideal for accurate sectional cuts.
	Wall saw/ cut-off grinding [39, 30, 40, 35, 41]	A stationary or mounted saw that slices vertical concrete walls or panels. Abrasive discs enable precise cuts, often in renovation or structural modifications.
	Joint cutter [42, 40, 36]	Specialized saws or cutting devices to create joints or expansion gaps in concrete slabs for cracking control or structural design.
Jet cutting	High-pressure water jet [43, 44, 45, 46, 29, 32, 39, 30, 47, 48]	Uses pressurized water, sometimes with abrasives, to erode and cut concrete structures.
	Sandblasting [31, 49]	Abrasive particles are propelled by compressed air to clean, texture, or remove layers from the concrete.
	Shot blasting [30, 31]	Small steel shots are mechanically blasted onto the concrete surface to clean, roughen, or profile the material.
	Flame jet [29, 30, 47, 31]	Application of high-temperature flames to concrete surfaces to remove layers of concrete.

Table 2 List of the identified processing methods for RCEs

Category	Processing method	Description
Milling	Hydraulic drum cutter [31]	An attachment with rotating drums equipped with picks to grind, carve, or profile concrete surfaces.
	Rotary tiller [50]	Mechanically rotates teeth or cutters to remove or texture concrete surfaces.
	Robot-assisted milling [51, 52, 53]	Automated milling systems using robotic arms or Computerized Numerical Control guidance to remove or shape concrete.
Grinding	Floor grinding [54, 55]	Abrasive discs or diamond pads rotate over concrete floors to level, smooth, or prepare surfaces.
	Concrete bush hammer [30, 31]	Uses a hammering tool with multiple pointed tips to chip and texture concrete surfaces.
Drilling	Core drilling [30, 34, 56]	Circular drilling using diamond-tipped cores to extract concrete cylinders or create precise openings for utilities, pipes, or anchors.
	Hammer drilling [34, 57, 58, 59]	Rotational drilling combined with percussive impacts to penetrate concrete efficiently.
	Thermal core drilling using oxygen lances [43, 39, 30, 47, 41]	This method involves drilling through concrete or reinforced concrete using high-temperature flames produced by oxygen-fuel lances. The oxygen lance melts or burns through steel reinforcement and concrete, allowing for precise openings or removal of structural elements.
	Microwave-based drilling [32, 60]	Uses focused microwave energy to weaken or fracture concrete internally before mechanical removal.

Table 2 List of the identified processing methods for RCEs

Category	Processing method	Description
Crushing	Hydraulic pulverizer [43, 39, 61]	A hydraulic attachment that crushes concrete and separates reinforcement steel in demolition or recycling operations.
	Non-explosive expanding demolition [43, 29, 32, 41, 62, 63, 64, 65, 66, 67, 68, 69]	A non-explosive, chemical powder that is mixed with water and poured into predrilled holes in concrete or rock. As it cures, the mixture generates pressure, causing the material to crack and break apart.
	Hydraulic concrete splitting/ hydraulic concrete bursting [29, 30, 41, 70]	Hydraulic devices (splitters or bursting tools) apply pressure to crack and fragment concrete structures in a controlled manner.
	Demolition hammer [30, 31, 70]	Handheld or machine-mounted hammering tools to break and fragment concrete mechanically.
	Electrical impulse method [29, 71, 72, 73, 74, 75]	This method applies short, high-voltage electrical pulses to concrete, generating internal stresses that cause cracking or fragmentation. The method can reduce dust and vibration compared to conventional mechanical demolition.
	Shattering by sound impulse [76]	Uses high-energy sound waves or vibrations to fracture concrete selectively, often in delicate or precision demolition tasks.
Cutting	Hydraulic jaw crusher [43, 29, 39]	Hydraulic-powered shears mounted on excavators or manipulators to cut reinforced concrete and steel structures during demolition.
	Laser beam cutting [29, 47, 77]	High-energy lasers used to cut, score, or ablate concrete surfaces with precision, experimental or for niche industrial applications.
Material supplementation	Shotcrete application [78]	Spraying of concrete or mortar onto surfaces using compressed air.
	Rebar connection using injection mortar [79]	Technique to anchor new reinforcement into existing concrete using chemical or hydraulic injection mortar, enabling secure retrofitting or structural strengthening. The method requires the drilling of holes in advance.
Rebar processing	Needle scaler [30, 31]	Pneumatic tool with multiple vibrating needles remove rust, old coatings, or debris from steel reinforcement surfaces.
	Rotary wire brush [80, 81]	Rotating brush with steel wires used for cleaning, descaling, or preparing reinforcement or concrete surfaces for bonding or finishing.
	Angle grinder [82, 83]	An angle grinder is a handheld power tool equipped with a rotating abrasive or diamond-tipped disc used to precisely cut, debur, or trim rebars to the required length and specifications.
	High-pressure water jet [43, 44, 45, 46, 29, 32, 39, 30, 47, 48]	Uses pressurized water, sometimes with abrasives, to erode and cut concrete structures.
	Sandblasting [31, 49]	Abrasive particles are propelled by compressed air to clean, texture, or remove layers from the concrete.

Table 2 List of the identified processing methods for RCEs

4.2 Collection of damage conditions and associated preparation processes

To identify the damage conditions of aged RCEs and the associated preparation processes, a guideline-based expert interview is performed building on a systematic literature review about damage conditions. This review also uses the approach by *vom Brocke* [27] with the methodological approach shown in Figure 3.

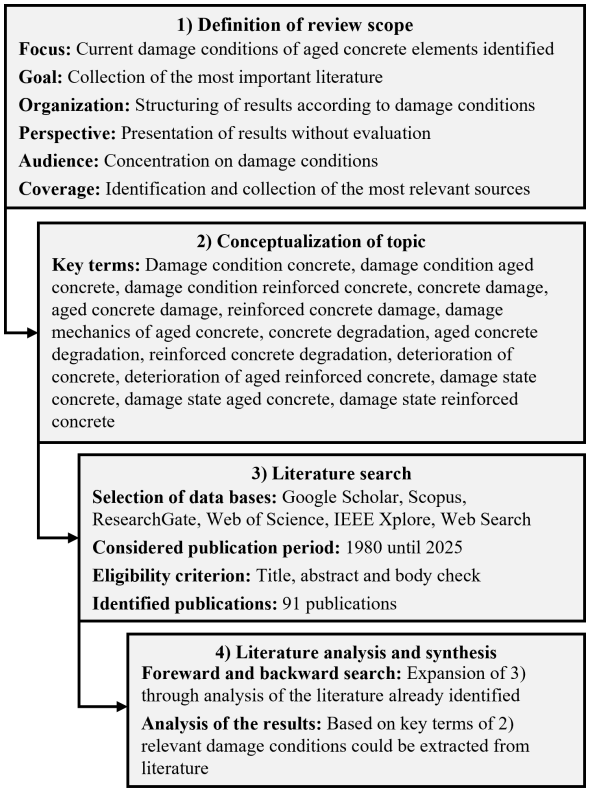


Fig. 3 Methodological approach for collecting damage conditions from the literature (Source: Own elaboration based on [27])

