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Photo, front cover: Magnus Rönn. The picture shows a desktop in wood. The waves in the image are annual rings.

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DESIGN THROUGH AVAILABILITY: REFORM IN THE ARCHITECTURAL DESIGN PROCESS FOR REUSE

HAVU JÄRVELÄ AND ANTTI LEHTO

Abstract

The reuse of building parts has gained focus as a strategy enabling Circular Economy in the built environment. The critical challenge in consolidating reuse is the need to reorganize the design process and the scarcity of information supporting the required system level change. Research on reuse in the built environment is mainly based on theoretical models instead of realized projects. This article studies reuse process factors, comparing three realized large-scale office building projects in Europe with reused bearing structures, through 14 semi-structured interviews with project participants and complemented by project documentation. The main research questions are (1) How does situational information on reusable parts affect the design process? (2) What strategies are applied in the design processes of reuse projects? The research scope is limited to the main actors of a project team, because a design project is by and large facilitated by them. We focus on the reuse of the frame and outer shell structures in buildings due to their structural significance and potential in reducing whole-life carbon emissions. The results suggest that the material search and design process phases run side by side rather than the material search being a separate step. The research clarified the previously missing knowledge on reuse-related design actions taken in each design process phase and consequently found the existence of repetitive iterative loops occurring throughout the process.

Keywords:
reuse, architecture, design process, circular economy, circularity

1 Introduction

To mitigate climate change in the built environment, the reuse of building materials has gained an increasing foothold parallel with the concept of Circular Economy (CE), which aims at a systematic change in the mode of production by avoiding waste, slowing and closing material flows and utilizing renewable energy. For practical implementation through circular business models, several value retention options, such as the 10 Rs, have been advocated in a hierarchical order (Campbell-Johnston et al., 2020; Reike et al., 2018). Of these value retention options, reuse has significant advantages over recycling because it diminishes emissions in the production phase (Bertin et al., 2022; Brütting et al., 2019), as demonstrated by life-cycle assessments (Brütting et al., 2018; Eberhardt et al., 2021; Iacovodicu & Purnell, 2016). In buildings, the load-bearing systems and exterior walls have significant potential for CO_2 savings, as this category of building parts accounts for more than 35% of the embodied carbon of buildings (Bertin et al., 2022; Häkkinen et al., 2015; Kaethner & Burridge, 2012).

1.1 State of the art

Reuse in buildings can mean reusing whole buildings (*adaptive reuse*), utilizing salvaged materials from existing buildings (*material reuse*), or designing for future reuse of materials (e.g., *Design for Disassembly*). Our focus is on material reuse, which in architectural design has been previously mentioned by a few authors. Addis (2006) illustrated how material search and qualification take place in the design stages through a renewed "flow chart", used also as a basis by Kozminska (2020). Gorgolewski (2008) highlighted some key aspects, such as coordination and timing of donor buildings (e.g., material search), the relevance of material documentation and qualification, and the need for quality control of disassembly. Dokter et al. (2020) interviewed several architects involved in circular design, finding increased complexity, extension in length and scope, and entailment of new roles and integrity of the actors involved. A design process that reduces embodied carbon in buildings in general, and the importance of the early design stages in it, has also been highlighted (Häkkinen et al., 2015). The design process is affected by the barriers to the larger adoption of CE in construction, such as the absence of value chains, limited markets of secondary materials, and scepticism towards circular practices in general (Bocken et al., 2016; Geissdoerfer et al., 2017).

The current research on the design process involving the reuse of materials is based on limited empirical knowledge, remaining by and large on an abstract and conceptual level (Addis, 2006; Dokter et al., 2020; Kanters, 2020; Kozminska, 2020). So far, research has been based on small-scale experimental buildings or limited reuse of certain materials and components. Data has been gathered through expert interviews and workshops (Cambier et al., 2020; Geldermans, 2016), or meta-research revealing strategical approaches and barriers to implementation (Adams et al., 2017; Charef & Lu, 2021; Eberhardt et al., 2021; Hart et al., 2019; Kanters, 2020).

In summary, various factors in the design process have been recognized, but there is little knowledge as to how the real-life circumstances of reusing materials and the aspect of situation-related material availability, which we name as *situational availability,* have affected the design process and the way reuse has unfolded in detail. Therefore, there is a call for overviews of projects where circular principles have been applied (e.g., Cambier et al., 2020).

1.2 Aim of the study

This study aimed to acquire knowledge on the architectural process that involves the large-scale reuse of salvaged materials. The architectural process is defined through phases (e.g., RIBA, 2020) and this study included all phases from the early stages to the construction. Our research builds on the experiences of professionals who have been involved in existing, large-scale reuse projects in Europe, including new buildings, adaptations and extensions.

The research scope is limited to the core actors who form the "project team" (Addis, 2006). In this study, the selection of actors consists of architects and/or interior designers, structural engineers, reuse consultants, project managers and clients (see Figure 1). We left aside secondary actors, such as municipal administrators. During the study, digital tools and material banks were left out of the scope, as it turned out that the actors had not used them. Another delimitation applied during the research is national legislation, which is currently under development in various countries in the EU and has been researched by other scholars.

Architectural design process

CORE FACTORS (SCOPE OF THIS STUDY)	Design phases	Actors (project team)	Methods and strategies
INFLUENCING FACTORS (OUTSIDE OF THE SCOPE)	Legislation	Secondary actors (e.g. municipality)	Other factors (e.g. material banks)

Figure 1
The scope of the study.

Our research questions are (1) How does situational information on reusable parts affect the design process? (2) What strategies are applied in the design processes of reuse projects?

The article is structured as follows: First, we present the methodology and findings of the literature review, which was done to find suitable case buildings and their core actors (Section 2). After this, we present the results (Section 3) and discuss them against the current knowledge (Section 4). Section 5 concludes our research by highlighting the relevant findings and pointing out needs for further research.

