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Circular economy of façades: Real-world challenges and opportunities

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ABSTRACT

Reuse and high-value recycling have a pivotal role to play in reducing waste and minimising carbon emissions in the built environment. Design strategies for such recovery methods have yet to be fully established in the façade industry. Meanwhile, stringent regulations, aimed at reducing *operational* carbon emissions of buildings and improving other performance criteria such as occupant safety, have stimulated the use of more complex façade systems that incorporate multiple functions. Other areas of the façade life cycle, such as *embodied* carbon and high-value material recovery, are rarely considered at the early design stage. This study adopts a mixed-method approach of data collection, to investigate the key challenges and opportunities associated with promoting high-value recovery options for façade products, as perceived by stakeholders in the façade supply-chain. Data was initially collected through an online survey completed by 69 stakeholders from across the façade knowledge/supply-chain. This was followed by 29 semi-structured interviews with selected survey respondents. It emerged that the advancement of circular design strategies is dependent on: increased awareness and quantification of the environmental value of circular design; cross-supply-chain buy-in on developments in take-back infrastructure including greater support for demolition contractors; and advancements in technological separation methods specific to façade components. Enhanced communication between stakeholders - notably between clients, facade contractors and material processors - acceptability criteria and product availability; and more holistic legislation based on whole life cycle emissions, to avoid the over-emphasis on operational efficiency, appear as vital requisites to increasing material efficiency. Finally, we illustrate where stakeholder priorities related to reuse converge and diverge, and thus we identify strategies for levering these factors to minimise environmental impact and optimise economic value in the façade sector.

Notation

CL#	Client/Developer
ARCH#	Architect
MC#	Main Contractor
FC#	Façade Contractor
MP#	Material Processor
DC#	Demolition Contractor

1. Introduction

1.1. Sustainability and embodied carbon in façade systems

The building industry contributes 33% of global greenhouse gas emissions (GHG) and continues to see rising levels of material consumption through new builds and refurbishment (Allwood et al., 2011; Hopkinson et al., 2018). The industry is therefore under unprecedented levels of scrutiny to rapidly transition to more environmentally sustainable practices. This requires a re-evaluation of all sub-systems at all stages of the building life-cycle. The operational energy efficiency of a building is significantly affected by the design and construction of the façade system, also commonly referred to as the building envelope. It has consequently received a great deal of attention in the quest to reduce operational carbon emissions. The envelope typically constitutes a low proportion of the total building weight relative to other building sub-systems e.g. the loadbearing structural system. However, it has been shown to contribute between 10 and 30% of the total embodied carbon emissions of the building (Clark, 2013; Cole and Kernan, 1996). Efforts to reduce operational emissions, together with other important performance criteria such as indoor comfort and occupant wellbeing, have led

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to composite, multi-functional façade systems that generally perform well during the building lifetime. These improvements in operational performance have had the unintended consequence of increasing the absolute value of *initial* embodied carbon of the building envelope itself. Furthermore, the multi-component nature and environmental exposure levels of the typical contemporary façade systems, results in shorter service lifetimes for some components, relative to those in the load-bearing structure (e.g. beams, columns etc.) (Brand, 1995; Hartwell and Overend, 2019). This leads to relatively short replacement cycles, and an increase in the associated *recurring* additions of embodied carbon, during the building lifetime. (Giesekam et al., 2014) predicted a likely overestimation in the assessment of operational emissions in the current literature, due to limited consideration of the future decarbonisation of the electricity supply over the building lifetime, over-estimations in building life expectancies and unaccounted performance. The focus on reducing operational emissions *alone* must therefore continue to be challenged.

So far, very little attention has been paid to the consequences of incorporating multiple skins and greater proportions of adhesive connections on the ease of disassembly and reuse of façade components. For example, many adhesive connections are non-reversible, meaning that from a design-for-disassembly perspective, connected components are difficult to recover for reuse and recycling (Guy and Ciarimboli, 2008). This, in turn, reduces the available stock of components and materials that have been recovered effectively for redeployment to reduce the embodied carbon of new designs. Future targets for reducing whole-life carbon emissions will not be met without an improved understanding of the ability to recover components from existing systems effectively.