Damage resulting from previous loads exceeding the load-bearing capacity of the RCE (major bending cracks, shear cracks, and plastic deformation of the reinforcement) are not taken into account and excluded from further examination as the effort involved in their evaluation and refurbishment is disproportionate to the benefit. The decision was made based on workshops and discussions with multiple experts from the research project. All identified damage conditions can be found in Table 6. A detailed description of the damage conditions can be found in the appendix in Table A1-A2. Based on the identified damage conditions follows a mapping against an initial draft of the preparation processes shown in [84, 85, 86, 87]. To detail this draft and adjust the steps to the use case of reuse, an interview with two selected experts is performed. The interviewed professors are part of the research project *Collaborative Research Center 1683* and have many years of research and professional experience in the field of civil engineering. Furthermore, one of the professors holds extensive long-standing industry experience in building pathology, conservation, and rehabilitation. The interview structure is based on Helfferich's three-stage principle and contains a sound content basis [88]. The creation of a pre-structured guideline based on the systematic literature review ensures that the interview has a clear focus in order to elicit exclusive knowledge from the interviewees [89]. Table 3 shows the general principles and specific applications for this interviews.

During the interview, three new types of damage conditions were identified, while it became apparent that some others should not be considered further in the context of fine processing of aged RCE. New types are "cracks and surface spalling resulting from coarse cutting with a hydraulic jaw crusher", "debonding induced by sawing during coarse cutting", and "drill holes for implementing coarse cutting techniques". The associated preparation processes and their sequence of execution have also been determined during the interview. The elimination was due to the fact that the effort and complexity of the preparation are not proportional to the desired end product, or the damage simply does not typically occur in ordinary civil buildings addressed in the research project. Eliminated were: "concrete damage caused by leaching", "concrete spalling due to reinforcement corrosion caused by stray currents", "concrete dissolution due to acids", "abrasion, erosion or mechanical attack" and "concrete spalling and cracks due to fire exposure". Table 6 represents a matching table for all relevant damage conditions and the associated preparation processes and provides the answer of the first two research questions. The damage conditions that are explicitly excluded for reuse

Table 3 Principles for an interview guide and the associated application

Principles according to Helfferich (based on [88])	Application of the principles
To facilitate the expression of respondents' thoughts and experiences, a narrative prompt is provided at the outset.	The respondent is presented with an initial list of damage conditions and associated preparation processes, which have been identified through a systematic literature review. The individual types of damage are discussed step by step, with the damage and preparation processes being presented without comment and the respondent then being asked to give an open evaluation.
A deliberate and systematic examination of aspects that have received inadequate attention in existing literature.	The new forms of damage that emerged during the interviews will be explicitly addressed again and detailed. Specifically, the associated preparation processes are to be recorded and documented.
Structured questions are discussed with the respondents.	The following questions will be addressed: • Does the damage occur in the context of aged structures in building construction? • Can the damage be repaired? • How do you estimate the effort required to repair the damage? • Is the cost of preparation proportionate to the cost of new production?

are highlighted with an "*". All preparation processes marked "If necessary" must only be carried out if a qualified expert determines that they are necessary (see chapter 5.2).

4.3 Assignment of processing methods to preparation processes

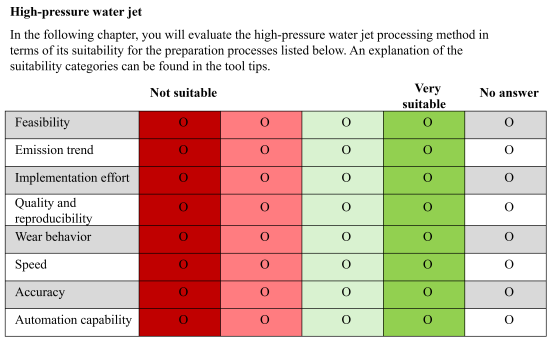
To identify the most suitable concrete processing method for a preparation process, a survey is conducted. Multiple factors for evaluating the suitability of a concrete processing method are extracted from the literature and verified by the authors. The factors feasibility [90, 91], emission trend [90], implementation effort [91, 92], quality and reproducibility [10, 90], wear behavior (maintenance effort) [93], speed [94], accuracy [94], and automation capability [10, 92] must be considered for an optimal evaluation of the suitability of the processing method. A detailed description can be found in the appendix Table A3. For the survey conduction the Computer Assisted Web Interview (CAWI) has been selected using the *LimeSurvey* software tool [95]. Table 4 delineates the survey design.

Table 4 Survey design for assessing the suitability of concrete processing methods

Survey design	Decision
Form of communication	Distribution of the online questionnaire by email to the selected sample. Reminder for participation after three weeks
Survey period	20.05.2025 – 15.07.2025 (Eight weeks)
Duration of the survey	20 minutes
Sample selection	135 total (88 researchers from the *Collaborative Research Center 1683*, 47 researchers from the *Chair of Production Systems*)
Number of responses	40 total (15 from *Collaborative Research Center 1683*, 25 from *Chair of Production Systems*)

Participants can select an appropriate suitability category from an ordinal scale ranging from "not suitable" to "very suitable" as recommended in [96] and shown in the survey excerpt in Figure 4. For the evaluation the responses are quantified with a point value ranging from one (not suitable) to four (very suitable), which are summed up to a total sum. Furthermore, participants are given the option to inform themselves about the suitability criteria at any time via tooltips (see Table A3 in the appendix). Of the 135 invited individuals, 40 provided complete responses, resulting in a response rate of 29.6%. The final sample consisted of participants from mechanical engineering ($n = 23$), civil engineering ($n = 15$), electrical engineering ($n = 1$), and computer science ($n = 1$). The majority is affiliated with the Chair of Production Systems ($n = 25$), and the remaining respondents to Collaborative Research Center 1683 ($n = 15$). To investigate the disciplinary imbalance resulting from participants from mechanical engineering

and civil engineering, a subgroup analysis examining the differences between these two groups is provided in the appendix (see Figures A6–A12). No significant differences were observed between the groups, suggesting that both shared a similar understanding.



