Components reuse in the building sector – A systematic review

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Components reuse in the building sector – A systematic review

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Abstract

Widespread reuse of building components can promote the circularity of materials in the building sector. However, the reuse of building components is not yet a mainstream practice. While there have been several studies on the factors affecting the reuse of building components, there is no single study that has tried to harmonize the circumstances affecting this intervention. Through a systematic literature review targeting peer-reviewed journal articles, this study intends to identify and stratify factors affecting the reuse of components of the superstructure of a building and eventually delineate correlations between these factors. Factors identified throughout this study are classified into six major categories and twenty-three sub-categories. Then the inter-dependencies between the barriers are studied by developing the correlation indices between the sub-categories. Results indicate that addressing the economic, social, and regulatory barriers should be prioritized. While the impact of barriers under perception, risk, compliance, and market sub-categories are very pronounced, the highest inter-dependency among the sub-categories is found between perception and risk. It suggests that the perception of the stakeholders about building components reuse is affected by the potential risks associated with this intervention.

Keywords: Reuse; Building components; Systematic literature review; Building sector; Construction and demolition waste; Circular economy; Superstructure

Abbreviations

BCR	Building Components Reuse
BIM	Building Information Modelling
BMR	Building Material Reuse
BREEAM	Building Research Establishment Environmental Assessment Method
CDW	Construction and Demolition Waste
CE	Conformité Européene (European Conformity)
DfD	Design for Deconstruction

DfMA   Design for Manufacture and Assembly

EC   European Commission

GHG   Greenhouse Gases

ICE   Institution of Civil Engineers

JIS   Japanese Industrial Standard

km   Kilometres

LCA   Life Cycle Analysis

LEED   Leadership in Energy and Environmental Design

NDT   Non-Destructive Test

RCA   Recycled Concrete Aggregate

RFID   Radio Frequency Identification

RL   Reverse Logistics

Introduction

The construction industry consumes between 30% to 50% of the natural resources (Anink et al. 1996, Herczeg et al. 2014, WSA 2012), produces up to 40% of the total waste stream (excluding the excavation waste) (Eurostat 2019, Clark et al. 2006, Defra 2019, UNEP 2015), and generates around 39% of the world's greenhouse gas emissions (Abergel et al. 2017). Above facts are alarming due to the urgent need to decrease the GHG (UNFCCC 2015) and because we are facing landfilling restrictions (Brewer and Mooney 2008) and resources deficiency globally ('Ellen MacArthur Foundation' 2013, Chen et al. 2010).

Depletion of the earth's resources as the result of fast economic expansion, continuous population growth, and the drastic increase in demand for products and services has led the governments to run resource-efficient economies ('Ellen MacArthur Foundation' 2013). Therefore, the regulatory authorities worldwide, such as the European Commission Waste Framework Directive 2008/98/EC (EU 2008) and the Demolition Protocol (ICE 2008), introduce waste hierarchies to improve the material efficiency across all the economic sectors,

including the building industry. According to these waste hierarchies "preparing for re-use"(or simply "reuse") is the second-best solution after "prevention" to decrease the high level of waste generation, and to decouple the economic growth from the resource consumption.

New design methods such as design for deconstruction (DfD) (Akinade et al. 2017, Tingley and Davison 2011) and design for manufacture and assembly (DfMA) (Kalyun and Wodajo 2012) are introduced to prevent or decrease waste throughout the entire lifecycle of new buildings. However, most of the existing buildings are not designed based on the above techniques, which results in the generation of a considerable amount of wastes during refurbishment or demolition phase. Although according to the waste hierarchies, reuse is preferred to recycling, most of the recovery of construction and demolition wastes (CDW) happens in the form of recycling and not reuse. For example, in the UK, nearly 91% of the non-hazardous CDW is recovered through recycling (Defra 2019).

While recycling can divert waste from the landfills, the processes involved are energy and resource-intensive and impose a noticeable pressure on the environment in terms of GHG and other sorts of emissions (Bill Addis 2006, WRAP 2008). Contrarily, reused building components (bricks, beams, columns, truss, etc.) have far lower environmental impacts when compared with recycled materials (Geyer et al. 2002). For instance, when new steel sections which have around 60% recycled content are used, their environmental impacts are still twenty-five times more than reusing the equivalent reclaimed steel sections (WRAP 2008). According to (Lazarus 2003), reusing reclaimed structural steel or timber sections can decrease the environmental impacts by 96% and 83%, respectively. It is primarily due to significantly lower treatment and reprocessing required for building components reuse (BCR) in comparison with recycling (Gorgolewski et al. 2008). Notwithstanding, the reuse rates in the building sector have declined in the last two decades in countries like the UK (Bill Addis 2006, Sansom and Avery 2014), and only a fraction of components at the end-of-life of a building are reused (e.g. 5% reuse rate for the reclaimed steel sections in the UK in 2012 (Sansom and Avery 2014)).

Building components reuse, and the factors affecting its uptake has been the focus of research for several years. However, there is no evaluation material synthesizing the factors affecting BCR to find the correlations between these factors and harmonize the circumstances affecting the reuse of building components. In the lack of such a study, reuse will not grow in the building industry because the fragmented body of knowledge available in the literature is unable to direct the stakeholders to take progressive steps towards circularity of

materials in this sector. This study thus aims to bridge this gap by analysing different aspects that influence the adoption of component reuse in new buildings, prioritizing the barriers to reuse in terms of their urgency to tackle, and draws roadmaps for future research. The authors intend to achieve these goals through a systematic review approach targeting peer-reviewed journal articles. Therefore, the authors identify the following objectives for the aim of this study:

(i)   To identify and stratify drivers and barriers affecting components reuse in the building sector.

(ii)   To delineate correlations between the barriers to prioritize the necessary actions.

Definitions, scope and limitations

The following terms are used frequently in this study and are defined as follows:

Adaptive reuse/Building reuse: Extending the life of an entire building (or at least some parts of it, for example, its structure) at the end of its useful life due to its historical/social values (Bill Addis 2006, Gorgolewski 2008).

Deconstruction: Careful disassembly of a building to maximize the reusability of its constituents (Bill Addis 2006, Munroe et al. 2006).

Recycling: A set of steps to collect, sort, transport, process, and convert a discarded material (scrap metal, packaging cartons, concrete blocks, etc.) into new products (new steel plates, recycled papers, recycled concrete aggregate (RCA), etc.) (Ferrer and Clay Whybark 2000).

Building material reuse (BMR): The use of building materials (e.g. RCA, crushed bricks, etc.) in the production of new building components (concrete columns, slabs, beams, etc.) (Bill Addis 2006).

Building components reuse (BCR): Bringing back a discarded building component (e.g. a beam, column, bricks, windows, doors, etc.) into its original function with minimum (or zero) treatments (Bill Addis 2006, Parker and Deegan 2007).

Reverse logistics (RL): A set of interventions (e.g. recycling, reuse, etc.) or design strategies (DfD, DfMA, etc.) to minimize CDW during the entire life cycle of a building (Iacovidou and Purnell 2016, Hosseini et al. 2015, Aidonis et al. 2008).

The scope of this study is limited to peer-reviewed journal articles because these types of research works are considered of high quality and validity (Schlosser 2007). This approach is in line with (Yi and Chan 2014) advice to investigate top-tier construction journals while performing literature reviews.

This paper focuses on BCR, and other types of reuse, such as adaptive reuse, recycling, and BMR are out of the scope of this study. While adaptive reuse is the most preferred option to prevent waste, because this paper focuses on the management of CDW after generation, adaptive reuse is out of the scope of this review. As explained in the introduction section, other waste treatment options such as recycling and BMR are highly energy and resource-intensive (Bill Addis 2006, WRAP 2008); therefore, not considered in the scope of this study. This trend is followed while selecting the proper search words in the methodology section, as well.

The terms building component(s) and element(s) are used interchangeably in this study. These are restricted to sections forming the superstructure of a building as defined by (BCIS 2012) that can be dismantled (through demolition, deconstruction or selective demolition) and reused for the same function with minimum (or zero) treatments (Bill Addis 2006, Parker and Deegan 2007). Therefore, this study does not consider substructure (foundation), plinth, finishes, fittings, furnishings, equipment, and services in its scope (BCIS 2012).

Two major examinations are performed to scrutinize the articles reviewed in this paper. The first method is focused on identifying and analyzing reuse drivers and barriers (cumulatively called factors), and the second method is focused on correlations and the possible inter-relationships between reuse barriers.

The next section explains the methodology employed in this study. The results and discussions section deals with the findings and deeply investigates the identified factors and summarises the study by presenting the discussion and the next steps through recommendations. Eventually, the article presents the conclusions and highlights its contribution to the body of knowledge.

Methodology

This study uses a systematic literature review method to identify various factors (drivers and barriers) affecting the reuse of building components on a global scale. A systematic review is a comprehensive and reliable process for locating the existing body of knowledge (published scientific work) regarding a very particular research question (GET-IT Glossary n.d., Denyer and Tranfield 2009). Because this process is based on a

defined search strategy with clearly specified objective(s), it can be used to analyse, synthesize and critically

evaluate the existing literature identified within the context of the research question (Denyer and Tranfield

2009, Bettany-Saltikov 2016). This methodology provides a strong basis for reliable judgments about "what

works" the best (Petrosino and Lavenberg 2007) and finds gaps in the literature for further research (Denyer

and Tranfield 2009). The systematic literature review is a well-known methodology for the study of the existing

knowledge in medical sciences because of its unique properties, as expressed above (Tranfield et al. 2003).

Nevertheless, the systematic literature review is acquiring its position among other research areas such as

engineering and management (Hosseini et al. 2015, Alaka et al. 2018, 2016, Charef et al. 2018).

The complete process of the systematic literature review is presented in figure 1. In this study, the Preferred

Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2018) checklist is used to step-by-step

perform and record the methodology. PRISMA checklist is widely used by researchers while performing

systematic literature reviews (Moher et al. 2009).

A pre-requisite to conducting a systematic review is a clear research question as well as knowing the proper

keywords to perform an effective search. Because a building at the end of its lifecycle is removed through

demolition (with some other variations such as selective demolition and deconstruction), to identify the

proper keywords, the authors performed an initial literature search using "deconstruction" and "demolition"

search words at stage 1. Through this initial search, 11 relevant papers were identified, which helped in the

selection of the search words listed in figure 1 (stage 2).

At stage 2, a Boolean search criterion is followed to answer the research question of this study. At this stage,

the search is limited to the "titles" of the articles. The initial search in Scopus showed that studies containing

discussions on the reuse of building components focus on construction and demolition waste management.