2 Methodology

The research was based on a qualitative approach. The three cases studied were selected through a literature review. Research data from these cases was gathered by interviewing the project experts with real-life experiences of the implementation of reuse and complementing this data with the projects' published reuse. The potential data discrepancies between the two sources were later discussed with the participants for fact-checking to form a more holistic understanding of the processes.

2.1 Literature review

The mapping review was conducted on five databases (Scopus, ScienceDirect, Web of Science, JSTOR, Google Scholar and our university library) with the search term "reuse AND architecture AND circular economy OR building part reuse OR building component reuse OR reuse in construction OR architecture of reuse OR circular building". The results were limited to English. Reuse project design publications were searched using Google with the same and partial search terms and complemented by the authors' findings collected during active practice of architecture. The purpose of the review was to find current knowledge of reuse in architecture and to discover comparable, realized cases for study. The territorial scope of the review was restricted to Europe.

The selection was further narrowed by the following criteria: (1) utilization of reused materials in the bearing structure and outer walls (as justified in Section 1.2); (2) being several storeys high (to anticipate scalability and impact); and (3) being built for real-life circumstances (e.g., actual use, heated interior space). Most of the results were characterized by a relatively limited implementation of reuse, such as façades. In particular, the buildings that have utilized circular principles in bearing structures are typically small in scale and/or demonstrative in their nature, such as pavilions, detached houses, and temporary buildings (Piccardo & Hughes, 2022), or store halls (Gorgolewski, 2008).

The criteria led to a very limited number of studied cases; only three buildings fulfilled the requirements (see Table 1). These three cases were selected for in-depth studies through interviews with the involved actors. Even though a limited number of cases may hinder the generalization of findings, the acquired knowledge has value in discovering novel phenomena, especially where the knowledge has been by and large created in practice by experts (Flyvbjerg, 2006).

Table 1
Summary of the literature review of European buildings built with reused materials and research scope requirements. The three marked rows indicate projects fulfilling all the requirements and thus selected for in-depth study.

Abbre-viation	Case	Year	Country	Type	Reuse of materials in struc-ture	Reuse of other materials	Reused structure in more than 2 floors	Real-life purpose	Source
BDZ	BedZED	2002	UK	Residential	●	●	—	●	ZEDfactory (2002); Addis (2006)
PLP	Plattenpalast	2009	Germany	Residential	●	●	—	○	whs architekten (2009); Kozminska (2020)
VWO	Villa Welpeloo	2009	Netherlands	Residential	●	●	—	●	Superuse studios (2009); van Andel (2012)
WAH	Waste House, UK	2012	UK	Residential	●	●	—	○	Baker-Brown (2017)
LIA	Liander Offices	2015	Netherlands	Office	—	●	●	●	RAU (2015)
PCI	Pavilion Circl	2016	Netherlands	Public/ Office	—	●	—	●	De Architekten Cie (2016)
PEP	People's Pavilion	2017	Netherlands	Public	—	●	—	—	Bureau SLA (2017)
CHC	Circle House Demonstrator	2018	Denmark	Public	—	●	—	—	GXN (2018); Vand-kunsten Architects (2017)
KEP	KEVN Pavilion	2020	Netherlands	Public	●	●	—	●	Superuse studios (2020)
KAG	Kristian Augusts Gate 13	2021	Norway	Office	●	●	●	●	Nordby et al. (2021)
BIO	BioPartner 5	2021	Netherlands	Office	●	●	●	●	ter Steege (2023)
KBH	KA118 Kopfbau Halle	2021	Switzerland	Office	●	●	●	●	Stricker et al. (2022)

● Requirement fulfilled
○ Requirement unclear
— Requirement not fufilled

2.2 Overview of cases

The three selected cases are in different urban contexts and vary in size: Kristian Augusts Gate 13 (KAG), 3,790 sqm, is situated in a city centre; Kopfbau Halle 118 (KBH), 1,266 sqm, is in a former industrial area; and Bio-Partner 5 (BIO), 7,000 sqm, is on a university campus. They are all office buildings, with BIO having a more specific use as a research laboratory. KAG and KBH include adaptive reuse of an existing building and addition, whereas BIO was built as new building on an empty lot. All the projects have reported either the share of reused materials (kg) and/or saved CO_2 emissions. In terms of weight, KAG reused 15% (Nordby et al., 2021), and BIO 16.6% (ter Steege, 2023) of the total building materials. Greenhouse gas reductions of embodied carbon are reported as KAG 40% (only the new part of the building), KBH 59% (old part of the building included), and BIO 41%. Even if the given numbers are not fully comparable due to differences in calculation methods, calculation system definitions, and in the integration of existing buildings, they do indicate a significant reduction in carbon emissions. All the cases have utilized steel from donor buildings for the bearing structure of the new building. Additionally, KAG reused hollow core slabs in three of the eight storeys. Other reused parts vary from windows and facade claddings (KAG, KBH) to various interior elements.

2.3 Sampling, data collection and analysis

The interviews were conducted as semi-structured solo interviews with three main themes: (1) the network and role of actors, (2) the design process, and (3) material qualification. All 14 interviews were conducted in English with times ranging from 40 to 140 minutes. Originally, each case selected in the literature review was to be represented in the first phase by the architect, the structural engineer and the client. After the first interviews, it was evident that the reuse coordinator, or, if there were no external consultants, the person who oversaw material search and qualification, should be added, as well as the project managers. The overview of the interviewees is presented in Table 2.

Table 2
Summary table of interviewed actors in the three projects studied.

Project	Architect	Client/ Developer	Interior architect	Project manager	Reuse consultant	Structural engineer
Kristian Augusts Gate 13, "KAG"	●	○	●	●	●	●
Kopfbau Halle 118, "KBH"	●	○	—	●	●	●
BioPartner 5, "BIO"	●	●	—	●	—	●

● Conducted interview
○ Actor not reached
— Not a separate actor in project

The interviews were conducted online, recorded and transcribed. The coding took place in two phases (see Table 3) in a Software for Qualitative Data Analysis (Atlas.ti). The first round of coding provided data analysis on the main aggregate dimensions in the data (e.g., process, actors, material search), whereas the second phase searched for patterns and consistencies, following the principle of two-phased coding (Gioia et al., 2013).