High-pressure water jet

In the following chapter, you will evaluate the high-pressure water jet processing method in terms of its suitability for the preparation processes listed below. An explanation of the suitability categories can be found in the tool tips.

	Not suitable			Very suitable	No answer
Feasibility	O	O	O	O	O
Emission trend	O	O	O	O	O
Implementation effort	O	O	O	O	O
Quality and reproducibility	O	O	O	O	O
Wear behavior	O	O	O	O	O
Speed	O	O	O	O	O
Accuracy	O	O	O	O	O
Automation capability	O	O	O	O	O

Fig. 4 Excerpt from the survey

The evaluation of the survey is based on the utility analysis [97]. The results of one participant for the preparation process "surface cleaning" can be seen in Table 5. The participant's evaluation of each suitability criteria is added to the total sum sum_{tot}. Based on this value, the most suited processing method selected by one participant can be derived, which is, in the case of this participant, the high-pressure water jet method with a total sum of 3.5.

Table 5 Exemplary result of the utility analysis for one participant for preparation process "surface cleaning"

Suitability criteria	High-pressure water jet	Sand-blasting	Needle scaler	Rotary wire brush
Feasibility	4	3	1	3
Emission trend	3	1	3	2
Implementation effort	3	3	1	3
Quality and reproducibility	3	3	2	3
Wear behavior	4	3	1	2
Speed	4	3	1	3
Accuracy	3	4	2	3
Automation capability	4	4	2	3
sum_{tot}	**3.5**	3.125	1.625	2.75

In order to take into account the results of all participants, the arithmetic mean value sum_{tot} is calculated for all processing methods. In Figure 5, sum_{tot} of the different concrete processing methods for the preparation process "surface cleaning" are shown. The most suitable process is marked with a dividing line, which highlights the difference between the less suitable concrete processing methods. In the case of the "surface cleaning" preparation process, the "water jet cutting" concrete processing method has been classified as the most suitable. Additionally, the standard deviation for each processing method has been added. Across all survey results, this ranges from 0.32 to 0.72. Further results of the survey are shown in the appendix in Figure A1-A5.

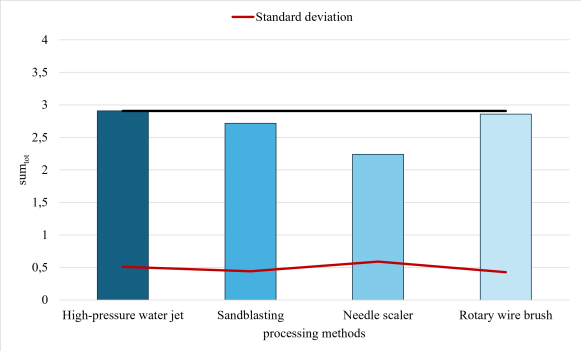


Fig. 5 Graphical representation of the results of the utility analysis for the preparation process "surface cleaning"

In the present utility analysis, all eight suitability criteria are weighted equally. Equal weighting was selected as a baseline approach because no objective empirical preference can be assumed prior to specific industrial deployment; depending on the local job site constraints, automation capability may be as critical as emission trend or processing speed.

Table 6 Matching table for damage conditions and associated preparation processes

Damage condition	Associated preparation processes
Frost damage [15, 48, 98, 99, 100, 101, 102, 103, 104, 105]	1. Removal of a thin surface layer of concrete 2. Application of new mortar or concrete layer 3. If necessary: Application of a coating as additional surface protection
Efflorescence and discoloration due to moisture ingress and ion transportation [15, 81, 106, 107, 108, 109, 110, 111, 112, 113]	1. If necessary: Removal of the near surface region with excessive contaminants concentration 2. Surface cleaning 3. If necessary: Application of a coating as additional surface protection
Osmotic blistering on coatings [114, 115, 116, 117, 118]	1. Removal of the coating 2. Surface equalization or smoothening by an intermediate mineral filling layer 3. If necessary: Application of a new protective coating
Salt contaminants [15, 119, 120, 121]	1. Removal of the near surface region with excessive salts concentration 2. Application of new mortar or concrete layer 3. If necessary: Application of a new protective coating
Concrete spalling (due to reinforcement corrosion caused by carbonation [68, 122, 123, 124, 125, 126, 127, 128, 129, 130, 131, 132], due to reinforcement corrosion caused by chloride ingress [122, 123, 133, 134, 135, 136, 137, 138, 139, 140, 141])	1. Removal of contaminated, aged or damaged concrete layer 2. If necessary: Removal of damaged reinforcement 3. If necessary: Structural strengthening (replacement of reinforcing bars by adding a new layer of reinforcement; extension with steel anchor reinforcement) 4. Rust removal 5. If necessary: Application of a corrosion protective coating on the rebars 6. Application of new mortar or concrete layer (restoration of concrete cover reinforcement protection) 7. If necessary: Application of a protective coating on the concrete surface
Debonding of reinforcement induced by sawing during coarse cutting [Expert interview]	1. Removal of contaminated, aged or damaged concrete layer 2. Surface cleaning 3. Application of new mortar or concrete layer (into the affected area)
Drill holes for implementing coarse cutting techniques [Expert interview]	1. Surface cleaning 2. Application of new mortar or concrete layer (in the bore holes)
Cracking and surface spalling resulting from coarse cutting with a hydraulic jaw crusher [Expert interview]	1. Removal of contaminated, aged or damaged concrete layer 2. Surface cleaning 3. If necessary: Removal of damaged reinforcement 4. If necessary: Structural strengthening (replacement of reinforcing bars by adding a new layer of reinforcement; extension with steel anchor reinforcement) 5. Application of new mortar or concrete layer (to increase the concrete cover)

Table 6 Matching table for damage conditions and associated preparation processes