Therefore, the first set of search words intends to ensure that any article containing these words are

considered. The AND combination with the second set of search words guarantees that all relevant articles

dealing with reuse in the building sector are included in the search. Because the scope of this paper is BCR and

not building reuse or BMR, keywords such as "refurbish" or "refurbishment", which primarily deal with

adaptive reuse of existing buildings (particularly historic buildings) or "material", which deals with material

reuse are not included in the search words (figure 1).

The cut-off date for stages 1 and 2 of the literature review is March 2019, whereas the cut-off date for stage 3

is January 2020. Because this study only focuses on peer-reviewed journal papers, following (Yi and Chan

2014), all other types of publications (book chapters, conference papers, trade journals, etc.) are excluded.

Hence, only "Articles" and "Articles in press" published in peer-reviewed journals are considered for this study.

Likewise, to limit the number of unwanted articles, irrelevant subject areas, as listed in figure 1 at stage 2, are

excluded from the search criterion. It is because search words such as "building", "construction", "structure",

"reuse", and "recover" are found in a broad range of scientific publications. Furthermore, since most of the

publications in this area are published post-2000, stage 2 considers the range of articles published between

2000 and March 2019.
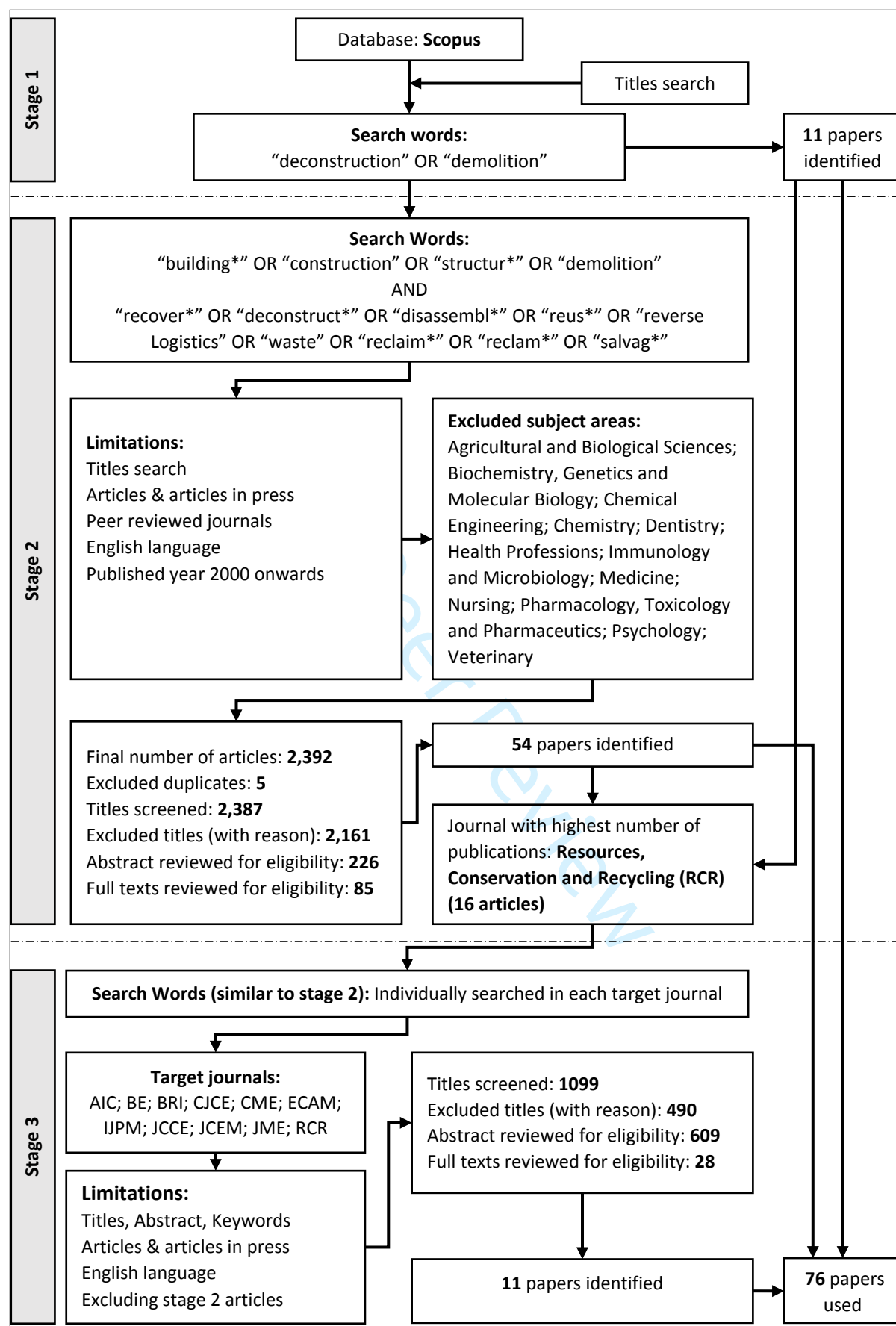
Figure 1 Systematic literature review framework (inspired by (Charef et al. 2018, PRISMA 2018, Yi and Chan 2014)*)*

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☐ Material Science

▨ Engineering

Ⅲ Environmental Science

◩ Waste management

⊠ Social Sciences

▣ Water and wastewater; Adaptive reuse; Geology; Mathematics; Physics (each 2%)

⬚ Neuroscience; Disaster management; Business; Economics; BIM; Other sectors; Reverse Logistics (each 1%)

■ Astronomy; Earthquake studies; Biology; Chemical Science; Decision Sciences; Circular economy; Medicine; Medical

Figure 2 Subject area of the excluded papers during the screening process at stage 2

Among the 2,387 article titles screened at stage two, 2,162 articles were found irrelevant and excluded. Figure 2 depicts the percentage of the subject areas of the excluded papers during the screening stage. The appearance of articles in areas like medical sciences (while were excluded from the subject areas) could be because of the interdisciplinary nature of some papers. The authors then reviewed the abstracts of the remaining 226 articles during the eligibility check of stage 2 (PRISMA 2018) (figure 1). At this stage, irrelevant papers such as those focusing on construction waste management other than reuse (Guo 2016, Jin et al. 2017), concentrating on other sectors like reverse logistics in electronics industry (Sirisawat and Kiatcharoenpol 2019), or talking about reuse but dealing with recycling or down-cycling (Migliore et al. 2015) are identified and excluded. The result is the exclusion of 141 more papers from the full-text review. The authors eventually reviewed 85 full-text articles from which we could find 54 papers relevant to the objectives of this study.

The search results from stages 1 and 2 indicate that the journal of *Resources, Conservation and Recycling (RCR)* has the highest number of publications (16 papers) among all other reviewed journals. Hence, following the framework pursued by Yi and Chan (2014), a third stage systematic literature review was performed considering all the ten first-tier construction journals plus *Resources, Conservation and Recycling (RCR)*. The complete list of all these journals are *Automation in Construction (AIC); Building and Environment (BE); Building Research and Information (BRI); Canadian Journal of Civil Engineering (CJCE); Construction Management and Economics (CME); Engineering, Construction and Architectural Management (ECAM);*

International Journal of Project Management (IJPM); Journal of Computing in Civil Engineering (JCCE); Journal of Construction Engineering and Management (JCEM); Journal of Management in Engineering (JME); Resources, Conservation and Recycling (RCR). At this stage, the identified search words were used to perform a Boolean search in the 'title/abstract/keywords' of each of the journals separately. Moreover, the year 2000 restriction was lifted at this stage (figure 1). All the above was to overcome the restrictive nature of the stage 2 limitations (figure 1), as well as to make sure that articles published in high-impact journals related to the built environment are considered.

During this process, 490 articles were excluded from abstract review for similar reasons observed in stage 2. For instance, while paper (Ling and Leo 2000) focuses on identifying drivers to promote timber formwork reuse, it is out of the scope of this study, which is the superstructure of a building. After reviewing 609 abstracts during the eligibility check, only 28 papers were identified for full-text review. While the reviewed full-texts contained a combination of the search words, the focus of the rejected papers was not in line with the aim of this study. Following the same protocol pursued at stage 2, a total number of 11 more papers were identified at this stage. According to what mentioned earlier and combining the identified papers at all three stages, 76 articles were found relevant to the objectives of this paper and reviewed. None the less, the identified new articles, as the result of the third stage systematic review, were all published after the year 2000, which validates the initial decision in restricting the publication date.

Results and discussions

Figure 3 shows the distribution of the papers reviewed in this study by the year of publication. According to this figure, the number of peer-reviewed journal articles has been increasing since 2014, which indicates an increasing focus on construction and demolition waste treatment through reuse. However, there is a decline in the number of publications in 2019, which needs further investigations to identify the root causes.
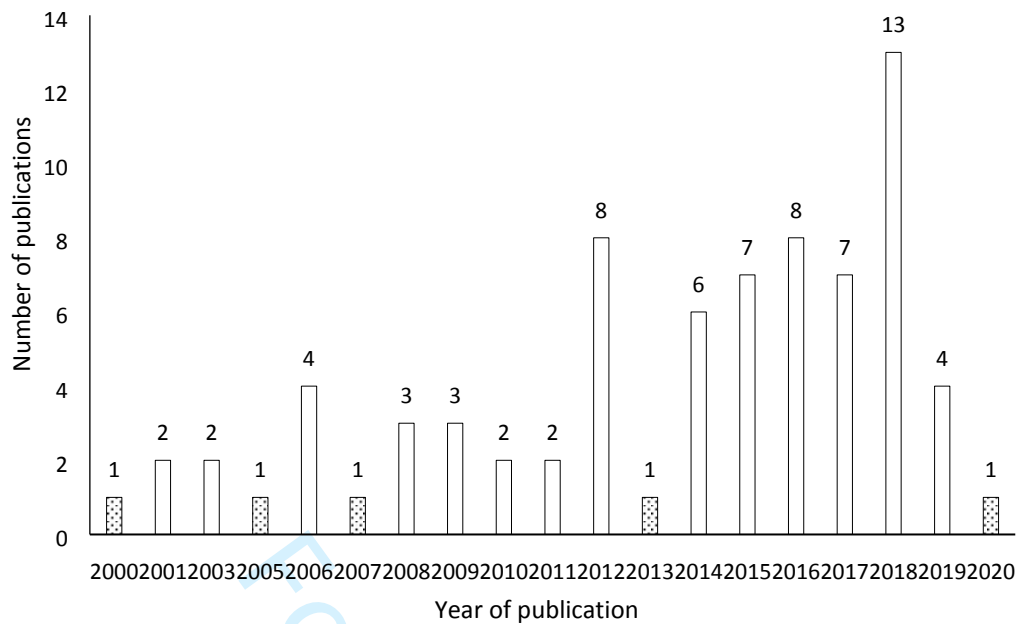
Figure 3 Publications by year

Figure 4 shows the geographic location of the reviewed articles in this study. According to this figure, waste

management in buildings through reuse is an international trend.