Regarding the design phases, the data was complemented with the existing reports of the cases (Nordby et al., 2021) and the two books published and under publication while conducting the research (Stricker et al., 2022; ter Steege, 2023). This provided more detailed information on the quantitative assessments and particularly on the design timeline and phases, because interviewing several months after the project completion is likely to hinder the accuracy of the answers. To overcome this barrier, a detailed project timeline of each case was first built according to the available literature (ibid.) and checked with the architect of each case through two additional interviews and an email enquiry.

Table 3
A summary table of the first and second order of the interview coding.

First order code	Second order code	Aggregate dimension
Architect's commitment to the project important.	commitment to reuse builds on the architect and the client/developer	Actor
The client and architect decide the mission.		
Multiple actors taking part in evaluation of singular building system.	collaboration between architect and other actors is closer than traditionally	
The contractor and architect have weekly design meetings during construction phase.		
Reuse consultant handled site visits and qualification.	new design role introduced for material search, demolition and qualification	
The architect handled part search and qualification alongside design.		
Demolishing contractor included early on in the project to evaluate demolishability.		
Transparent communication between actors required.	common commitment of actors necessary for reuse	
Importance of everyone having ownership of the project.		
Tacit knowledge supporting material search and evaluation.	unpredictable factors strongly affect the search	Material search
Serendipity is present is finding materials.		
Material search includes institutional or big company participation.	overcoming lack of existing part databases with collaboration	
Networking and contacting others used as a tool in studied project design process.		
Market for reused parts in poorly developed.		
Loosely defined call for materials sent to manufacturers and demolition contractors.		
Demolition contractors important in material search and evaluation.	involvement of multiple actors in reusability evaluation	
Expert or specialist of certain building system needed in material search and evaluation.		
Time window for extracting and designing with materials before demolition is short.	timelines of demolition and new construction required intermediate storage	
Donor building demolition schedules are handled via intermediate storage.		
Storage enables systematic quality checking and modifications.		
General part suitability followed by stricter testing or search for documentation.	qualification as the result of small design iteration loop	
Lack of documentation can lead to discarding.		
Gradually defining a design solution instead of committing to it from the start.	strategies developed to work with uncertainty during design	Method
Allocating more costs towards design work on the expense of the material price.		
Unsolved problems are left to be solved in next design phase.		
Visiting a demolition site used as a tool in material search and evaluation.	increased site visit importance through design process	
Mention of importance of being present on-site during construction.		
All small-scale parts are not found reused and are substituted with new ones.	accepting partial circularity and focusing on major structures	
Design process scheduling does not allow for finding all parts as reused.		
Design work more about material relations than specifications.	design process experienced as assembling a collage	
Materials shape the design, not the other way around.		
Reused bearing part modelled with safety margins and selectively tested.	handling of risks via clear responsibilities	
Presenting design solutions for part reuse before tenders.		
Plan based responsibility sharing instead of regulation-based.		

First order code	Second order code	Aggregate dimension
Attitude of an actor changes from hesitation to positive during multiple design meetings.	more communication needed to change attitudes and procedures	Attitude
Pedantic documentation convinced building control.		
Demolishing bearing structures required accuracy surpassing traditional demolition.		
Project propelled development of temporary storage facilities.	wider interest in reuse emerges after a finished project	
New reuse professions/companies emerged after the project.		
Legislation interpretation changed to ease and clarify reuse process.		
Architect needs to commit to reuse and start building positive attitude early.	requirement of time to build commitment	
Excitement for reuse builds slowly during the project.		
Designers need to come up with novel ideas and evaluate them.	proactive attitude required from the designers	
Spreading info of the project through different channels creates a network.		
Finding specific parts required many site visits.	requirement of more time or resources during design process	Process
Redesigning façade of building multiple times based on available windows.		
Learning which parts' reuse saves a lot in CO_2 emissions or price.	reuse process knowledge developed during the project	
Started to do predefined material parameters used to filter possible donor sources.		
Building permit was defined more exactly after materials were found.	altered design phase and building permit scheduling	
Need for an extra design phase, material search.		
Multiple different strategies for reuse developed.	material uncertainty addressed via narrowing design scope	
Leaving tolerance between the different building systems.		
Usually, during decision-making some materials were unknown.	iterative design loops	
Parts assessed through multiple steps and with multiple actors.		

3 Results

This section presents the results of the data analysis and is structured in sections, following the design process phases (Sections 3.1–3.2). The material search and qualification have a strong reciprocal relationship with the design process. The search and qualification of materials are presented in separate sections in sequential order following the phases of the design process. Sections 3.3–3.8. present vital dimensions of the reuse design process that arise from the coding.

3.1 Design phases

The national building design phase conventions vary per project, but the overall phases are comparable when considered in broader segments. The timelines of the three studied projects were mapped by clarifying them in separate interviews and are illustrated in Table 4. The duration of the phases had some variation between the cases, so therefore the phase duration has been eliminated from the table. In the following sections, different process aspects are allocated to the predesign phase, the preliminary design phase and the detailed design phase.

Table 4
Summary timelines of design processes in the three studied projects categorised by design phases and design process actions.