Damage condition	Associated preparation processes
* Concrete spalling due to thermal expansion [15, 142, 143, 144, 145, 146, 147, 148, 149, 150, 151, 152, 153, 154, 155, 156]	1. Removal of contaminated, aged or damaged concrete layer 2. Surface cleaning 3. Application of new mortar or concrete layer (restoration of concrete cover reinforcement protection)
* Concrete spalling (and cracks due to fire exposure [15, 142, 143, 144, 145, 146, 147, 148, 149, 150, 151, 152, 153, 154, 155, 156], due to reinforcement corrosion caused by stray currents [157, 158, 159, 160, 161, 162])	1. Removal of contaminated, aged or damaged concrete layer 2. If necessary: Removal of damaged reinforcement 3. If necessary: Structural strengthening (replacement of reinforcing bars by adding a new layer of reinforcement; extension with steel anchor reinforcement) 4. Rust removal 5. If necessary: Application of a corrosion protective coating on the rebars 6. Application of new mortar or concrete layer (restoration of concrete cover reinforcement protection) 7. If necessary: Application of a protective coating on the concrete surface
* Abrasion, erosion or mechanical attack [15, 122, 163, 164, 165, 166, 167]	1. Near-surface concrete removal (removal of the affected concrete layer and loose parts) 2. Surface cleaning 3. Application of new mortar or concrete layer
* Damage (concrete damage and / or reinforcement corrosion) caused by leaching [15, 168, 169, 170]	1. Removal of contaminated, aged or damaged concrete layer 2. Rust removal 3. Surface cleaning 4. If necessary: Removal of damaged reinforcement 5. If necessary: Structural strengthening (replacement of reinforcing bars by adding a new layer of reinforcement; extension with steel anchor reinforcement) 6. If necessary: Application of new surface protection to the reinforcement 7. Application of new mortar or concrete layer (restoration of reinforcement protection) 8. If necessary: Apply new surface protection to the mortar or concrete surface (e.g. polymer coating)
* Concrete dissolution due to acids [122, 170, 171, 172, 173, 174]	1. Removal of contaminated, aged or damaged concrete layer 2. Surface cleaning 3. Application of new mortar or concrete layer (restoration of reinforcement protection) 4. If necessary: Application of new surface protection to the reinforcement

To improve the quality of the survey the guideline of the American Association for Public Opinion Research (AAPOR) was applied [175]. Therefore, the sample focuses on researchers of the "Collaborative Research Center 1683" and of the Chair of Production Systems. The selection represents a very specialized group of people (experts in the field of reinforced concrete, concrete processing, automation and production systems). The inclusion of a larger unknown group could distort the accuracy of the results. Nevertheless, future studies should expand the panel to broader international industrial practitioners to enhance generalizability. The participants evaluate the processing method after a short introduction. The possible answers were limited to a four-point scale from "Not Suitable" to "Very Suitable." The four-point scale ensured that participants automatically had to indicate a tendency in one direction, as there was no middle (neutral) answer option. The overall application of the AAPOR guideline and all survey results can be found in [176]. The survey instrument and interview guideline can be provided upon request.

The quantitative survey results established a preliminary ranking of concrete processing methods based on overall technical suitability. Subsequently, two in-depth expert interviews were conducted to qualitatively cross-validate these quantitative findings, identify contextual boundary conditions, and address structural gaps. The synthesis of survey data and expert interviews followed a two-step rule:

1. Validation and refinement: If survey results yielded high consensus (e.g., high-pressure water jetting for surface cleaning), the expert interviews served to specify operational boundary conditions. For instance, experts differentiated "rust removal" into two distinct branches based on standard preparation grades [177]: If preparation grade Sa 2.5 is targeted, which is required prior to applying a coating to the reinforcement, "sand blasting" must be employed. If, on the other hand, a preparation grade of Sa 2 is intended, treatment with the concrete processing method "high-pressure water jet" is sufficient, allowing the subsequent application of mortar.
2. Exclusion and structural splitting: Outliers or technically unfeasible survey options were corrected. For example, 3D concrete printing methods have been excluded from the refurbishment use case, being utilized only for the production of new concrete elements. For the "application of new mortar or concrete" the methods of "pouring of concrete" (application of concrete of varying consistency to the damaged area), "casting into formwork" (formwork is placed around the existing component and subsequently poured) and "shotcrete application" have been identified as the most suitable ones. The preparation process "structural strengthening" was divided into two categories. Near the edge, "structural strengthening" can be performed along the longitudinal axis of the reinforcement. Within the concrete element, strengthening can be performed along the surface by removing the concrete cover through milling.

The experts are the same experts interviewed in Chapter 4.2. During these interviews some of the survey results have been confirmed, some have been revised. The assignment of the supplemented procedures to the preparation processes was carried out using the interviewees' specific expert knowledge. The overall results of the suitability assessments of the concrete processing methods for the preparation processes can be found in Table 7 and answer the third research questions. If more than one concrete processing method can be used for each preparation process due to their equal suitability the alternative is shown in brackets and must be selected by an expert.

5 Methodology development for derivation of fine processing steps

5.1 Overview

The methodology for the derivation of fine processing steps can be developed based on the matching tables 6 and 7. The following Figure 6 extends the initial overview of the fine processing, detailing the black box of the methodology for deriving fine processing steps with focus on preparation. The preparation is only necessary if the

Table 7 Matching table for the preparation processes and the most suitable concrete processing methods

Preparation processes	Processing methods
Surface cleaning / Removal of the coating	High-pressure water jet (Sand blasting)
Removal of a thin layer of concrete / Removal of a the near surface region	High-pressure water jet (Sand blasting, Shot blasting)
Removal of contaminated, aged or damaged concrete layer (at the edge)	Wall saw (Demolition hammer)
Removal of contaminated, aged or damaged concrete layer (Extensive)	High-pressure water jet
Rust removal	Sand blasting (High-pressure water jet)
Removal of damaged reinforcement	Angle grinder
Application of new mortar or concrete layer / Surface equalization or smoothening by an intermediate mineral filling layer	Pouring of concrete (Casting into formwork, Shotcrete application)
Structural strengthening (To the longitudinal axis of the reinforcement)	Core hole drilling, filling with injection mortar and place reinforcement
Structural strengthening (Longitudinal axis parallel to the surface)	Concrete Milling, place reinforcement and encase in concrete
Application of a coating to the reinforcement or to the mortar or concrete surface	Automated coating

RCE has a damage. An aged RCE without damage does not require any of the listed preparation processes.