Figure 4 Publications by location

Tables 1 and 2 show that the authors of the reviewed papers employed various methodologies to perform

their research. These methodologies are identified for the individual papers in table 1 for reuse drivers & table

2 for reuse barriers. The variety of techniques used, including various qualitative and quantitative methods,

show the attempts made by different authors to study different aspects of BCR, which reveals the increasing

importance of this intervention among researchers. For instance, a series of studies performed in Australia

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employs mixed methodologies such as interviews and questionnaire surveys and targets various stakeholders to investigate drivers and barriers to reverse logistics in the South Australian construction context (Chileshe et al. 2016b, Rameezdeen et al. 2016, Chileshe et al. 2016a, 2018, 2015). These studies show the importance of a holistic approach in seeking the experts' opinions (through qualitative methods (Saunders et al. 2016)) and the actual experiences (through quantitative methods (Saunders et al. 2016)) to identify deficiencies in the body of knowledge and eventually promote practices like reuse in the building sector. While it is tempting to discuss different research methods and methodologies employed in the 76 papers reviewed (and compare advantages and limitations of them), the above is out of the scope of this study and can be investigated separately.

Throughout this study, the authors identified 57 drivers and 130 barriers affecting the reuse of building components. From a sustainability perspective, the reuse of building components has social, environmental, and economic advantages (Jaillon and Poon 2014); hence, certain factors can be categorized under these three groups. However, the successful implementation of any intervention (here, the reuse of building components) to promote sustainability in the building sector highly depends on the technical feasibility (such as durability), the regulatory enforcement (minimum performance requirements set by regulations), and competency and willingness of the organizations engaged (knowledge, skills, infrastructure, innovation, etc.)(Nußholz et al. 2019). Therefore, an interdisciplinary approach towards sustainability becomes crucial while addressing the shortcomings in the body of knowledge on reuse (Kajikawa et al. 2014). On this basis and following (Pomponi and Moncaster 2017, Tingley et al. 2017), the authors grouped the identified reuse drivers and barriers under economic, environmental, social, technical, regulatory, and organisational categories (Tables 1 and 2).

Besides, to better present the identified reuse drivers and barriers and to avoid congested tables, under each major category, the authors grouped the factors into further sub-categories, as shown in tables 1 and 2. These sub-categories are defined based on the common characteristics of groups of factors. For instance, "Lower cost of reused components" and "Increased cost of landfilling" are economic drivers and are grouped under sub-category "Cost" in table 1. It is because in case of the former, the lower cost of the component can decrease the total cost of the project and in case of the latter, landfilling is expensive and reusing the element can reduce additional costs. This approach has been pursued in the case of barriers to BCR, as well.

Reuse drivers

Figure 5 shows the distribution of the observed drivers in the reviewed papers. According to this figure, the

principal identified drivers are economic (25%), organizational (23%), environmental (17%), and social (15%).

The sub-categories of the factors shown in this figure present a similar trend between main categories and

sub-categories. Among the drivers, "cost" is the most reported sub-category, followed by "energy and GHG" ,

"organizational sustainability", and "willingness" sub-category of drivers. These observations are discussed

further in the following subsections.
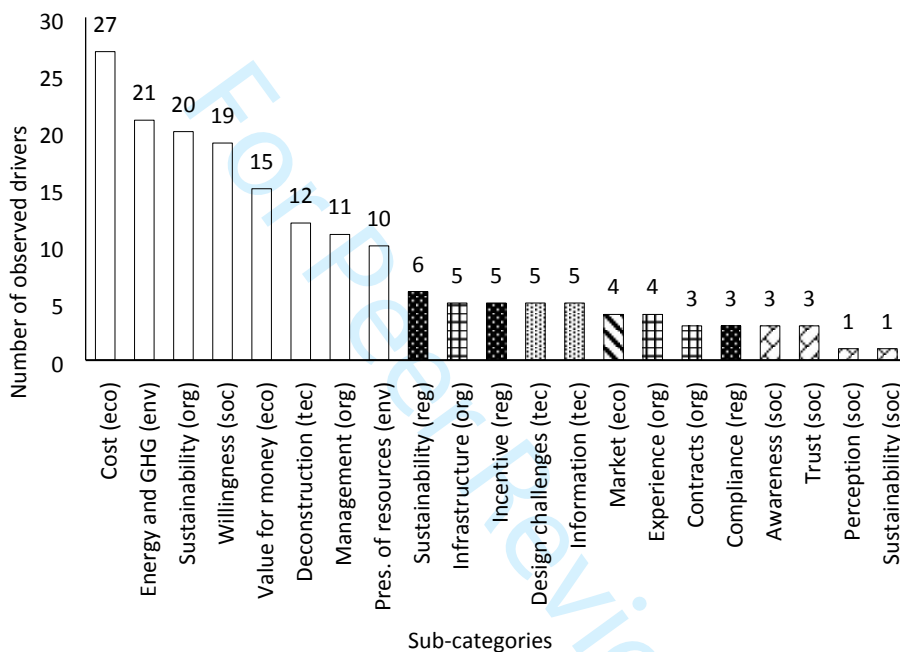
Figure 5 Distribution of the observed reuse drivers (eco: economic; env: environmental; org: organizational; reg: regulatory; soc: social; tec: technical)

Economic drivers

From the reviewed articles, it is observed that the potential cost savings as the result of using recovered

building components can promote reuse. For example, according to (MacKinnon 2000, Klang et al. 2003,

Gorgolewski et al. 2008, da Rocha and Sattler 2009, Dunant et al. 2017, Chileshe et al. 2018), the lower price of

the reused components can contribute to the cost savings in the construction projects. Likewise, according to

(Cooper et al. 2016), reusing steel sections results in the purchase of fewer new steel sections. If the price for

the reused components is attractive, the demand for them can increase (Klang et al. 2003), which in the long

run supports the growth of a reuse market (da Rocha and Sattler 2009, Tingley et al. 2017) and increases the

revenue from the resale of these components (Klang et al. 2003, Dantata et al. 2005, da Rocha and Sattler

2009, Dunant et al. 2017, Chileshe et al. 2018, Sea-Lim et al. 2018). Moreover, the increased cost of landfilling

can act as a reuse driver because it increases the disposal cost of construction and demolition wastes (CDW)

(Dantata et al. 2005, Gorgolewski 2008, Chinda and Ammarapala 2016, Chileshe et al. 2016a). By reusing the

recovered building components, this extra cost can be decreased (Pun et al. 2006). However, these factors

highly depend on the geographic location of the building, which might have an opposing effect on reuse. For

instance, (Huang et al. 2018) report that the lower cost of landfilling is an impediment to reuse. The study is

performed in China, where cheap landfilling discourages choosing other waste treatment options such as

reuse or recycling.

Organizational drivers

According to the literature, reducing CDW generated by the firms (Pun et al. 2006, Guy 2006, Schultmann and

Sunke 2007, Densley Tingley et al. 2012, Aye et al. 2012) (among others[1]) and promoting the green image of

the companies to improve competitiveness (Rogers 2011, Durão et al. 2014, Chileshe et al. 2016b, Chinda and

Ammarapala 2016, Chileshe et al. 2016a) (among others) rank the highest among all other organizational

drivers.

One method to increase the reuse rates by the organizations is through integrating reuse in the design process

of new projects (Gorgolewski et al. 2008, Gorgolewski 2008, Rogers 2011, Tingley et al. 2017) (among others).

As a result and to support this idea, some articles suggest that by integrating reuse in the contractual

requirements, reuse rates will increase (MacKinnon 2000, Gorgolewski et al. 2008, Gorgolewski 2008). Also,

the existence of a reclaimed components management coordinator (Gorgolewski 2008, Tingley et al. 2017),

and the knowledge of a known list of structural components to reuse early on in the design phase are

suggested to potentially increase the adoption of reuse by the firms (Gorgolewski 2008, Rose and Stegemann

2018). The latter can be facilitated by the coordination between the owners of the demolition site and the new

building. However, in many instances, this coordination never happens (Dunant et al. 2018, Nußholz et al.

2019). One solution, as observed by (Nußholz et al. 2019), is companies' entrepreneurial activities to integrate

circular principles. According to this study, a Danish company involved in brick reuse could overcome certain

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[1] This term indicates that there are other references identifying the same factor.

limitations by changing its business model by integrating deconstruction into its scope to safeguard a more sustainable supply of the reused bricks.

Training operators for effective deconstruction (Dantata et al. 2005, Shaurette 2006, Elias Özkan 2012), availability of space for the storage of the reusable components after deconstruction (Rogers 2011), and the knowledge and experience in using reused components (Tingley et al. 2017), as well as proper separation of the reusable components after deconstruction (Rogers 2011, Elias Özkan 2012, Ding et al. 2016, Ajayi et al. 2017) are among other factors driving reuse.

Social drivers

Factors such as society's environmental concerns (Chileshe et al. 2016a), or the increased awareness of the full benefits of reuse among the stakeholders (MacKinnon 2000) are identified as drivers to reuse. (Nußholz et al. 2019) reports recognition of reuse in the public debate can enhance public awareness and promotes reuse.

However, from a social perspective, positive perception and willingness of the stakeholders such as clients (Shaurette 2006, Gorgolewski et al. 2008, Gorgolewski 2008, Arif et al. 2012, Sansom and Avery 2014, Dunant et al. 2017, 2018), designers (Gorgolewski et al. 2008, Gorgolewski 2008, Rameezdeen et al. 2016, Dunant et al. 2017, Tingley et al. 2017, Dunant et al. 2018), and contractors (Gorgolewski et al. 2008, Rogers 2011, Chileshe et al. 2016b, Dunant et al. 2017, Chileshe et al. 2018) to integrate reused components into their projects are determining.

Unlike new building components that can be sourced from the market with proper quality certificates, salvaged building components are usually not available off the shelf and cannot be trusted. However, according to a few articles, informality, and good relationship among the stakeholders is reported to overcome this challenge and promote reuse (Shaurette 2006, da Rocha and Sattler 2009, Chileshe et al. 2016b).