Term in paper	**Predesign phase**	**Preliminary design phase**	**Detailed design phase**	**Construction phase**
Kristian Augusts Gate 13, "KAG" (Norway)	Strategisk definisjon *(Strategic definition)*; Mulighetsstudie *(Feasibility study)*	Skisseprosjekt (Preliminary design); Forprosjekt (Developed design)	Detaljprosjekt (Detailed design)	Byggefase *(Building phase)*
Kopfbau Halle 118, "KBH" (SIA 112, Switzerland)	Bedürfnissformulierung Lösungsstrategien *(Formulation of needs)*; Machbarkeitsstudie *(Feasibility study)*	Vorprojekt *(Preliminary design)*; Bauprojekt *(Construction design)*; Bewilligungs-verfahren *(Approval process)*	Ausschreibungen, Vergaben *(Tenders)*; Ausführungs-planung *(Implementation planning)*	Ausführung *(Building)*
BioPartner 5, "BIO" (STB 14, Netherlands)	Initiatief Haalbaarheid *(Strategic definition)*; Haalbaar-heidsstudie (Feasibility study); Project-definitie (Project definition)	Schets-ontwerp *(Concept design)*; Voorontwerp (Preliminary design); Definitief ontwerp *(Definitive design)*	Technisch ontwerp (Technical design); Prijs- en con-tractvorming (Pricing and contracting); Uitvoeringsgereed ontwerp *(Construction-ready design)*	Directievoering *(Building phase management)*
Sustainability goals introduced				
Reuse introduced				
Reuse selected as strategy				
Design team formed				
Volume sketches				
Bearing structure material search				
Bearing structure purchased				
Non-bearing material search				
Structural design of bearing parts				
Contractors hired				

3.1.1 Predesign phase

The interest of the client in sustainable building was perceived as a prerequisite for reuse in all the studied projects. The architects' preceding interest and experience of reuse was present in all the cases and the possibility for reuse was presented by the architects during the predesign phase in KAG and KBH. This initiative was then evaluated with the client and the other parties. In KAG some of the donor buildings were discovered through a consultant's previous projects. This allowed for a more streamlined material search in the following phases.

The interviews revealed that involving numerous parties in the project took place even before starting the design work. Most of the participants highlighted the importance of the feeling of common involvement (Section 3.6). This feeling was partly developed in predesign workshops that had the goal of mapping the possibilities of reuse from several viewpoints before deciding on the final approach. The importance of involving all the other actors might be explained by the lack of previous experience with reuse projects and the need for active collaboration during the whole process.

Most participants pointed out that accepting uncertainty during the first phases of the design was obligatory. All the projects included separate meetings between the client and the architects in defining the reasoning and possibilities of reuse. This was identified as important in further defining reuse as a goal and helping to select other parties based on the established goals. In the predesign phase reuse was approached in all projects on a conceptual level through graphs and studies, leaving multiple design paths open. These different alternatives for volumes and reuse concepts were tested through feasibility studies.

3.1.2 Preliminary design phase

Reuse affects the design phase leading to the building permit. In this phase, the design is strongly connected to the material search process (Section 3.2), which started in all three projects before the building permit.

Participants indicated that more time or resources were needed for two specific tasks: searching for available materials and/or iterating the design based on the found or available reusable resources (Section 3.4). The design process tasks leading to increased resourcing included finding specific parts, requiring almost 20 site visits (BIO), or redesigning the façade three or four times based on available windows (KAG). The need for extra resources was partly caused by the serendipity aspect regarding at which point during the design process new donor buildings were found. Evaluating and including the available parts affected the architects' and other designers' work in all projects and had to be coordinated before submitting the building permit application or continuing onward in the project. Participants in all the studied projects indicated that this work caused iterations in the design.

The studied projects utilized two primary strategies in the design processes leading to the application for a building permit. The first strategy, in KAG, was to begin with the building's overall dimensioning and only afterwards search for similarly dimensioned parts. The opposite strategy, in KBH and BIO, was to first find the reused parts and then dimension the building with these parts for the permit. The selection of the strategy did not depend on the material qualities or the site as KAG and KBH share site-specific dimension constraints and KBH and BIO utilize bearing steel structures that allow the possibility to alter their dimensions according to need. Irrespective of the selected dimensioning strategy, multiple iterations in design work, that do not occur in traditional building projects, were required in all three projects.

In KAG the possibility of refining façade drawings only after the building permit application allowed for going forward with fewer delays. Reducing uncertainty of the availability of the reused parts, discovering them in advance and systemizing the design iterations were seen as strategies with the potential to reduce the work and costs related to reuse.

Design with reuse was experienced as affecting all the interviewed architects' conceptual way of designing. In reuse cases, design work was described as being more about material relations than specifications. All the interviewed participants felt they had to tolerate more uncertainty in the preliminary design phase; many materials affecting the appearance of the buildings were not known yet. Tying the different parts aesthetically together was only concluded during the design phases after applying for the building permit. In KBH a strategy was selected to work from the bearing parts towards smaller entities and the material search scope was narrowed accordingly as the design evolved and became more accurate. However, no common methods in the secondary structure design process existed between the projects during the preliminary design phase. The general opinion among participants in this phase was that the selected strategy or reused parts was secondary and should not impede the functionality of the design.

3.1.3 Detailed design phase

The architect's role as a key figure in decision making and information exchange in the detailing and construction phases was strongly emphasized by almost all the participants. The detail drawing phase included providing more detailed testing results and documentation of the parts and their installation (Section 3.3). In KAG, the structural design of the bearing steel parts was done to a large extent after the building permit, whereas in KBH and BIO it was carried out before the permit and only partly revised in the detailed design phase.

Even though most of the realized projects have installed small signs explaining the origin of the parts to the visitor, this was seen somewhat as an extra gimmick rather than acting as a useful means for documenting material passports during the detailed design phase. One participant mentioned that a material passport system might even make it harder to reuse building parts as it would introduce an extra layer of documentation on top of the other tasks in this phase.

3.1.4 Construction phase

Participants from all the studied projects mentioned close collaboration between the constructor and the architect during the construction phase. In KAG and KBH, the architect and building contractor reported meeting on site several times per week to coordinate the use of numerous materials and parts. Some participants of these collaborating parties mentioned that more time was spent on site coordinating the challenges than in drawing details for them. The contrast between the status quo of constructing according to predrawn detail drawings and a reuse project's extensive need for collaboration on site was mentioned in most interviews. The effect on reuse projects seems to be explained by the roles of the architect in coordinating the desired architectural entirety, as they know the latest ongoing material search results and are in regular contact with the other actors related to the found parts.