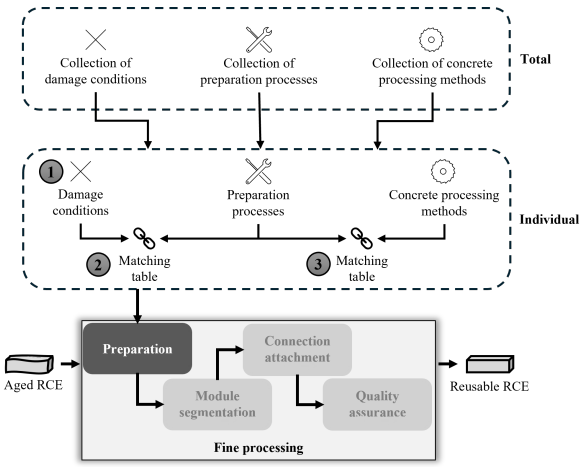


Fig. 6 Overview of the proposed methodology

As illustrated in Figure 6, the methodology is comprised of three sequential steps. The first step is to obtain the RCE under investigation, in order to assess the individual damage conditions. Result of step one is a comprehensive list of damage conditions that have been identified. The second step involves the utilization of the aforementioned list to derive the necessary preparation processes. In a third step, specific concrete processing methods are assigned to the preparation steps. The proposed methodology is limited to the building construction sector, which precludes its application in road construction and other areas (due to the absence of relevant damage conditions and corresponding preparation processes). It should be noted that load-history-induced structural damage (such as plastic deformation) must be assessed during the initial structural audit of the donor building prior to extraction. The proposed methodology specifically targets element-level preparation, bridging non-destructive structural diagnostics and established repair frameworks (e.g., EN 1504) within an automated production line.

5.2 Step 1: Selection of the damage conditions

Step one of the methodology for deriving fine processing steps with focus on preparation involves the identification of damage conditions in the aged RCEs. The selection of existing or potential future damage conditions is based on the matching table in Table 6. The detailed assessment of the condition of the RCE is investigated by [14], whose output is used for step one. To assess the damage conditions of the aged RCEs, many information and the application of non-destructive testing methods are required. These investigations can only be performed by experts.

5.3 Step 2: Derivation of preparation processes

Building upon the identified damage conditions, the second step involves the derivation of the necessary preparation processes that must be applied to the specific RCE. Therefore, Table 6 encompasses all required preparation processes for each damage condition. Initially, the preparation processes corresponding to all identified damage conditions are sequentially documented. To achieve an optimized preparation process chain, this initial list is refined based on spatial dependencies, conditional triggers, and sequential rules:

- Spatial dependencies and duplicate removal: Duplicate preparation processes are only removed if they refer to global, element-wide operations (e.g., full-surface cleaning or global coating) or if multiple damages overlap at the exact same physical location. If damages occur at spatially distinct locations on the RCE, the localized preparation process must be retained and mapped to its respective local spatial coordinates.
- Conditional processes: Processes marked as conditional (e.g., "If necessary: Removal of damaged reinforcement") are bound to specific diagnostic thresholds. For instance, reinforcement removal is only triggered if non-destructive testing confirms a cross-sectional loss exceeding defined structural limits or severe corrosion.The specific thresolds must be defined in future work.
- Sequential order and process dependencies: The consolidation into a final chain of fine processing follows logical technical dependencies. As a general rule, subtractive steps precede additive steps to establish an adequate substrate.

The ordered subtractive preparation processes are detailed below:

- Removal of a thin layer of concrete / Removal of a the near surface region
- Surface cleaning / Removal of the coating
- Removal of contaminated, aged or damaged concrete layer (at the edge)
- Removal of contaminated, aged or damaged concrete layer (extensive)
- Rust removal
- Removal of damaged reinforcement

The additive preparation processes follow in sequential order:

- Application of new mortar or concrete layer / Surface equalization or smoothening by an intermediate mineral filling layer
- Structural strengthening
- Application of a coating

Figure 7 illustrates this process flow using the example of an RCE exhibiting two damage types: "frost damage" and "cracking and surface spalling resulting from coarse cutting with a hydraulic jaw crusher."

5.4 Step 3: Assignment of the concrete processing method

The established preparation processes for the aged RCE can finally be matched with the required concrete processing methods based on the provided matching table (see Table 7). It should be explicitly acknowledged that both the initial derivation of the matching tables and the final selection between alternative processing methods rely heavily on expert judgment. When multiple processing methods are technically feasible, expert input or rule-based heuristics are required to evaluate trade-offs such as cycle time, surface roughness requirements, etc. The process chain

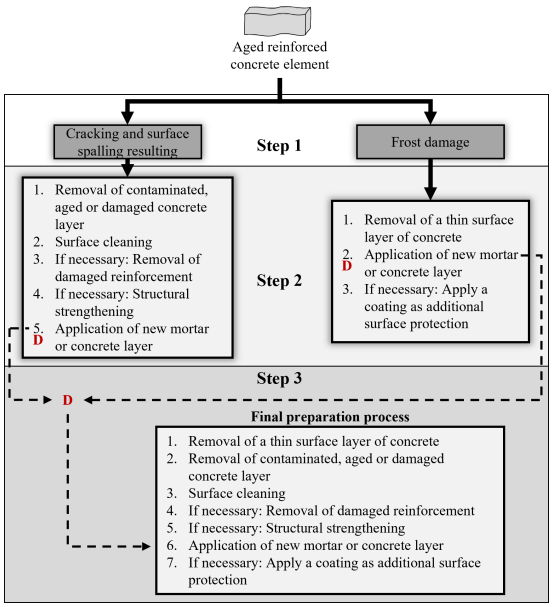


Fig. 7 Example of duplicate removal

derived in Figure 7 is extended, resulting in the details provided in Table 8.

6 Application of the methodology

The presented methodology for deriving fine processing steps with focus on preparation for aged RCEs must now be applied and demonstrated on a real RCE. For this purpose, components from the "Collaborative Research Center 1683" will be used [12, 178, 179]. The real RCE selected for the application of the methodology is a former column with a cantilever arm that was extracted from an office building at Ruhr University Bochum during its demolishing. Figure 8 depicts the example RCE alongside the original structure. The reinforcement corrosion visible there is not attributable to the aging process, but rather to the component's storage outdoors for several months.

According to step 1, the existing damage conditions of the exemplary concrete component must be documented. Following the relevant analysis and consultation with a suitable expert, the following damage condition has been identified: cracking and surface spalling resulting from coarse cutting with a hydraulic jaw crusher (see Figure 8). The preparation processes are derived



Fig. 8 Real component with its source building

from Table 6 and result in the collection of preparation processes presented in Table 9. Since there is only one condition of damage no duplicates need to be removed. The final step involves the assignment of concrete processing methods to the individual preparation processes using Table 8. The final result of applying the methodology is presented in Table 9 and includes all the preparation processes and assigned concrete processing methods required for fine processing the exemplary RCE.