1.2. Circular economy principles applied to buildings

The theory of the circular economy (CE) conceptualises the minimisation of resource input and waste, emission, and energy leakage through the incorporation of design strategies that promote durability, effective maintenance, repair, reuse, remanufacturing, refurbishing and recycling (Ellen MacArthur Foundation, 2013; Geissdoerfer et al., 2017; Segerson et al., 1991). (Gallego-Schmid et al., 2020) completed a literature review to analyse the link between CE and climate mitigation. They found that material reuse stands as one of the most promising CE solutions for reducing GHG emissions in the EU construction sector. (Ritzen et al., 2019) evaluated the environmental savings associated with the reuse of components recovered from a 10-floor residential building in new dwellings and showed that reuse could reduce the initial embodied carbon emissions by 90%.

Existing studies suggest that the opportunities for reuse are dependent on: the ability to deconstruct components from existing buildings; perceived risk in specifying reuse components; available reuse market; cost-effective remanufacturing and reuse certification processes; online marketing, component labelling and BIM; and shifts in procurement policies and regulation to stimulate demand for reused product (Giesekam et al., 2014; Hopkinson et al., 2018; Tingley and Davison, 2011). The research on reuse and recycling to date has tended to focus on its general applicability to the built environment (Hobbs and Adams, 2017; Kay and Essex, 2009; Pomponi and Moncaster, 2017); and single component systems such as structural framework and/or narrow sub-sets of material such as steel, concrete and glass (DeBrincat and Babic, 2018; Densley Tingley et al., 2017; Dunant et al., 2017; Eberhardt et al., 2019; Gorgolewski, 2008; Gorgolewski and Morettin, 2009; International Council for Research and Innovation in Building and Construction, 2014; Rose and Stegemann, 2018; Tam et al., 2018). Whilst these offer valuable insights into the challenges arising from reuse strategies in the built environment, façades are unique in that they are often multi-material systems with many different connection types that fulfil specific functions, designed and maintained by a global supply-chain. Thus, the appraisal of the most appropriate form of recovery requires a deep understanding of how key design and specification decisions influence the ability to reuse façade systems.

1.3. This study

Recovery of façade systems and/or components for multiple uses can be distinguished by the following scenarios: direct system reuse, disassembly and component reuse, and recovery through recycling. The purpose of this study is to critically assess the associated challenges and opportunities for each recovery scenario, as perceived by stakeholders in the façade supply-chain. Various stakeholders, each with different levels of involvement and influence, contribute to the façade design and specification process. Therefore, the survey and interviews targeted a broad range of stakeholders including clients/developers, architects, main contractors, façade contractors/consultants, material processors and demolition contractors. The findings of this study aim to guide the development of novel façade-specific design and recovery strategies, new business models, technological and environmental research, to enable the high-value recovery of façade systems and their constituent components to become more conventional practice.

2. Methodology

The research adopted an explanatory mixed-method approach. First, data was collected through an online survey (Section 2.2), to obtain qualitative and quantitative information from individuals (Bryman et al., 2015; Silverman, 2017). Secondly, this information was examined in more detail through follow-up semi-structured interviews (Section 2.4) conducted with survey respondents that indicated their willingness to be interviewed. The data collection process is illustrated in Appendix (A1). The two-phase data collection allowed for a broad set of themes and topics to be identified from the responses in the survey phase, which were then explored in more detail in the interview phase. The semi-structured interviews were conducted virtually by the authors and served to develop an understanding of the context of the survey responses, and identify areas of complementary and competing findings between the surveys and interviews. Additionally, the interviews served to verify that the survey questions had been understood correctly, and allowed for any other related topics to surface in a natural manner. The data collected enabled the authors to highlight areas of convergence, inconsistency and contradiction between stakeholder groups, and consequentially provide a well-informed insight into the challenges and opportunities for deploying circular economy principles in practice. The salient steps of the approach are described below.

2.1. Stakeholder identification and targeting

The transfer of information and products and/or services between stakeholder groups in the façade supply-chain have been mapped in Fig. 1. All relevant stakeholder groups highlighted in Fig. 1, were targeted in the distribution of the online survey.