Table 1 Summary of reuse drivers

S N	Author	Cntr.[a]	Research method[b]	Economic A: Cost	B: Market	C: Value for money	Env D: Energy and GHG	E: Preservation	Organizational F: Contracts	G: Experience	H: Infrastructure	J: Management	K: Sustainability	Regul. L: Compliance	M: Incentive	N: Sustainability	Social O: Awareness	P: Perception	R: Sustainability	S: Trust	T: Willingness	Technical U: Deconstruction	V: Design	X: Information
1	(MacKinnon 2000)	US	DR; GI; I(4); OBS	1					1								1							
2	(Sára et al. 2001)	IT	CS(1); LR				1	1																
3	(Li et al. 2003)	HK	CS(2); S													1								
4	(Klang et al. 2003)	US	CS(1); I(10); Q(10/10)	2	1	1	1																	
5	(Dantata et al. 2005)	US	CS(5); LR			1				1														
6	(Pun and Liu 2006)	AU	TF																			1		
7	(Pun et al. 2006)	AU	CS(1)			2							1									1		
8	(Shaurette 2006)	US	Q(296/83)							1						1				1	1			
9	(Guy 2006)	US	CS(4)										1											
10	(Schultmann and Sunke 2007)	DE	T										1									1		
11	(Gorgolewski et al. 2008)	CA	AR; CS(3)	3					1			1									3	1	2	1
12	(Gorgolewski 2008)	CA	AR; CS(2)	3					1			3			1						2		1	1
13	(Tam and Tam 2008)	HK	CS(1); I(20)												1		1							
14	(da Rocha and Sattler 2009)	BR	CD; CS(1); DO(5); GM(4); SSI(27)	2	1	1														1				
15	(Nordby et al. 2009)	NO	CS(1)																					1
16	(Dewulf et al. 2009)	BE	CS(1)					1																
17	(Denhart 2010)	US	CS(4)			1																1		
18	(Rogers 2011)	AE	CS(1)								2	1	2					1			1			
19	(Forsythe 2011)	AU	CS(9); DO; UI			1																1		
20	(Chau et al. 2012)	HK	CS(13)				1	1																
21	(Arif et al. 2012)	IN	CS(2); SSI(15)	1																	1			
22	(Lachimpadi et al. 2012)	MY	CS(8)																			1		
23	(Boyd et al. 2012)	US	CS(2)				1																	
24	(Densley Tingley et al. 2012)	GB	CS(1); LR					1					1									1		
25	(Coelho et al. 2012)	PT	CS(15)				1					1												
26	(Aye et al. 2012)	AU	CS(1)				1	1					1											
27	(Elias Özkan 2012)	TR	AR; CS; DO(21); I							1	1													
28	(Hglmeier et al. 2013)	DE	CS(1)																			1		
29	(Sansom and Avery 2014)	GB	Q(160/32)																1					
30	(Elias-Ozkan 2014)	TR	CS(2)			1	1	1					1											
31	(Pongiglione and Calderini 2014)	IT	AR; CS(1)	1																		1	1	1
32	(Durão et al. 2014)	PT	CS(2)										1											
33	(Diyamandoglu and Fortuna 2015)	US	CS(1)	1	1	1	1																	
34	(Yeung et al. 2015)	CA	DO(4)																			1		
35	(Wu et al. 2016)	CN	CA													1								
36	(Cooper et al. 2016)	GB	CS(2); LR; SSI(17)	1		1																		

S N	Author	Cntr.[a]	Research method[b]	Economic			Env		Organizational					Regul.			Social					Technical		
				A: Cost	B: Market	C: Value for money	D: Energy and GHG	E: Preservation	F: Contracts	G: Experience	H: Infrastructure	J: Management	K: Sustainability	L: Compliance	M: Incentive	N: Sustainability	O: Awareness	P: Perception	R: Sustainability	S: Trust	T: Willingness	U: Deconstruction	V: Design	X: Information
37	(Rameezdeen et al. 2016)	AU	SSI(8)																		1			
38	(Ding et al. 2016)	CN	CS(1); LR; SSI(12)								1													
39	(Chileshe et al. 2016b)	AU	LR; Q(539/49); SSI(6)										2							1	1			
40	(Ajayi et al. 2016)	GB	FGI(23)																			1		
41	(Chinda and Ammarapala 2016)	TH	CS(2); I(6); LR	1				1					1			1								
42	(Chileshe et al. 2016a)	AU	LR; SSI(8)	1									1						1					
43	(Tatiya et al. 2017)	US	CS(1); LR; SI(3)	1																				
44	(Ajayi et al. 2017)	GB	FS; Q(200/131)								1	1												
45	(Surahman et al. 2017)	ID	CS(2)				1						1											
46	(Chau et al. 2017)	HK	CS(1)																					
47	(Dunant et al. 2017)	GB	I(30); Q(24)	1		1															3			
48	(Faleschini et al. 2017)	IT	CS(1)				1																	
49	(Tingley et al. 2017)	GB	LR; SSI(13)	1	1		1	1		1		2	1								1			
50	(Yeung et al. 2017)	CA	CS(1)				1	1																
51	(Machado et al. 2018)	BR	LR				1																1	1
52	(Gottsche and Kelly 2018)	IE	ACT(1); CS(5)			1	1						1											
53	(Gálvez-Martos et al. 2018)	EU	CA										1											
54	(Brütting et al. 2019)	CH	CS(2)	2			1																	
55	(Chileshe et al. 2018)	AU	Q(260/26)	1		1							2	2	2	1					1			
56	(Sea-Lim et al. 2018)	TH	SD			1																		
57	(Mahpour and Mortaheb 2018)	IR	CS(1); Q(81/81)												1									
58	(Rose and Stegemann 2018)	GB	CD; CS(6); DO; SSI(21)									1	1											
59	(Dunant et al. 2018)	GB	I(30)	2																	2			
60	(Zaman et al. 2018)	NZ	CS(1)				1																	
61	(Dunant et al. 2019)	GB	EM				1																	
62	(Nußholz et al. 2019)	DK	CS(3); Q(3); SSI(3)	1		1	1	1					1	1		1	1				1			
63	(Brambilla et al. 2019)	GB	CS(1)				1																	
64	(Eberhardt et al. 2019)	DK	CS(1)				1																	
			Total numbers:	27	4	15	21	10	3	4	5	11	20	3	5	6	3	1	1	3	19	12	5	5

[a] **Country:** According to ISO 3166

[b] **Research Method:** (ACT) Action Research (n = number of case(s), if provided); (AR) Archival research (n = number of case(s), if provided); (CA) Comparative analysis; (CD) Company documentation; (CS) Case study (n = number of case(s)); (DO) Direct observation (n = number of case(s)); (DR) Document review; (EM) Economic models; (EX) Experiment; (FGI) Focused-group interview (n = number of interviewee(s)); (FS) Field study; (GI) Group Interview; (GM) Group meetings (n = number of attendant(s)); (I) Unspecified type Interviews (n = number of interviewee(s)); (LR) Literature review; (OBS) Observation; (Q) Questionnaire (n = number of sent Q / m = number of completed Q); (S) Survey (i.e. empirical survey, etc.); (SD) System dynamics; (SI) Structured interviews (n = number of interviewee(s)); (SSI) Semi-structured interviews (n = number of interviewee(s)); (T) Theoretical study; (TF) Theoretical framework; (UI) Unstructured interview

[c] The numbers in the table corresponds to the number of drivers grouped under each sub-category.

Environmental drivers

One potential reuse driver is the scarcity of landfilling sites, which helps the environment by avoiding dumping the reusable waste into landfills (Chinda and Ammarapala 2016, Chau et al. 2012). According to the literature, reuse can decrease the use of virgin materials and water consumption (Tingley et al. 2017, Sára et al. 2001, Densley Tingley et al. 2012, Aye et al. 2012, Yeung et al. 2017). As mentioned in the introduction, because of the considerable advantages of reuse, components reuse can improve the environmental footprint of buildings worldwide. By reusing building components embodied energy and carbon of construction can be decreased (Klang et al. 2003, Tingley et al. 2017, Yeung et al. 2017, Brütting et al. 2019) (among others). Brütting et al. (2019) show that a structure made with the reused steel sections have considerably lower embodied energy and CO_2. In their study, the authors developed a discrete structural optimization method to reuse the existing stock of the steel sections. They used LCA to compare the environmental impacts of conventional design with the proposed method (Brütting et al. 2019).

Other drivers

Based on the reviewed articles, deconstruction instead of demolition can enhance the reusability of the recovered components (Gorgolewski et al. 2008, Hglmeier et al. 2013, Pongiglione and Calderini 2014, Yeung et al. 2015) (among others). According to (Gorgolewski et al. 2008, Gorgolewski 2008, Pongiglione and Calderini 2014), the availability of information about the characteristics, details, certificates, and drawings of the recovered building components can positively contribute to increasing the reuse rates, as well.

In projects with recovered building components, the proper estimation of the required sizes and lengths at the beginning of the design phase is reported to promote reuse (Gorgolewski et al. 2008). Some articles advise that reusing the recovered components, such as the structural components, to serve the same purpose (for instance, similar loads) has a positive impact on the success of this intervention (Gorgolewski et al. 2008, Gorgolewski 2008, Pongiglione and Calderini 2014).

The environmental policies (Chileshe et al. 2018) and green building rating systems such as BREEAM and LEED are reported to have a positive impact on reuse rates (Shaurette 2006, Gorgolewski 2008). The availability of regulatory and financial incentives to encourage deconstruction and reuse, as well as the existence of regulations supporting these interventions can potentially promote reuse (Chileshe et al. 2018). However,

according to the reviewed articles, such ordinances are currently not available (Yeung et al. 2015, Chileshe et al. 2016b, 2016a, Tingley et al. 2017, Rose and Stegemann 2018).