Several interviewees mentioned how important the on-site work was in coordinating the aesthetic qualities of the projects. The reported challenge in on-site collaboration was the need to inform the subcontractors of the differences that are caused by reuse when compared with a conventional project. For instance, when provided parts were left visible, there was a need for more careful work and holding back on visible markings in the materials. This involved more careful installation without visible markings. Ensuring the communication of the general aesthetic goal to all parties was done by the architects and other actors during on-site visits. Remarks regarding the feeling of newness as the building's quality factor were present in some interviews. This was regarded as being a result of the careful coordination and selection of the building materials, which was not only based on functionality but also on aesthetics.

3.2 Material search

The material search was primarily organized and concluded by either a separate reuse consultant or the architect who invited other actors, such as demolition contractors and specialists in building parts, to the site visits. The architect or reuse consultant was responsible for the qualification and upkeep of the database of the selected parts in all the projects. Timing for the bearing part material search was inconsistent between the projects, ranging from the preliminary design phase to the detailed design phase.

Different regulatory landscapes of reused part qualification in the three cases led to differences in how the material search was focused. In KAG many materials were sourced from other properties owned by the client of the project. From a local regulatory viewpoint these parts did not change their ownership or thus enter the market. In KAG, bearing parts from other owners led to schedule-wise demanding legislative work and testing carried out by the municipality. In BIO and KBH the regulatory landscape was more accepting, and the materials were sought primarily from projects owned by others. In these two cases, the local regulations allowed for schedule-wise acceptable qualification testing of parts led by the architect and the structural engineer. In BIO, the testing was designed by the structural engineer and concluded in a separate laboratory. The results of the self-organized testing were accepted by the municipality.

Quick demolition and reuse decision-making schedules were present in all the projects. To facilitate the decision-making process in tight timeframes, a separate team was assembled to visit the potential donor buildings in KAG. This team consisted of representatives of all the relevant parties: the client, the architect, the engineers, the consultants and the constructors. In KAG and KBH the findings from the demolition site were documented in a shared database including information on the parts' current purpose, material qualities and presumed purpose. KAG had the strategy of narrowing down the material search from bearing to interior parts as the design evolved.

Large private and institutional property owners were present in KAG and BIO, acting as material donors. As all the projects had multiple donor buildings, these institutional actors enabled sufficient material flows for the needs of the new building. Due to a lack of information on the coming deconstruction sites and national digital material banks/vendors, the material search was strongly influenced by personal involvement, and even luck. The actors used several methods, ranging from systematic searching or wish lists to detecting a potential donor building while passing by. In addition, the participants' networks and personal relations played a role in finding some of the donor buildings as no existing databases were available. The material search was experienced as time and resource intensive. The requirement for either extra time or resources was a consistent finding in all three studied projects.

3.2.1 Material search at predesign phase

In the feasibility studies of the predesign phase, exact reused parts were either not mapped at all or were primarily approached through general concept work and graphs. These studies aimed at presenting strategies and possibilities for reuse and keeping multiple design paths open.

None of the projects started the material search during this first design phase. Finding collaborators and developing a network for finding, qualifying and utilizing reused materials was a prerequisite in enabling moving towards the following design phases.

3.2.2 Material search at the preliminary design phase

The preliminary design phase was the most intensive for material search. Actors performing the material search varied between projects. However, the central role of the architect was consistent, working actively in finding potential sources for material salvage. In BIO, the search was done by the architect, in KAG by a separate team consisting of representatives of the client, the engineers, the consultants and the constructor, whereas in KBH a material hunting party organized the visits for the architects.

In KBH and BIO, the bearing parts were found and purchased already before applying for the building permit. In both cases, reused steel bearing structures affected the dimensioning of the building. The participants pointed out that the lack of a national demolition site database posed a challenge in timing the material search. The involvement of the demolition contractors in this phase was considered important for finding demolition sites and enabling the reuse of bearing parts before the building permit application.

3.2.3 Material search at the detailed design phase

All the examined projects discovered some of their donor buildings only after submitting the building permit application. This situation applied primarily to interior dividing walls, final surfaces and other non-bearing interior structures. However, in KAG the bearing steel parts were found and purchased after submitting the permit application. Various strategies were mentioned in obtaining reused materials in this phase. KAG developed a wish-list approach, noting the required qualities of the sought materials and approaching the different material suppliers and demolition parties with this list, instead of a defined quota for certain materials, to avoid too narrow search domains.

In the phases after the building permit, most non-bearing and façade parts were selected not solely based on functionality but also on their aesthetic qualities. All the projects rejected several potential donor sources due to the aesthetic properties of the parts. Aesthetic properties leading to rejection included unwanted horizontal divisions of interior glass panels in BIO, or unwanted exterior cladding sheet textures in KAG. Supplementary materials and findings affected the design process through iterations in design (Section 3.4). In KBH, the strategy of isolating the different structural entities into independent modules helped to avoid some of the iterations.

3.2.4 Material search at the construction phase

All the projects had concluded the bearing part material search before the building phase. KAG and BIO reported minor material searching during the construction phase, focusing mainly on surface materials and fixed furniture. The materials in this phase were reported to originate from manufacturing company surplus caused by faulty orders or temporary event constructions rather than demolition sites. Some of these materials had not been installed earlier and were comparable to new production. Strategies reported on the usage of such parts included allocating different floor materials to different spaces instead of aiming at uniform floor surfaces in the whole building.