It must be mentioned, that the application of the method to only one RCE is a important limitation. Due to the limited availability of RCEs within the project, only elements with a single damage could be assessed so far. In the future RCEs must be examined, in which at least two to four damages occur simultaneously. First, a selection should be made to examine RCEs with multiple damages that cover the entire spectrum of identified damages. Subsequently, the step-by-step application of the presented method must take place, along with the identification of potential obstacles. This procedure will allow the optimization and final validation of the method

Table 8 Preparation processes with the associated processing methods for the example in Figure 7

Step	Preparation process	Processing method
1	Removal of a thin surface layer of concrete	High-pressure water jet
2	Removal of contaminated, aged or damaged concrete layer (at the edge)	Wall saw
3	Surface cleaning	high-pressure water jet
4	If necessary: Removal of damaged reinforcement	Angle grinder
5	If necessary: Structural strengthening	Core hole drilling, filling with injection mortar and place reinforcement
6	Application of new mortar or concrete layer	Pouring of concrete
7	If necessary: Application of a coating as additional surface protection	(Automated) coating

Table 9 Fine processing for an example RCE

Step	Preparation process	Processing method
1	Removal of contaminated, aged or damaged concrete layer (at the edge and extensive)	Wall saw (demolition hammer) / high-pressure water jet
2	Surface cleaning	high-pressure water jet
3	If necessary: Removal of damaged reinforcement	Angle grinder
4	Structural strengthening	Core hole drilling, filling with injection mortar and place reinforcement
5	Application of new mortar or concrete layer	Pouring of concrete

7 Conclusions

This publication presented a three-step methodology for deriving fine processing steps focusing on the preparation of aged RCE. Starting point are eight damage conditions that can occur with the aged RCE. For enabling its refurbishment, each damage condition can be assigned to necessary preparation processes by a developed matching table. Finally, these preparation processes can be matched with the most suitable concrete processing methods by using a second matching table. In the context of automating the fine processing, the methodology presented here serves, on the one hand, as the foundation for developing individual production cells designed to map the preparation processes along with their assigned concrete processing methods. On the other hand, it provides the basis for enabling a customized process flow for each RCE through the production system for fine processing. This ensures that each RCE passes through only those production cells that are necessary based on its damage conditions.

As already indicated in Figure 1, the presented methodology must be extended to include the derivation of fine processing steps with the focus on module segmentation, connection attachment and quality assurance. This requires, firstly, defining a set of target geometries that need to be produced based on the origin geometric properties of the RCE. Secondly, reliable connection types must be developed that enable the detachable coupling of several RCEs to form a new load-bearing structure. Therefore, a multidisciplinary collaboration between different domains is necessary that defines relevant criteria for the derivation of the

specific fine processing step. Furthermore, it is necessary to address the software-technical integration of the methodology with the production system to be developed. The goal should be to enable the automated production of an individual concrete element, with the necessary information (specific preparation processes, actual geometry data, etc.) being automatically processed.

The system boundary of the presented methodology lies in the damage condition assessment. Without a correct and unequivocal identification of damage, the methodology will not yield applicable results. This causes a high dependency of the methodology's success on the accurate damage assessment of the aged RCEs and requires the availability of an expert or specific measurement technologies. Furthermore, the actual methodology only covers a subset of the damage conditions of the overall fine processing. While the focus here is solely on preparing the eight types of damage, successful reuse also necessitates considering damage conditions caused by the transport or the fine processing steps itself (i.e. delaminations after cutting with the concrete saw). Another limitation is the limited number of experts interviewed in the context of capturing the preparation processes and assigning the processing methods. In the future, these should be supplemented by additional external experts to further increase the independence of the results. A potential limitation of this study lies in the distribution of survey respondents across the participating institutions and domains. While candidates from two separate institutions were invited, the majority of respondents ($n = 25$) were affiliated with the Chair of Production Systems. Although the sample captures interdisciplinary perspectives, the institutional skew may impact the external validity and generalizability of the findings. Future research should evaluate the proposed methodology with broader, multi-institutional samples to further validate these results. Finally, the lack of demonstration of the presented methodology in an automated production system for fine processing must be cited as a limitation. The practical application of the outlined methodology is the subject of future research in order to prove its validity and feasibility.

The future focus of the development of the automated production system for fine processing is on the implementation of all identified fine processing steps. Therefore, a series of production cells, each mapping an individual fine processing step, is combined to an overarching production system. In detail, the specific automation, tooling, transport equipment, and auxiliary resources required for each respective process must be selected and virtually tested. This will allow for forecasting general feasibility, proving the objective of reduced faulty RCEs and shorter process times. Regarding the exclusion of damage from reuse, a further support method should be developed that allows for the evaluation of damage conditions with respect to suitable reuse. In this context, damage must be categorized according to its degree of severity, and threshold values must be determined to define when reuse is still viable and when it is not. To this end, a criteria-based decision-support tool needs to be developed to evaluate damages with regard to their suitability for the reuse application.

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Appendix A

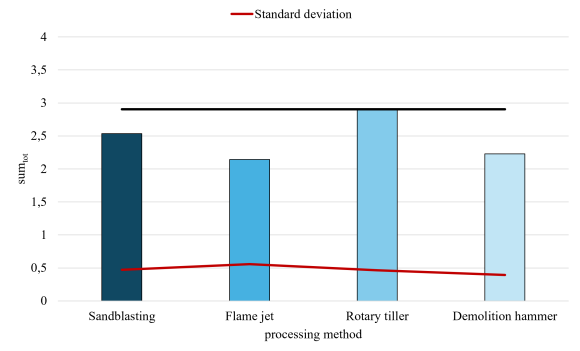


Fig. A1 Results of the utility analysis for the preparation process "Removal of a thin layer of concrete / Removal of a the near surface region"

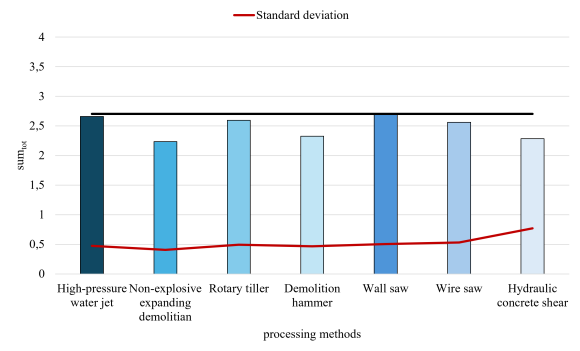


Fig. A2 Results of the utility analysis for the preparation process "Removal of contaminated, aged or damaged concrete layer"