Reuse barriers

Figure 6 shows the distribution of the observed barriers in the reviewed papers. According to this figure, the identified barriers are primarily economic barriers (39%), followed by the technical (23%), and social barriers (15%). The sub-category of the factors shown in this figure reveals additional information about the observations. Among the identified factors, "cost" is the most reported sub-category of barriers followed by "design challenges", "compliance", "market", "deconstruction", and "perception". However, unlike the main categories, the third rank in sub-categories, "compliance", is a regulatory barrier. These observations are discussed further in the following sections.
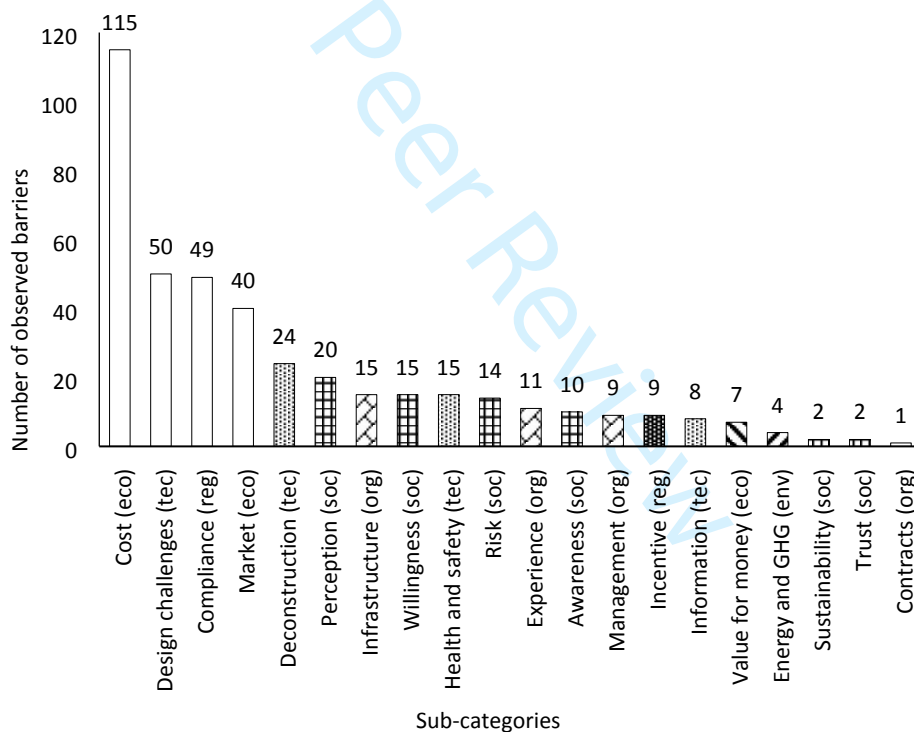

Figure 6 Distribution of the observed reuse barriers (eco: economic; env: environmental; org: organizational; reg: regulatory; soc: social; tec: technical)

Economic barriers

While deconstruction can increase the reusability of the recovered building components (Bill Addis 2006, Munroe et al. 2006), it is associated with extra efforts (Gorgolewski et al. 2008, Chileshe et al. 2015, Rameezdeen et al. 2016). Dantata et al. (2005) highlight that the time required to deconstruct a 1000 to 2000

square foot building is three to five times higher than the time needed for the demolition of the same building. According to the reviewed articles, the time required for deconstruction and reuse, and the consequent project scheduling is one of the main barriers to reuse (MacKinnon 2000, Dantata et al. 2005, Shaurette 2006, Gorgolewski et al. 2008, Gorgolewski 2008) (among others). It is because there is usually a high pressure to complete construction projects as early as possible (Chinda and Ammarapala 2016). The tight project schedule negatively affects the efficient disassembly of the existing buildings and lowers the chance for the recovery of reusable building components (Sansom and Avery 2014).

During the deconstruction phase, more time is required to carefully remove and sort the recovered building components (Gorgolewski 2008), which increases the cost of sorting (Rameezdeen et al. 2016). Sometimes the deconstruction time extends beyond anticipations because of issues such as the lack of space for the equipment, complexity of the building design, and the geographic location of the building (Tatiya et al. 2017). These extra charges can yield in higher deconstruction cost (when compared to the demolition of the same building) (Dantata et al. 2005, Chileshe et al. 2015, Yeung et al. 2015, Tingley et al. 2017, Rose and Stegemann 2018, Dunant et al. 2018) and eventually increase the price of the recovered components (Shaurette 2006, Chileshe et al. 2015, Rameezdeen et al. 2016, Chileshe et al. 2016a, Tingley et al. 2017, Dunant et al. 2018).

Another economic barrier to the BCR is the higher cost of design with the reused components (Gorgolewski et al. 2008, Gorgolewski 2008, Dunant et al. 2017). It is because the design team needs to put extra efforts to find the reused elements (Gorgolewski et al. 2008), and the design needs to remain as flexible as possible (Gorgolewski et al. 2008). Sometimes it is required to purchase the identified reused components early in the project (Gorgolewski et al. 2008, Gorgolewski 2008) to cope with the uncertainty about the timely availability of the desired elements (Gorgolewski et al. 2008, Chileshe et al. 2015). Consequently, this practice may raise cash flow problems and increase the overall cost of the project due to additional storage costs, which is another barrier to the BCR (Gorgolewski et al. 2008, Gorgolewski 2008, da Rocha and Sattler 2009, Yeung et al. 2015, Chinda and Ammarapala 2016) (among others).

All the above explain the increased labour cost (Klang et al. 2003, Dantata et al. 2005, Shaurette 2006, Gorgolewski et al. 2008, Rameezdeen et al. 2016, Chinda and Ammarapala 2016) (among others), transportation cost (Gorgolewski et al. 2008, Gorgolewski 2008, da Rocha and Sattler 2009, Pongiglione and

Calderini 2014, Yeung et al. 2015, Rameezdeen et al. 2016) (among others), and storage cost associated with deconstruction and reuse which are identified as barriers to the BCR in several articles.

In some cases, the fabrication cost of the recovered building components might be higher than the fabrication cost of the new elements (Dunant et al. 2017, Tingley et al. 2017, Dunant et al. 2018). Dunant et al. (Dunant et al. 2017) explain that because reused steel components are associated with existing connections, holes, stiffeners, welds, end-plates, etc., the preparation of these components might increase the overall cost of fabrication because of the extra time, labour and machinery required. Other additional charges which can increase the overall price of the recovered components are cost of testing (Gorgolewski 2008, Yeung et al. 2015, Rameezdeen et al. 2016, Tingley et al. 2017, Dunant et al. 2018), cost of treatment of the salvaged parts (Chini and Acquaye 2001, Huuhka and Hakanen 2015, Dunant et al. 2018), cost of insurance (Tingley et al. 2017), and cost of marketing for the recovered building components (Dantata et al. 2005).

Another barrier to reuse, as reported in several articles, is the lack of an established market for the reused building components (Shaurette 2006, Gorgolewski et al. 2008, Gorgolewski 2008, Chileshe et al. 2016b, Rameezdeen et al. 2016, Chinda and Ammarapala 2016, Chileshe et al. 2016a) (among others). This factor, which is partially the outcome of the tight project schedules (Tatiya et al. 2017), results in the lack of sufficient supply for the reused components with the desired characteristics (dimension, quality, etc.) (Gorgolewski 2008, da Rocha and Sattler 2009, Dunant et al. 2017, Tingley et al. 2017, Brütting et al. 2019, Rose and Stegemann 2018). According to (Dunant et al. 2018), the above restriction encourages the contractors to sell their reusable waste to the recycling companies regardless of their high quality (Sansom and Avery 2014, Huuhka and Hakanen 2015, Yeung et al. 2015, Tingley et al. 2017, Yeung et al. 2017). If the demand for the reused building components increases (Chileshe et al. 2016b), the market for these products can grow sustainably. In contrast, lack of demand (Shaurette 2006, Rogers 2011, Huuhka and Hakanen 2015, Chileshe et al. 2016b, Tingley et al. 2017) or uncertainty about the need for the reused components (Rose and Stegemann 2018) causes the scepticism about the revenue from the reused components resale (Yeung et al. 2015, Chileshe et al. 2016a, Rose and Stegemann 2018, Dunant et al. 2018). All the above negatively affects the chance for the growth of a reuse market. With an underdeveloped reuse market, the supply chain remains fragmented, and the information about the supply and demand cannot be shared, which further decreases the reuse rates (Gorgolewski et al. 2008, Rameezdeen et al. 2016, Rose and Stegemann 2018).

According to the literature, higher deconstruction costs can hinder its application (Dantata et al. 2005, Chileshe et al. 2015, Yeung et al. 2015, Tingley et al. 2017, Rose and Stegemann 2018, Dunant et al. 2018, Tatiya et al. 2017) and might elevate the financial risks associated with deconstruction and reuse (Rameezdeen et al. 2016). However, this finding is in contrast with the observations in (da Rocha and Sattler 2009). According to this study, in Brazil, the cost of deconstruction is lower than demolition due to the low cost of manual labour and the high demand for demolition products (da Rocha and Sattler 2009). In a separate study, Dantata et al. (2005) suggest that if the productivity of the deconstruction team increases or the wages decreases or the disposal cost rises, the overall cost of deconstruction decreases, and it becomes a desirable option in Massachusetts. Therefore, it can be concluded that the socio-economic context of the location of a building can convert some barriers to drivers and vice-versa.

Technical barriers

(Ajayi et al. 2015) suggest that by integrating design for deconstruction (DfD) during the design stage of a building, recovery of building components for reuse would be facilitated. According to the literature, the lack of such intervention is a barrier to reuse (Chileshe et al. 2015, Huuhka and Hakanen 2015, Ajayi et al. 2015, Chileshe et al. 2016b, Tatiya et al. 2017, Dunant et al. 2017) (among others). Some outcomes of this design gap are permanent joints (welding, etc.) (Gorgolewski 2008, Pongiglione and Calderini 2014, Tingley et al. 2017), composite joints (Tingley et al. 2017), and hard to access connections (Tingley et al. 2017), which can negatively affect deconstruction and make the recovery of the building components challenging (Huuhka et al. 2015).

Because deconstruction is not considered at the design stage, building components are prone to more damage during the deconstruction phase (Chini and Acquaye 2001, Gorgolewski 2008, Pongiglione and Calderini 2014). Damages to the reused building components can decrease the quality of the elements and affect their reusability (da Rocha and Sattler 2009, Durão et al. 2014, Huuhka and Hakanen 2015, Tatiya et al. 2017). Damages can also happen as the result of corrosion (Chini and Acquaye 2001, Huuhka et al. 2015, Yeung et al. 2015), post-production modifications (holes for ductwork, etc.) (Chini and Acquaye 2001, Yeung et al. 2015), presence of water (Yeung et al. 2015, Tatiya et al. 2017), exposure to weather conditions (Huuhka and Hakanen 2015), fire (Yeung et al. 2015, Tatiya et al. 2017), during refurbishment (nail removal, etc.) (Chini and Acquaye 2001), by the living organisms (termite, bacterial attack, etc.) (Chini and Acquaye 2001), fatigue

(Yeung et al. 2015), frost (Huuhka et al. 2015), degradation (Durão et al. 2014), type of joints (Gorgolewski 2008), and during storage and transportation of the recovered components (Gorgolewski 2008) (impact (Yeung et al. 2015), etc.).

Difficulty in designing with the reused components is another barrier to the widespread reuse of the building components (Gorgolewski et al. 2008, Pongiglione and Calderini 2014, Tingley et al. 2017, Brütting et al. 2019). As discussed in earlier, the design of the new buildings with reused building components needs to remain flexible. It is because the design should be able to accommodate alternative dimensions of the reused components due to the uncertainty in the availability of the desired sections (Gorgolewski et al. 2008, Gorgolewski 2008). Brütting et al. (2019) argue that unlike structures made out of new steel sections where components with different cross-sections and lengths can be fabricated to the required shape, in the case of the reused steel sections, this luxury doesn't exist and the properties of the available components dictate the structure geometry.