3.3 Material qualification

Qualification of the parts was managed by different means in the cases studied. In KAG and KBH, the architect oversaw the handling of the required documentation, while in BIO it was the task of sustainability consultants. Qualification was the possible result of a small design iteration loop, starting from material search, leading to the assessment of general suitability and ensuring quality by documentation or laboratory testing (Section 3.4). In non-bearing parts, a lack of documentation could lead to discarding the material. The focus and amount of qualification-related work seems to be linked to the municipalities' interpretation of the construction regulations and therefore differed in every project. Most of the projects have caused side effects either in the following national interpretation of these rules and/or in establishing new professions to help with finding and qualifying the reused parts.

3.3.1 Material qualification of the bearing structure

The qualification of bearing parts required external lab testing, taking one or two months, ordered by the municipalities in KAG and by the client in BIO. None of the projects tested all the bearing parts in a laboratory. In BIO, testing of the bearing parts was implemented through a two-step strategy: first evaluating the approximate bearing potential by calculating the donor building forces and then further testing selected parts and joints to confirm the results. This method enabled risk management without the need for assessing all the bearing parts individually in a laboratory. Safety margins were added to the structural design by shortening the spans of the bearing structures from their original dimensions, by including new parts to enforce the joints or by partly utilizing newly produced parts. A similar strategy of batch-based bearing part testing was reported in KAG and KBH.

Participants from all the projects experienced steel structure qualification to be relatively straightforward because the material has defined profiles, quality classes and testing methods. Qualification of bearing concrete parts was present only in KAG and caused an increase in required work per qualified part primarily due to context-related reasons for the lack of defined testing methods.

3.3.2 Material qualification of other building parts

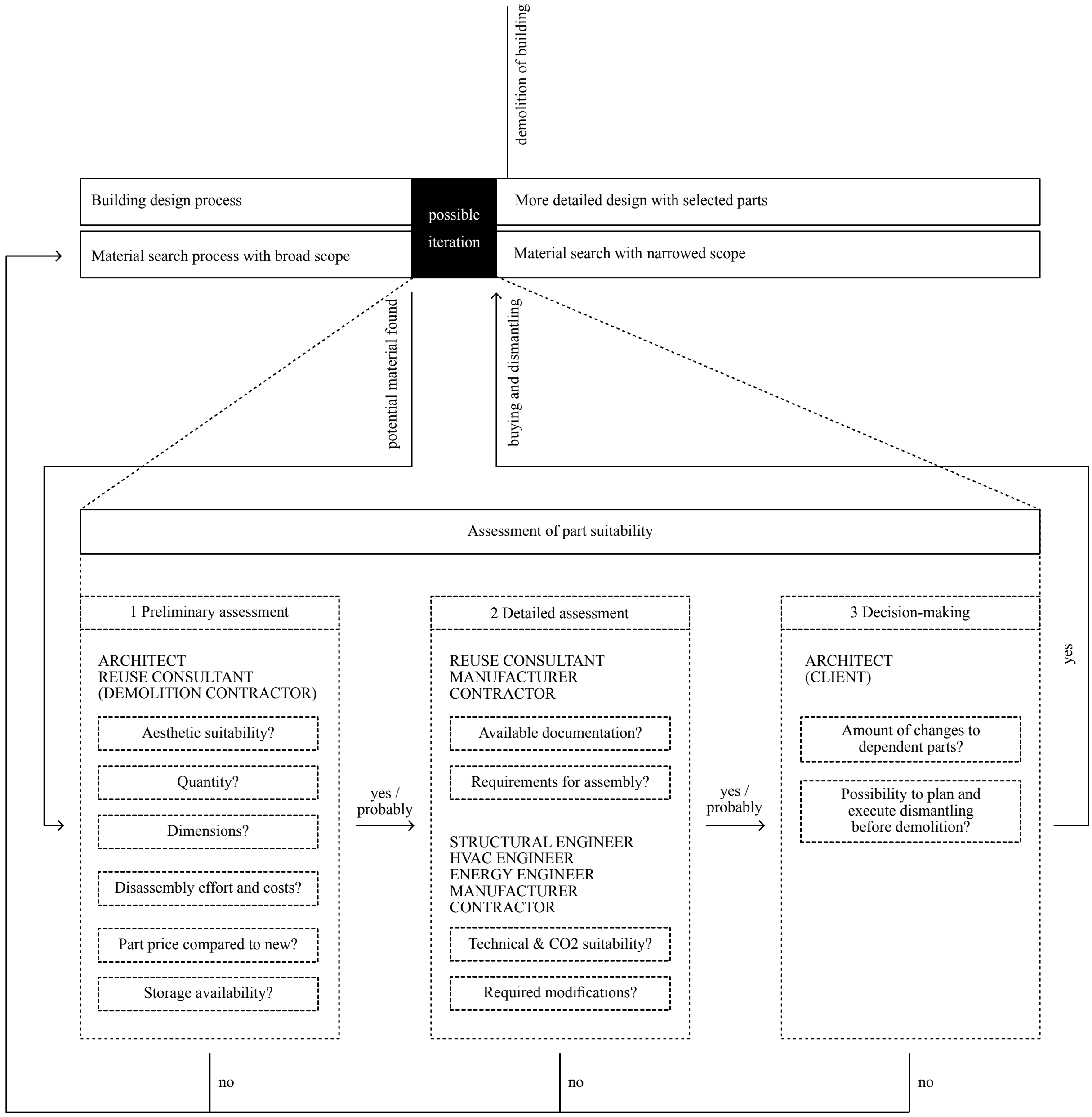
Various actors took part in the qualification for the non-bearing reused parts. Participants from all the projects reported that qualification happened in parallel with the material search. No separate design phase was identified for the qualification-related tasks. Inconsistency in national interpretations of the European building code and responsibilities of material donors affected the amount of qualification-related work.

Original part manufacturers were identified as a valid source for acquiring part documentation in specific parts, such as windows, partition doors and steel stairs. Several strategies for assuring safety and providing qualifications were mentioned. These included searching for part original documentation, lab-testing the part's physical qualities, contacting the manufacturers, assessing the part's current loads, under-stressing the parts compared to their initial use and enforcing the parts with new connections.