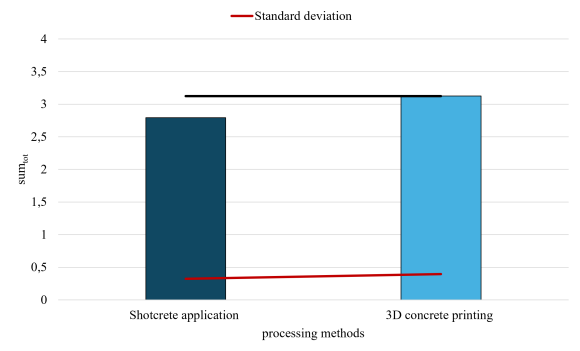


Fig. A3 Results of the utility analysis for the preparation process "Application of new mortar or concrete"

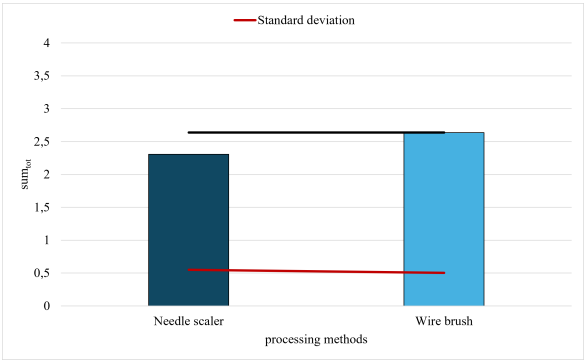


Fig. A4 Results of the utility analysis for the preparation process "Rust removal"

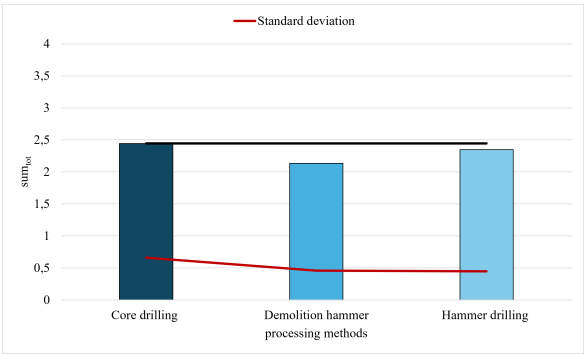


Fig. A5 Results of the utility analysis for the preparation process "Structural strengthening"

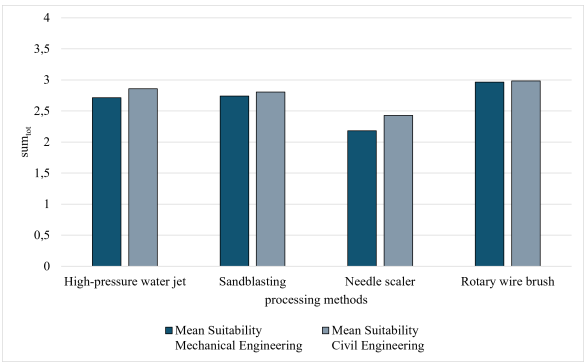


Fig. A6 Subgroup analysis of the utility analysis for the preparation process "Surface cleaning"

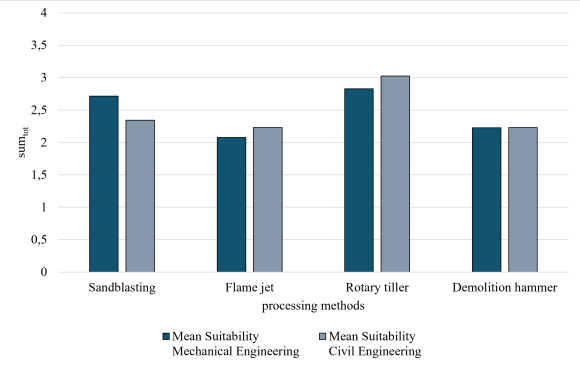


Fig. A7 Subgroup analysis of the utility analysis for the preparation process "Removal of a thin layer of concrete / Removal of a the near surface region"

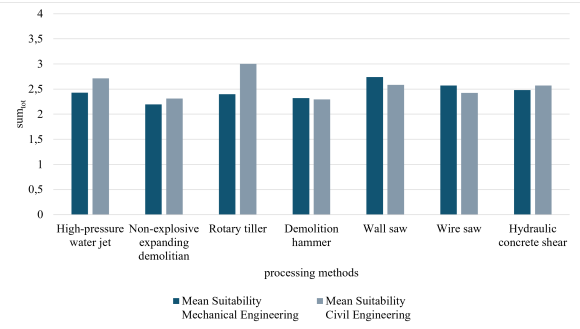


Fig. A8 Subgroup analysis of the utility analysis for the preparation process "Removal of contaminated, aged or damaged concrete layer"

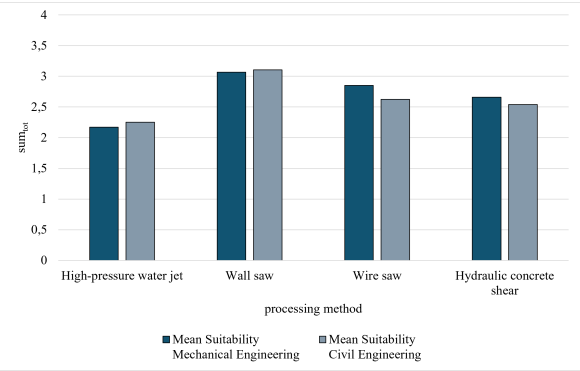


Fig. A9 Subgroup analysis of the utility analysis for the preparation process "Application of new mortar or concrete"

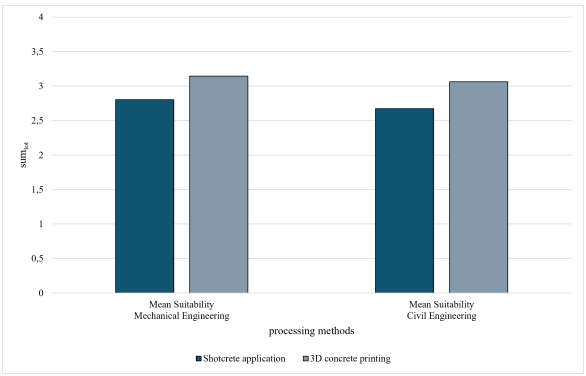


Fig. A10 Subgroup analysis of the utility analysis for the preparation process "Rust removal"