Pongiglione and Calderini (2014) discuss that in the process of designing a new structure using the recovered components, due to architectural and structural reasons, new structural elements should be used as well. However, to secure the safety of such structures, the new components should be over-dimensioned, which eventually results in overdesigned structures (Gorgolewski et al. 2008, Gorgolewski 2008, Pongiglione and Calderini 2014, Brütting et al. 2019). It is either because of the lower strength of the reused components or when the remaining capacity of the reused components is unknown (Huuhka and Hakanen 2015, Yeung et al. 2015). The latter happens when the information about the characteristics, details, certificates, and drawings of the reused components are not available (Gorgolewski et al. 2008, Gorgolewski 2008, Huuhka and Hakanen 2015, Yeung et al. 2015, Tingley et al. 2017, Rose and Stegemann 2018). Other design challenges while reusing recovered building components are designing with long spans (because such elements might not be readily available) (Gorgolewski et al. 2008, Huuhka and Hakanen 2015, Brütting et al. 2019), difference in the loading requirements of the old and the new buildings (Gorgolewski et al. 2008), and the mismatch between the old spans and the new features (Huuhka and Hakanen 2015).

Additional health and safety precautions necessary for deconstruction, component recovery, and reuse are some other technical barriers to reuse (Sansom and Avery 2014, Chileshe et al. 2015, Huuhka and Hakanen 2015, Yeung et al. 2015, Rameezdeen et al. 2016, Chileshe et al. 2016a, Tingley et al. 2017). It is because,

during the deconstruction of a building, or while treating a component for reuse, there is a risk of

encountering hazardous, banned or contaminating coatings on the reused components (Rameezdeen et al.

2016, Tatiya et al. 2017, Tingley et al. 2017). In case of facing hazardous materials such as lead or asbestos,

specific procedures and licensed contractors are required (Rameezdeen et al. 2016).

Social barriers

The negative perception of the stakeholders about the reused building components can act as a barrier to

reuse (MacKinnon 2000, Klang et al. 2003, Chileshe et al. 2015, Huuhka and Hakanen 2015, Rameezdeen et al.

2016, Chileshe et al. 2016a) (among others). One reason behind this is the visual appearance of the reused

components that might be interpreted as lower quality when compared with a new element (Durão et al.

2014, Tingley et al. 2017, Dunant et al. 2017). For instance, Durão et al. (2014) report that the architects refuse

to use recovered wood in visible places due to its poor appearance. However, the visual appearance can be a

point of further discussion since it is highly subjective and can be attractive to some people (Nußholz et al.

2019). Other reason behind this negative perception, and at a larger scale the construction sector resistance

against reuse (Gorgolewski 2008, Durão et al. 2014, Rameezdeen et al. 2016, Tingley et al. 2017), stems from

the potential risks perceived by the stakeholders during deconstruction or while using the recovered building

components (Shaurette 2006, Gorgolewski 2008, Chileshe et al. 2015, Rameezdeen et al. 2016, Dunant et al.

2017, Tingley et al. 2017).

The occupational health concerns (Klang et al. 2003, Rameezdeen et al. 2016), liability and fear (da Rocha and

Sattler 2009), lack of trust to the supplier of the reused components (Dunant et al. 2017, 2018), and

unsatisfactory working environment during the treatment of the reused components (Klang et al. 2003) can all

worsen the lack of interest to integrate the reused components in the projects (Chileshe et al. 2016b,

Rameezdeen et al. 2016). Among the stakeholders, perception of clients (da Rocha and Sattler 2009, Chileshe

et al. 2015, Dunant et al. 2017, Rose and Stegemann 2018), contractors (Shaurette 2006, Gorgolewski 2008),

and designers (Gorgolewski 2008) have a higher impact on the successful integration of recovered components

into a new building. However, if the client does not support reuse (Huuhka and Hakanen 2015, Rameezdeen et

al. 2016, Tingley et al. 2017, Rose and Stegemann 2018), there is a very less chance that designers or

contractors risk the project by introducing such components. On the other hand, according to (Gorgolewski

2008), if the client is motivated to use the reused building components, the barriers such as the unwillingness

of the design team (Chileshe et al. 2015, Rameezdeen et al. 2016) or the contractors (Gorgolewski 2008) can

be handled effectively. Nevertheless, the inequality in the distribution of risk among the stakeholders (Dunant

et al. 2018) can yet challenge motivated clients and architects.

Gorgolewski (2008) argues that while choosing deconstruction to remove the existing buildings improves the

supply of the reused components, due to the perceived economic and programming reasons, it is not yet a

preferred option among the contractors (Gorgolewski 2008). One reason for such reluctance is because the

stakeholders are unaware of the full benefits of deconstruction and reuse (Gorgolewski 2008, Chileshe et al.

2015, Huuhka and Hakanen 2015, Chileshe et al. 2016b, Rameezdeen et al. 2016). As mentioned earlier, some

of the benefits of deconstruction and reuse are the cost savings and less pollution to the environment.

Therefore, educating the stakeholders on the advantages of deconstruction and reuse, as identified by

(Gorgolewski 2008, Chileshe et al. 2015), could be an effective measure to cope with some social resistance

against reuse.

Table 2 Summary of reuse barriers

SN	Author	Cntr.[a]	Research method[b]	Economic			Env	Organizational				Regul.		Social						Technical			
				A: Cost	B: Market	C: Value for money	D: Energy and GHG	F: Contracts	G: Experience	H: Infrastructure	J: Management	L: Compliance	M: Incentive	O: Awareness	P: Perception	Q: Risk	R: Sustainability	S: Trust	T: Willingness	U: Deconstruction	V: Design	W: Health and safety	X: Information
1	(MacKinnon 2000)	US	DR; GI; I(4); OBS	1											1								
2	(Chini and Acquaye 2001)	US	EX	1								2										5	
3	(Klang et al. 2003)	US	CS(1); I(10); Q(10/10)	1											1	1	1						
4	(Dantata et al. 2005)	US	CS(5); LR	4																			
5	(Pun and Liu 2006)	AU	TF		3																		
6	(Pun et al. 2006)	AU	CS(1)	4	3							1			1								1
7	(Shaurette 2006)	US	Q(296/83)	3	2				1	2		1			1	1							
8	(Guy 2006)	US	CS(4)	4								2									5	1	
9	(Gorgolewski et al. 2008)	CA	AR; CS(3)	8	2						1										5		1
10	(Gorgolewski 2008)	CA	AR; CS(2)	6	2				1	1		2		1	3	1			2	1	5		1
11	(da Rocha and Sattler 2009)	BR	CD; CS(1); DO(5); GM(4); SSI(27)	2	1							2			1	1					1		
12	(Nordby et al. 2009)	NO	CS(1)	2								1					1			2	1		
13	(Jaillon and Poon 2010)	HK	AR; CS(7); DO(7); I(35); Q(84)																	1			
14	(Rogers 2011)	AE	CS(1)		1																		
15	(Forsythe 2011)	AU	CS(9); DO; UI	3		1															1	2	
16	(Arif et al. 2012)	IN	CS(2); SSI(15)								2		1										
17	(Coelho et al. 2012)	PT	CS(15)						1														
18	(Elias Özkan 2012)	TR	AR; CS; DO(21); I							2		1								1			
19	(Hglmeier et al. 2013)	DE	CS(1)									1											
20	(Gangolells et al. 2014)	ES	Q(658/74)						1														
21	(Sansom and Avery 2014)	GB	Q(160/32)	2																			1
22	(Jaillon and Poon 2014)	HK	CS(2); LR																	2			
23	(Pongiglione and Calderini 2014)	IT	AR; CS(1)	1																1	3		
24	(Durão et al. 2014)	PT	CS(2)												1				1		2		
25	(Chileshe et al. 2015)	AU	LR; Q(539/49); S	4					1		1	2		1	3	1			2	1		1	
26	(Ferreira et al. 2015)	PT	CS(1); LR																		2		
27	(Huuhka and Hakanen 2015)	FI	Q(11/11)	3	2		1					5		1	1	1			1	1	3	1	2
28	(Huuhka et al. 2015)	FI	AR(276); LR									1								1	2		
29	(Yeung et al. 2015)	CA	DO(4)	6		1			1		1		1								5	1	2
30	(Ajayi et al. 2015)	GB	FGI(25); LR														1			1			
31	(Cooper et al. 2016)	GB	CS(2); LR; SSI(17)	5																			
32	(Rameezdeen et al. 2016)	AU	SSI(8)	9	2							5		2	1	2			4			2	
33	(Chileshe et al. 2016b)	AU	LR; Q(539/49); SSI(6)		2				2	1		3	2	3					1	1			
34	(Chinda and Ammarapala 2016)	TH	CS(2); I(6); LR	4	1					2													
35	(Chileshe et al. 2016a)	AU	LR; SSI(8)	4	1	1						2	1		1	1							1
36	(Tatiya et al. 2017)	US	CS(1); LR; SI(3)	5	1															1	2	1	

S N	Author	Cntr.[a]	Research method[b]	Economic			Env	Organizational				Regul.		Social						Technical			
				A: Cost	B: Market	C: Value for money	D: Energy and GHG	F: Contracts	G: Experience	H: Infrastructure	J: Management	L: Compliance	M: Incentive	O: Awareness	P: Perception	Q: Risk	R: Sustainability	S: Trust	T: Willingness	U: Deconstruction	V: Design	W: Health and safety	X: Information
37	(Dunant et al. 2017)	GB	I(30); Q(24)	5	2				1	1		6			2	1		1		1			
38	(Tingley et al. 2017)	GB	LR; SSI(13)	9	3	1		1				6	2	1	2	1			2	3	1	3	1
39	(Yeung et al. 2017)	CA	CS(1)	2																1			
40	(Machado et al. 2018)	BR	LR							1										1	3		
41	(Gálvez-Martos et al. 2018)	EU	CA		2																		
42	(Huang et al. 2018)	CN	CD; LR; SSI(40)	1	1							2											
43	(Brütting et al. 2019)	CH	CS(2)		1																3		
44	(Sea-Lim et al. 2018)	TH	SD	2						1													
45	(Rose and Stegemann 2018)	GB	CD; CS(6); DO; SSI(21)	3	4	1				1	2	1	1		1				1	1			1
46	(Dunant et al. 2018)	GB	I(30)	9		1			1	1	1				2			1					
47	(Mahpour 2018)	IR	LR; Q(6/6)												1								
48	(Zaman et al. 2018)	NZ	CS(1)	1		1			1	1		1											
49	(Nußholz et al. 2019)	DK	CS(3); Q(3); SSI(3)	1	3					1	1	2	1						1				
50	(Brambilla et al. 2019)	GB	CS(1)				2													1			
51	(Basta et al. 2020)	EG	CS(1); TF																		2	1	
			Total number:	115	40	7	4	1	15	15	9	49	9	10	20	14	2	2	15	24	50	15	8