3.4 Iterative design loops and decision-making

Participants experienced the choosing of the materials as a part of the design work. In all the projects, the interviewees pointed out several iterative loops during the design process occurring parallel to the material search. The iterations were caused by uncertainties in materials: (1) sizes and amounts of available parts, (2) quality and physical performance based on expert knowledge (e.g., structural engineer's estimate on suitability), qualification results, (3) aesthetic properties, (4) timing of availability, and (5) costs. During decision-making moments, the materials that would be available in the coming phases were often not known. Questions of who makes the final decision to use the available part or not were raised in all projects. A strategy mentioned was giving the designer on whose domain the part is located to have the final say and ensure transparent communication related to part selection via meetings and workshops.

The iteration loops consisted of separate steps, beginning with a preliminary assessment of the part qualities, a more detailed technical assessment and final decision making (See Figure 2). In BIO, the complete loop, from finding the potential materials to deciding to dismantle them, could be as fast as a single day for non-bearing interior walls. Close collaboration between the different parties was required in including these changes in dependent parts and their designs. Examples of these interdependent part iterations were windows affecting the structural detail of bearing structures and altering pillar positions in KAG, available steel beam dimensions affecting the cantilevering shape in KBH, or reused beam connections affecting the ventilation system solutions in BIO.



3.5 Material dismantling and storage

Involving the demolition party early in the project was seen to be important in all the projects. Collaboration between the architect and the demolition party helped in deciding the potential of reuse and the methods of dismantling. Some challenges identified in the demolition were the tight time schedules and the required accuracy for the dimensions and shape of the dismantled parts, which surpassed the commonly required accuracy for demolition. The projects included two different demolition tender situations: the first case, in KAG, in which reuse was part of the original demolition tender, and the second case, in BIO, in which reuse was brought to tender after starting the demolition work. Success in the latter case was possibly due to the cooperation between the

Figure 2
Generalized summary of an iteration loop, its actors and decision-making steps during a design process involving reused parts.

client, architect, demolishing institutional actors, the requirements for careful demolition caused by surrounding laboratories and the common will to evolve by all the actors.

Participants presented similar strategies for upkeeping the quality of intact demolition: having separate consultants on site leading the disassembly or making the same party handle both the demolition and new construction with the bearing parts.

All the projects included intermediate storage between demolition and the new building. The storage was provided by the municipality in KAG, by the client in KBH and by institutional landowners in BIO. Intermediate storage was regarded as obligatory for making the process possible as most of the participants pointed out that demolition timelines are short and timing with the new construction is partly based on luck.

In KAG and KBH there were over 20 donor buildings per project fulfilling the needs for new construction. Temporary in-between storage was a prerequisite for being able to use these materials efficiently in new construction. The in-between storage also enabled systematic quality checking and modifications for reused parts. Storage quality depended on the part and the season and, due to these factors, some of the reused bearing elements could be stored in outside conditions, thereby avoiding extra costs.

The predemolition inventory and marking of the parts eased their reuse, and carefulness in in-between storage classification was seen as an important factor in enabling part reuse. Challenges in this phase included cases in which the identifying specifications and the parts were separated, resulting in a loss of knowledge and the unfortunate consequence of having to discard these parts.

3.6 Involvement of the actors

Finding the right actors, building trust, and involving the different parties were mentioned in all the projects. A common theme in most interviews was building a sense of ownership of the project. Scepticism towards the possibility of building part reuse was said to decrease during the advance of the design process in all three cases. Common workshops and discussions about the means of realization of reuse were reported as giving the actors more freedom to propose new strategies. Participants experienced this shared ownership of the challenges as necessary because no single actor could oversee all the design domains although all the domains were affected by the reuse. Component manufacturers and specialized trade shops were mentioned as prerequisites for providing various components with enough documentation for reuse and installation. This also required transparent communication between the actors.

3.7 Costs and time

Most of the reported costs related to part reuse were said to be based on the added design work time rather than the reused material prices. The reported costs of reused part types compared to new ones varied vastly per part type. Costs were assigned more towards the design and qualification hours with the reused parts being comparably inexpensive. For example, KBH reported the total construction costs to be on a par with new construction, but a significant part of the costs was assigned to the design work rather than the materials as would be expected in a traditional case. Participants from all projects agreed that a completely circular building would be difficult due to the high cost of finding and qualifying certain specific reused parts on schedule and thus the focus should be on beneficial construction parts with the most potential, such as bearing steel structures, façade parts and windows. This shared experience had no inconsistency among the participants even though the projects had different results in the final construction price when compared with the national average: KAG went over traditional construction prices, KBH stayed on a par and BIO was cheaper than status quo construction. However, all the participants reported non-predictable and short demolition schedules added to the uncertainty of available parts and increasing timetable risks because a systematic framework for reuse design scheduling does not yet exist.

3.8 Methods and strategies

Participants identified various learning aspects from various phases of the project, resulting in the following patterns.

3.8.1 Scoping material search

Participants elaborated their material search network and processes during the project, supplementing the missing material databases. Participants from KBH and BIO mentioned developing a strategy of going from bearing structures towards minor ones. This would enable narrowing the material search scopes for each phase and help systematically avoiding uncertainties during later phases of the design process. Learning about which specific reused secondary parts have CO_2-savings and/or big price cuts compared to new ones enables a more systematic selection of reuse domains.

3.8.2 Accepting uncertainty

Uncertainty was acknowledged as a common experience amongst architects and other participants. Many parts of buildings remained in practice undetermined longer than in conventional projects, even if illustrations were done, for example, for the authorities. While reviewing the process afterwards, the architects of BIO and KAG pointed out the method of leaving things open. In this, a certain feeling or look of a building part, for instance of a façade, is created, but without making a final decision. In KAG the exact façade materials were unknown when submitting the building permit. The municipality accepted specifying façade drawings only later when the materials had been found. In KBH, a similar method was used by leaving tolerance between different components, such as windows and the openings in the wall.