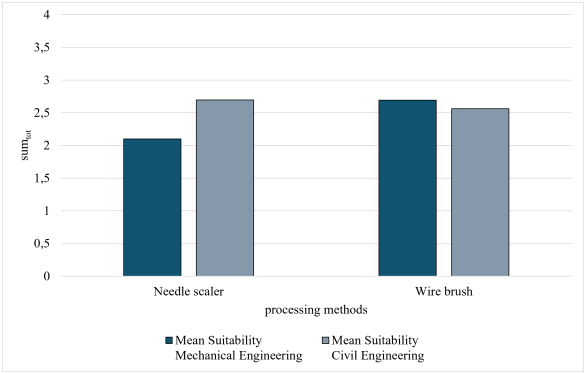


Fig. A11 Subgroup analysis of the utility analysis for the preparation process "Structural strengthening"

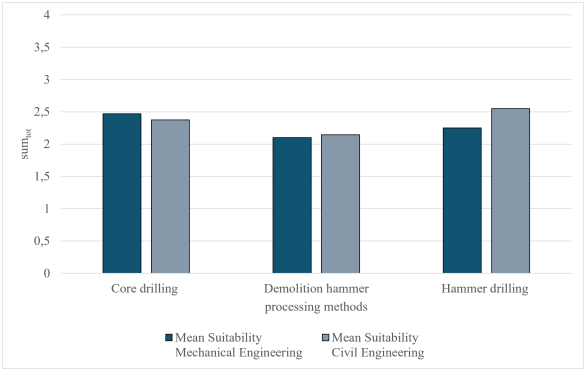


Fig. A12 Subgroup analysis of the utility analysis for the preparation process "Surface cleaning"

Table A1 Description of the general damage conditions

Damage condition	Description
Frost damage	In the event of direct contact between the RCE and water, spalling of the concrete can occur at low ambient temperatures, as the water in the concrete pores freezes and increases its volume.
Efflorescence and discoloration due to moisture movement	Water-soluble salts migrate from the concrete interior to the surface due to moisture evaporation and then crystallize. This process forms a solid or loose residue on the concrete surface.
Osmotic blistering on coatings	Moisture and water-soluble salts accumulate at the interface coating, causing the coating to locally detach and subsequently form blisters. This is an aesthetic problem and not necessarily a damage condition of a RCE.
Salt contaminants	Crystallized salt on the concrete surface form a hard, thick crust due to inadequate rinsing. This crust formation may involve internal crystallization pressures that can induce further surface damage.
Concrete spalling (due to reinforcement corrosion caused by carbonation, due to reinforcement corrosion caused by chloride ingress)	Atmospheric carbon dioxide penetrates the concrete, lowering the concrete's natural alkalinity. This destroys the protective passive layer around the steel, allowing moisture and oxygen to rust the metal, which expands and cracks the surrounding concrete. Chloride ions from de-icing salts penetrate the concrete matrix and directly attack the steel's protective oxide film. This triggers localized pitting corrosion and can lead to volume expansion of the steel rust that violently spalls the outer concrete cover.
Debonding of reinforcement induced by sawing during coarse cutting	When sawing concrete, stresses and vibrations are generated along the cutting line. In multi-layered components or in already damaged RCE, these stresses can lead to the formation of horizontal cracks and cause the reinforcement to detach from the concrete.
Drill holes for implementing coarse cutting techniques	Local weak points created by the application of coarse demolition methods, such as drill holes for mounting a wall saw.
Cracking and surface spalling resulting from coarse cutting with a hydraulic jaw crusher	The use of heavy, impacting, or crushing tools, such as hydraulic jaw crusher, during coarse cutting leads to high local stresses on the remaining concrete. This can result in surface spalling and generates cracking near the cutting zone.
Concrete spalling due to thermal expansion	Thermal stresses arise due to temperature gradients (e.g., solar radiation on one side) or significantly different coefficients of thermal expansion between material layers (e.g., coating on concrete). If these stresses cannot be relieved, they lead to deformation, cracking, or delamination.

Table A2 Description of the general damage conditions

Damage condition	Description
Concrete spalling (and cracks due to fire exposure, due to reinforcement corrosion caused by stray currents)	High temperatures, such as those encountered during a fire, induce physical and chemical alterations in the RCE. This includes the thermal expansion and cracking of the concrete cover, and damage to the reinforcement. Next to fire exposure, stray currents from external sources (e.g. railway systems) can cause corrosion of the reinforcement steel near the current exit point.
Concrete damage caused by leaching	Concrete leaching leads to dissolving and washing away calcium hydroxide from the cement paste. This process significantly reduces the structural strength of the RCE and leaving embedded steel reinforcement vulnerable to corrosion.
Concrete dissolution due to acids	Acids directly attack the concrete by dissolving the alkaline components of the cement matrix. This causes concrete dissolution, resulting in the softening and decomposition of the surface and the subsequent material loss.

Table A3 Criteria for the suitability assessment of concrete processing methods

Criteria for the suitability assessment	Description
Feasibility	Feasibility describes the degree to which a processing technology is technically, organizationally, and realizable under the given framework conditions.
Emission trend	Emission trend describes the type, scope, and influence of the emissions generated during the processing technology on humans, the environment, and the production surroundings.
Implementation effort	Implementation effort describes the total temporal, personnel, technical, and organizational expenditure required to successfully integrate a processing technology into an existing or new production process.
Quality and reproducibility	Quality and reproducibility describe the degree to which a processing technology consistently delivers the required product quality and is capable of reliably reproducing the results in repeated runs under identical conditions.
Wear behavior	Wear behavior describes the degree and type of tool or equipment wear that occurs when a concrete processing method is used, as well as its effects on process stability, quality, maintenance effort, and costs.
Speed	Speed describes the degree to which a concrete processing method can efficiently execute a preparation process within a specified time without compromising quality.
Accuracy	Accuracy describes the degree to which a concrete processing method is capable of consistently and reliably meeting the required geometric, dimensional, and positional tolerances of a preparation process.
Automation capability	Automation capability describes the degree to which a concrete processing method can be technically and economically integrated into an automated process, while maintaining process stability, quality, and flexibility.

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