[a] **Country:** *According to ISO 3166*

[b] **Research Method:** *(ACT) Action Research (n = number of case(s), if provided); (AR) Archival research (n = number of case(s), if provided); (CA) Comparative analysis; (CD) Company documentation; (CS) Case study (n = number of case(s)); (DO) Direct observation (n = number of case(s)); (DR) Document review; (EM) Economic models; (EX) Experiment; (FGI) Focused-group interview (n = number of interviewee(s)); (FS) Field study; (GI) Group Interview; (GM) Group meetings (n = number of attendant(s)); (I) Unspecified type Interviews (n = number of interviewee(s)); (LR) Literature review; (OBS) Observation; (Q) Questionnaire (n = number of sent Q / m = number of completed Q); (S) Survey (i.e. empirical survey, etc.); (SD) System dynamics; (SI) Structured interviews (n = number of interviewee(s)); (SSI) Semi-structured interviews (n = number of interviewee(s)); (T) Theoretical study; (TF) Theoretical framework; (UI) Unstructured interview*

[c] *The numbers in the table corresponds to the number of drivers grouped under each sub-category.*

Regulatory barriers

One of the challenges ahead of reuse is that the existing regulations do not support deconstruction and reuse (Gorgolewski 2008, Hglmeier et al. 2013, Chileshe et al. 2015, Huuhka and Hakanen 2015, Huuhka et al. 2015, Chileshe et al. 2016b, Rameezdeen et al. 2016) (among others). Rameezdeen et al. (2016) argue that bureaucracy is a barrier ahead of necessary approvals for deconstruction projects in South Australia. According to this study, even after getting approvals for deconstruction, since existing regulations do not allow the storage of the salvaged components and consider them as waste (Rameezdeen et al. 2016), the reuse of the recovered components is hindered. This study suggests that governments should support the reuse of recovered components in the new constructions (Rameezdeen et al. 2016); however, in reality, it is not the case (Chileshe et al. 2016b, 2016a). (Rameezdeen et al. 2016) further discuss that, while regulations support recycled-content products, due to the inconsistency and the lack of coordination among the regulatory bodies (Rameezdeen et al. 2016, Chileshe et al. 2016a), regulatory agencies have a prohibitive approach towards deconstruction and reuse. It should be noted that these studies focus on the Australian construction sector, and the results should be considered cautiously (Chileshe et al. 2016b, Rameezdeen et al. 2016, Chileshe et al. 2016a).

Lack of quality certificates for the reused components can negatively affect reuse (Chini and Acquaye 2001). (Dunant et al. 2017) explore this barrier by highlighting the need for the traceability of the steel sections, which is essential to certify, fabricate, and erect the segments. Usually, the traceability of the reused steel sections cannot be guaranteed (Dunant et al. 2017, Tingley et al. 2017), and in many instances, all the segments need to be tested to certify their properties and assure the quality. However, according to this study, in case of stricter requirements on CE marking (Dunant et al. 2017, Tingley et al. 2017), even the individual testing fails to certify the reused components.

Lack of confidence in the quality of the reused components negatively affects reuse in new constructions (Shaurette 2006, Chileshe et al. 2015, Ajayi et al. 2015, Chileshe et al. 2016b, 2016a) (among others). (Huang et al. 2018) observed that there is a negative attitude towards using recovered construction and demolition waste among the building construction companies because of the lack of guarantees for these components. According to the reviewed articles, currently, there are no standards to certify the quality of the reused components (Chini and Acquaye 2001, Dunant et al. 2017, Huang et al. 2018). Therefore, the lack of

procedures to evaluate and guarantee the performance of reused components (Shaurette 2006, Tingley et al. 2017), and the fact that the existing codes, standards, and procedures do not consider BCR (Gorgolewski 2008, Huuhka and Hakanen 2015, Rameezdeen et al. 2016, Tingley et al. 2017) further decrease the reuse rate in buildings.

Organizational barriers

Because deconstruction and reuse are still uncommon practices (Dunant et al. 2017, 2018), the number of companies with experience in deconstruction and reuse is low (Chileshe et al. 2016b). According to the literature, the lack of skills, experience, and knowledge in deconstruction, salvage, and using reused components negatively affect the reuse of the building components (Shaurette 2006, Gorgolewski 2008, Chileshe et al. 2015, Yeung et al. 2015, Chileshe et al. 2016b). Unlike demolition, deconstruction requires enough space for the storage, sorting, and treatment of the recovered building components. However, an inexperienced contractor cannot correctly estimate the space required for the storage of the recovered components after deconstruction. This lack of space for storage (Shaurette 2006, Gorgolewski 2008, Chinda and Ammarapala 2016, Dunant et al. 2017, Rose and Stegemann 2018, Dunant et al. 2018) results in the transportation and storage of the recovered components at a different location,, and would increase the overall cost of the reused elements.

Lack of systems thinking (Rose and Stegemann 2018), ownership (Arif et al. 2012), and integration of reuse in the design process of the new projects (Rose and Stegemann 2018) are identified to decrease the reuse rates in the building sector. (Yeung et al. 2015) highlight the importance of a decision-making framework in informing the contractors and the client regarding when alternative reuse options should be investigated. According to this study, this decision-making framework helps in making informed decisions about deconstruction and reuse and maximizes the advantages of potential reuse by identifying the necessary steps to be taken by the stakeholders (Yeung et al. 2015). Other observed organizational barriers are proprietary lock-in (Tingley et al. 2017), need for infrastructure and equipment to perform deconstruction (Shaurette 2006, Chileshe et al. 2016b, Sea-Lim et al. 2018), and inconsistency in waste management practices (Arif et al. 2012).

Environmental barriers

While component reuse is identified as a sustainable end-of-life treatment of the superstructure of a building (Klang et al. 2003, Tingley et al. 2017, Yeung et al. 2017, Brütting et al. 2019), there are concerns regarding the adverse effects of this practice due to increased GHG emissions related to deconstruction activities and transportation of the recovered elements (Brambilla et al. 2019, Nußholz et al. 2019, Huuhka and Hakanen 2015).

Brambilla et al. (2019) performed a study to evaluate the environmental impacts of various steel-concrete composite floor systems. In this study, the authors performed a comparative LCA and compared the four composite connections, including a novel a demountable steel-concrete composite floor system and three conventional systems. The authors concluded that a transport distance between 20 km and 200 km has no significant impact on environmental advantages achieved by the demountable system. However, they concluded that a distance of 1000 km could diminish the environmental benefits achieved by this system. The authors also discussed that deconstruction of the demountable composite structure takes more time compared to demolition, which results in the emission of higher amounts of GHGs since the heavy machinery and equipment need to operate longer (Brambilla et al. 2019).

Prioritizing reuse barriers

Previous observations provide an insight into the challenges ahead of component reuse in the building sector; however, prioritizing them needs a further investigation about the inter-dependency of these factors. Reviewing the co-occurrences of data is a way to identify the impact of various variables of a research topic on one another and to reveal their potential correlations. And identifying the correlation between the key variables helps in better devising solutions to achieve the objectives of the study (Rameezdeen et al. 2016, Eck and Waltman 2009). In this section, we analyze the inter-relationship between the observed barriers through developing the co-occurrence of all the 19 sub-categories available in table 2.

In this study, we considered a binary approach for the presence (1) or the absence (0) of the sub-category of the barriers in table 2 to identify their co-occurrences and eventually develop their correlations. It means that if in table 2, under a particular sub-category for a specific paper, no barrier is observed, value 0, which means absence, is considered. On the other hand, the available observations (regardless of their number) are converted to 1.

Table 3 shows the co-occurrence of the sub-categories of reuse barriers in the reviewed articles. For example, sub-category A & sub-category B (AB) appear 15 times together in all the articles reviewed in this study. To analyze the correlation between the sub-categories, we also developed the co-occurrence index (C-Index) of the pairs of the sub-categories. In this work, we calculated the c-Index using the software "R" (version 3.6.1) (R Core Team 2019) through "jaccard" package (Chung et al. 2018), which is based on equation 1 (Atlas.ti 2014). In this equation, n12 is the co-occurrence frequency of the two sub-categories (the number of times the two sub-categories show-up together; hence is not equal to n1+n2), and n1 & n2 are the total numbers of occurrences of each of the sub-categories in all the studies. C-Index varies from 0 to 1, with 1 showing the highest correlation and 0 indicating no relationship. The null hypothesis is that there is no correlation between the pairs of the sub-categories. To test the null hypothesis, we use the p-value through the embedded test in the "jaccard" package (jaccard.test.exact) (Chung et al. 2018). If the p-value is less than 0.05, then the null hypothesis is false, and statistically, there is a correlation between the pairs of the sub-categories (James et al. 2017).

$$C - Index = \frac{n12}{(n1 + n2) - n12} \qquad (1)$$

In table 3, the highlighted cells represent the high levels of co-occurrence between the sub-categories. The corresponding c-index of these pairs of sub-categories of the barriers are sorted and listed in table 4. Also, the p-value, which indicates if the correlation is significant or not (James et al. 2017), is listed against each of the pairs.

According to table 4, there is a significant correlation between perception and risk, with the c-index of 0.63, ranking the highest among other sub-categories. It indicates that the perception of the stakeholders about reuse is affected by the potential risks associated with this intervention. Perception co-occurs with compliance, cost, and market, as well (all are significant with p-values 0.004, 0.02, and 0.02, respectively). It reveals the importance of addressing the economic and regulatory obstacles to promote reuse among the stakeholders. The second and third highest ranks belong to the cost and compliance as well as market and compliance, with the c-indices of 0.49 and 0.45, respectively. It shows that an established reused market requires to offer products with reasonable prices complying with state-of-the-art codes and regulations. On the other hand, the

existence of ordinances, as well as the best practices on the reused components, would help the growth of a

reuse market.