3.8.3 Phases and resources

Participants identified reserving a separate design phase for material search or extra resources for it during preliminary design as a possible factor in minimizing the overlap of the material search with the detailed design phase. One learning aspect specifically mentioned in BIO was getting to know the part testing conventions and schedules and being able to utilize the information in structuring future design processes.

Participants who mentioned evolving material search processes (Section 3.2) included systematizing the demolition site search, streamlining material documentation, testing for design work and including a separate material hunter to help the planning architect. Upcoming digital databases of demolition sites were mentioned as a complementary tool in systematizing material search.

KAG propelled the development of local municipal temporary storage facilities that would enable easier intermediate storage. Other remarks about further enhancement of temporary storage included making the documentation of the parts more systematic to avoid documentation losses during storage.

3.8.4 Risk management

Risk management was curated through different strategies and parties. Involved larger companies or institutional actors were seen as important in inviting more parties to join the pioneer project and giving it more credibility at the beginning of the project. One of the risk management strategies was to present comprehensive designs for the realization of part reuse even before asking for tenders in order to prevent the fear of unknown risks being reflected in higher tender prices. Attitudes and involvement were consistently reported as enabling reuse in challenging scenarios. An approach for plan-based sharing of responsibilities instead of regulation-based strict responsibility borders were experienced as useful.

3.8.5 Regulations

Because the municipalities' interpretation of the construction regulations was inconsistent in all the projects, what was learnt differed somewhat. KAG reported regulatory challenges caused by vast material donor responsibilities whereas KBH and BIO experienced no similar challenges. KAG learnt that involving big private and municipal property owners as material donors enabled sufficient material flows for the needs of the new buildings without extensive requalification because when a part either stays on the same plot or in the hands of the same owner it doesn't enter the market. Most participants reported consistent change in regulations and the surrounding business field as enabling more common reuse during the process.

4 Discussion

This research deepened the knowledge on how reuse building processes are affected by material search and what design strategies were applied in realized reuse projects. The cases studied represent the very first steps towards bearing part reuse on a larger scale.

Previous research on CE in the construction sector has focused on macro scale circularity (Kanters, 2020; Kozminska, 2020), availability of tools (Cambier et al., 2020) or circularity as assessing a material property (Geldermans, 2016). The focus on tools or material assessments as primary enablers of the transition is partly in contrast with the experiences gathered from the studied projects. They indicate that the preconditions for performance in circularity are primarily the involvement of the client, the architect and the rest of the design team. Tangible hands-on work and extensive communication between the actors seem to lead to the discovery of circularity potential in various materials, to developing novel knowledge and thus accelerating CE in the building sector. The involvement of larger companies or institutional actors in the material search reveals the lack of larger part databases and reuse operators. This might be explained by the pioneering nature of the projects; they have adopted the means available to overcome the poorly developed reused material supply chain.

Moreover, previous knowledge of reuse design processes (Addis, 2006; Kozminska, 2020) lacks detail of the phasing and misses the ongoing iterative loops. Our results indicate that reuse projects require a continuous and repetitive iterative loop that occurs in the various phases of the design process. Material search in all three studied projects was an ongoing process alongside design work and could not be thought of as a separate step preceding design in the process timeline as presented in previous research (Addis, 2006; Dokter et al., 2020). The results provide a more detailed description of the several iterative material selections and decision-making loops in short time spans, including the assessment of material qualities and purchase of materials. The procedures form a set of decisive points in the design process. When the number of reused materials increases in a building, the more profound the effect these loops have on the design process and the resulting architectonic expression of a building.

The construction sector's recognized struggles with attitudes towards reuse (Cambier et al. 2020; Dokter et al., 2020) seem to diminish during design processes involving reuse in all the studied cases. This signals the need for more reuse pilot projects as a successful way to change wider attitudes. Due to the different national customs, regulations, sites and programmes, the studied projects have approached the challenges related to reuse from different perspectives. These inconsistent factors have made qualification processes and the responsibilities of the various actors differ from each other. Due to the lack of reuse part qualification guidance, the permit process requirements were proactively negotiated by the architects.

In terms of limitations, the post-process conducted interviews pose uncertainties in capturing accuracy in the schedule data when compared to research collected during an actual design process or comparing timelines with raw data points. For these reasons, the research was focused primarily on the broader picture of the design process and the relations between different process variables. The focus on European large-scale bearing structure reuse projects led to a small number of office building cases. Finding further potential in systematizing reuse design processes across different building types would require even more large-scale case study projects as well as research documentation during the process, including a wider territorial scope.

5 Conclusions

A series of semi-structured interviews was conducted with key design process actors from three European projects that included bearing structure reuse in order to gain insight into the design process of realized reuse projects. The results of comparing reuse building processes with status quo design processes indicated the need for extra resources for material search, increased intensity of on-site work and communication between actors, the need for intermediate storage and the importance of an early-on sustainability goal on the part of the client and the architect.

The research supports the current knowledge on reuse. However, it additionally suggests that the material search and design process phases should run side by side instead of material search being a separate step. The research clarified the previously lacking knowledge on reuse-related design actions taken in each design process phase and consequently found the existence of repetitive iterative loops occurring throughout the process.

Further studies are needed to understand how the lessons learnt from realised reuse projects utilizing existing material resources from demolished building stock could guide Design for Disassembly with virgin materials. A larger selection of cases with reused bearing parts could further clarify the systematizing potential for reuse building design processes. Therefore, the results of this study should be regarded as a basis for further research.

Authorship contribution statement

Havu Järvelä: Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing, Visualization, Project administration. Antti Lehto: Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing, Visualization, Project administration.

Declaration of Competing Interest

The authors declare that there are no conflicts of interest.

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