Table 3 Co-occurrence of sub-categories of reuse barriers

Code	Economic			Env	Organizational				Regul.		Social						Technical			
	A: Cost	B: Market	C: Value for money	D: Energy and GHG	F: Contracts	G: Experience	H: Infrastructure	J: Management	L: Compliance	M: Incentive	O: Awareness	P: Perception	Q: Risk	R: Sustainability	S: Trust	T: Willingness	U: Deconstruction	V: Design challenges	W: Health and safety	X: Information
A	-	16	7	2	1	7	9	6	17	5	6	12	11	2	2	7	10	12	11	6
B		-	4	2	1	5	8	4	13	5	6	9	9	0	2	7	7	7	6	5
C			-	0	1	3	3	3	4	4	1	3	3	0	1	2	2	3	4	3
D				-	0		1	1	2	1	1	1	1	0	0	2	2	1	1	1
F					-	0		0	1	1	1	1	1	0	0	1	1	1	1	1
G						-			6	2	3	4	5	0	2	3	4	2	2	2
H							-	3	8	3	2	4	4	0	2	4	6	2	0	2
J								-	3	4	1	2	2	0	1	3	2	2	2	3
L									-	5	7	10	9	1	1	8	10	8	7	4
M										-	2	3	2	0	0	4	3	2	3	3
O											-	5	5	0	0	6	5	3	5	3
P												-	10	1	1	7	6	5	5	4
Q													-	1	2	5	6	4	5	3
R														-	0	0	1	1	0	0
S															-	0	1	0	0	0
T																-	6	4	4	4
U																	-	9	4	4
V																		-	6	5
W																			-	3

Table 4 C-Indices of the correlation between major sub-categories.

Seq. No	Code	Sub-category pair	C-Index	P-value
1	PQ	Perception & Risk	0.63	<0.00001*
2	AL	Cost & Compliance	0.49	0.007*
3	BL	Market & Compliance	0.45	0.006*
4	AB	Cost & Market	0.44	0.04*
5	LP	Compliance & Perception	0.40	0.004*
6	BQ	Market & Risk	0.38	0.004*
7	LQ	Compliance & Risk	0.38	0.004*
8	AP	Cost & Perception	0.36	0.02*
9	AW	Cost & Health and safety	0.35	0.001*
10	BP	Market & Perception	0.35	0.02*
11	AQ	Cost & Risk	0.34	0.007*

Seq. No	Code	Sub-category pair	C-Index	P-value
12	LU	Compliance & Deconstruction	0.33	0.2
13	AV	Cost & Design challenges	0.32	0.5
14	UV	Deconstruction & Design challenges	0.32	0.1
15	AH	Cost & Infrastructure	0.26	0.2
16	AU	Cost & Deconstruction	0.25	0.4
*Denotes a significant correlation (less than 0.05)				

The fourth highest rank belongs to cost and market with a c-index of 0.44. It indicates that without a competitive price, a well-established market for reused elements is unlikely to grow. Moreover, it depicts that the growth of the reused components market can help to make the cost of reused components more competitive. However, the correlation between these two sub-categories is not very significant (p-value close to 0.05). It is interesting because, in most of the reviewed papers, both sub-categories are repeated. It can be further interpreted that these two sub-categories are similar, and no special consideration for prioritizing this pair is required as the improvement in one promotes the other one.

From table 4, we can observe that the social, economic, and regulatory barriers co-occur frequently. Therefore, it seems that any further action to promote reuse should prioritize actions to be taken under these themes. Notwithstanding, this result is different from our initial observation in figure 6, where the economic factors were ranked the highest, followed by the technical, social, regulatory, and organizational barriers.

Discussion

The observed environmental advantages of reuse indicate that this intervention is an effective strategy that should receive more attention to reduce the environmental footprint of the building sector.

From an economic perspective, the advantages of reuse in terms of cost savings and profit are key drivers. According to the reviewed articles, economic barriers can be categorized into supply chain level, component level, and project level. At the supply chain level, in the absence of a mature reuse market, the sustainable supply of recovered components for use in the superstructure of a building is challenging. While some innovative companies such as Gamle Mursten in Denmark integrate deconstruction into its core business (Nußholz et al. 2019), most companies are reluctant to change their business model. Hence, as advised by (Dunant et al. 2018, Nußholz et al. 2019), close cooperation between construction and demolition companies

can address this barrier. At the component and project levels, a strict financial risk assessment at the beginning

of the project should be performed. Because this intervention is rather new, the availability of resources to

decrease the financial risks would be helpful (Gorgolewski 2008, Tingley et al. 2017). Such financial incentives

have the potential to promote deconstruction and reuse activities and could help the growth of reuse markets,

and potentially make the price of the recovered elements more competitive (Table 4).

Notwithstanding, other attempts could be made to make the cost of the recovered components competitive.

One possible solution is following the successful example of increasing the landfilling tax in the UK (Defra 2007,

2019). Considering the waste hierarchy, if the cost of other waste treatment options increases in favour of

reuse, the additional costs due to deconstruction, treatment, and testing could be compensated. However,

there are reports of illegal landfilling in reaction to the increased landfilling taxes (da Rocha and Sattler 2009,

Rameezdeen et al. 2016). Therefore, further research in different geographical locations should be conducted

to recognize the mechanisms leading to such behavior and provide guidelines to prevent it.

From a social perspective, the factors affecting reuse can be categorized into perception, awareness, and risks.

Most of the discussions in the literature from a social perspective are focused on the perception and

willingness of the stakeholders regarding reuse and are less focused on the advantages of reuse for the general

public. Therefore, further research should be conducted to establish the benefits of reuse for society.

Nevertheless, the negative perception of the stakeholders towards reuse is recognized in the literature as an

impediment to its adoption in the building sector. Based on table 4, this negative perception is associated with

the perceived risks at different stages of projects with recovered building components as well as the need for

compliance to the regulatory requirements and is fueled by the concerns about the health and safety of the

stakeholders. Therefore, steps should be taken to improve the perception of the stakeholders about the

recovered building components. For instance, the development of standard test procedures to test, evaluate,

and certify the recovered building components can positively contribute to this attempt. Such standards and

guidelines can address the reported concerns and resistances in the construction sector against the recovered

building components and help the growth of a reuse market by offering quality products.

The regulatory barriers can be categorized into incentive level and compliance level, for which, the advantages

of the availability of regulatory incentives were discussed earlier. At the policy level, the reported regulatory

barriers highlight that the existing codes and regulations do not consider deconstruction and reuse, which, in

the long run, inhibits the integration of the recovered building components in the superstructure of the

buildings. Moreover, as discussed earlier, the existing standards only certify new components and not the

recovered elements. According to the previous section, the capability of suppliers in offering second-hand

components with proper quality certificates and guarantees could potentially help the growth of a reuse

market (Table 4). In this regard, one possible solution is the development of new standards to certify

recovered building components. An example of the successful development of certifying standards is provided

by (Nußholz et al. 2019). In this study, the case study companies developed certifying standards to assure the

quality of their products. Moreover, proper standards and procedures should be developed for the effective

deconstruction of the existing buildings and guide designers to integrate the recovered building components

into the design of new buildings. Because of the variety of building designs in different periods and locations,

proper databases for the existing buildings should be developed to assist such guidelines. These databases

should contain the historical reports for each building, including the refurbishments, fire, extensions, and the

potential end-of-life treatment plans.

According to the literature, the advantages of reuse in reducing the CDW and increasing the competitiveness

of the firms are key organizational drivers. However, most of the companies in the building sector do not have

enough experience in deconstruction and reuse, which results in following other end-of-life treatment options

such as demolition and recycling. Therefore, companies should take necessary actions to train the workforce

to improve the productivity of their deconstruction activities and increase the reusability of the recovered

building components. As discussed earlier, one possible driver to encourage companies to change their

business model is the availability of regulatory incentives. However, further research should be performed to

analyze the driving forces, which would help companies to integrate circularity in their business models.

The technical barriers can be categorized into deconstruction level, performance level, and health and safety

level. As observed in the reviewed literature, at the deconstruction level, the biggest challenge to recover

building components is that buildings are not designed for deconstruction. While innovative design techniques

can address this barrier in new buildings, it remains a significant challenge ahead of deconstruction of the

existing built stock. At the performance level, one of the barriers to the reuse of building components after

recovery is the reusability of the element (due to damages, availability of information, design challenges, etc.).

According to the definition of reuse, the reusability can be defined as the extent to which the recovered

building component in its new life could perform similarly to its earlier life. It is because most of the existing buildings are not designed for deconstruction, details about the existing buildings are unavailable, and proper guidelines and skills for effective deconstruction do not exist. As mentioned earlier, deconstruction can increase the reuse rate; however, there is no available guideline to help the practitioners to estimate the reuse potential of the building components before deconstruction. Therefore, further research to develop cheap and reliable techniques to investigate the reusability of building components is necessary. Moreover, while the DfD is identified as a solution to the end-of-life treatment of buildings, this design method is based on new building components. Hence, further research should be conducted to integrate the recovered building components into this design technique. At the health and safety level, as observed in table 4, there is a strong correlation between cost and health and safety requirements of a project with deconstruction and reuse. It indicates that the increased health and safety precautions necessary for deconstruction and reuse activities (as the result of the presence of hazardous materials, etc.) could potentially increase the overall cost of the project.

Conclusion

This study has contributed to identifying, categorizing, and prioritizing the factors affecting the reuse of components of the superstructure of a building at its end-of-life through a systematic literature review. In this study, a three-stage systematic review targeting peer-reviewed journal articles was employed. After choosing proper search words and identifying, screening, and checking for eligibility, 76 journal articles were identified and reviewed thoroughly. These papers are derived from top-tier construction journals and represent the state-of-art in the body of knowledge on this topic. After identifying the reuse barriers and drivers in these articles, we categorized them based on the identified themes. Then, through the development of a correlation matrix, we tried to understand the potential interdependencies between the barriers and sought the possibility of prioritizing them. The results of this study can be used as a guideline by researchers and stakeholders in the building sector to take progressive steps towards the circularity of materials in this sector.

According to the reviewed articles, the reuse of building components is a sustainable approach that can reduce the environmental footprints of the buildings considerably. However, various obstacles hinder reuse. In this study, the challenges facing the building sector in integrating reused components in the superstructure of new buildings were uncovered, while the advantages of BCR were highlighted. Consequently, the study presented

actions necessary to be taken, which could promote BCR in the building sector and recognized future research areas to address the identified gaps in the literature.

An initial look at the barriers revealed that addressing the economic factors were playing a significant role in the successful implementation of reuse in the building sector, followed by technical, social, regulatory, and organizational barriers. After analyzing the inter-relationship between the sub-categories of barriers, it was observed that while addressing reuse obstacles requires a holistic approach, actions to overcome the social, economic, and regulatory barriers should be prioritized.

In contrast to the mentioned contributions, this study has some limitations. The most important limitation of this study is its focus on the reuse of components in the superstructure of buildings, and the fact that the observations may not be generalized to the substructure of buildings and the overall construction sector. Therefore, it is advised to perform such investigation in other sub-divisions of the construction industry, such as foundations, roads, bridges, and infrastructures. Moreover, this paper is limited to top-tier peer-reviewed journal articles in the building sector. Hence, the correlations observed in table 4 should be considered with caution.

Declaration of conflict of interest

None.

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