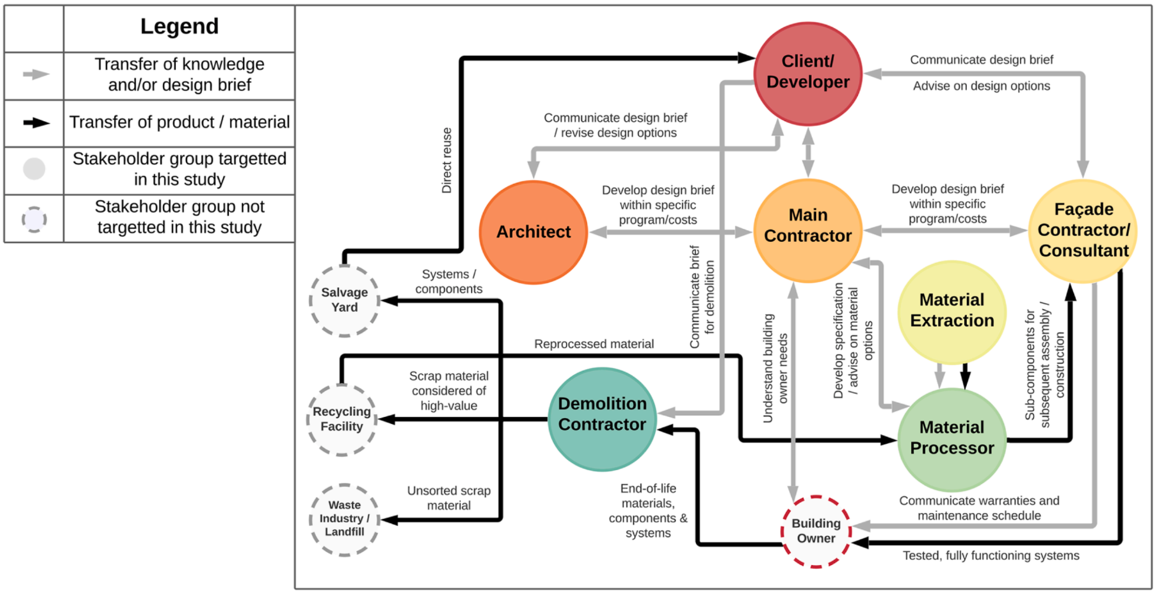


Fig. 1. Stakeholder map showing stakeholders involved in the façade supply-chain and existing flows of knowledge and products/services. Façade consultants have been grouped within the façade contractor stakeholder group. The material processor group includes all primary and secondary manufacturers.

2.2. Online survey format

The online survey was hosted via (Qualtrics, 2019), and made available from April 2018 – June 2020. The online format was deemed the most appropriate in ensuring maximum uptake of initial respondents (69 total), given the ease of distribution and high likelihood of accessibility. The survey was tested and revised based on responses from other researchers within the Glass and Façade Technology (gFT) research group at the University of Cambridge prior to distribution. It was subsequently shared with the gFT network of industry partners and advertised at university façade conferences at which several industry partners were present. Respondents with or without practical experience of façade reuse were approached. The survey was distributed via email, alongside a brief explanation of the aims of the survey, and an advisory consent form. It featured 22 core questions, with additional questions dependent upon which stakeholder group the participant self-identified with. The questions were designed along the recommendations of (Andres, 2012; Creswell and Creswell, 2018). The core questions focused on identifying the position of the respondents in the façade supply-chain; gathering company demographic data; and understanding their existing operations. They sought to establish the influence and responsibility of respective stakeholders on reuse strategies; perceived reasons for façade replacement; existing awareness and experience of façade reuse; and to explore the main barriers and drivers to the incorporation of reuse in façade design. The questions were of a mixed type: closed-ended questions that requested the assignment of relative weightings to given answers, or multiple-choice answers; multiple-choice rating scales; and open-ended questions that allowed for free-text feedback. A full list of the survey questions can be found in Appendix (A1).

2.3. Survey information retrieval

Results from all closed-ended questions and experiences of building element or façade reuse were collected and stored for statistical analysis. Basic information retrieval techniques adapted from (Luhn, 1957), were used to analyze the responses from the two compulsory open-ended questions in which respondents were asked to outline the specific barriers and motivations to façade reuse. The process of data analysis has been detailed in Appendix (A2). Each individual response was subsequently encoded with their relevant themes. The normalised frequency of terms $F_{ij,}$ for each theme *j,* was then used to identify the most significant barriers and motivations across the supply-chain. Comparisons between stakeholder groups were made by using a well-established statistical approach for information retrieval known as *term frequency-inverse document frequency* (TF-IDF), originally developed by (Jones, 1972). This accounts for the rarity of terms across responses, and therefore provides a more representative measure of the term frequency to each individual stakeholder group (Aizawa, 2003; Salton and Buckley, 1988). See Appendix (A) for relevant calculations. The sum of TF-IDF for each stakeholder group *g,* was calculated and used as a measure of the relative priority of each theme to each stakeholder group. The recognition of these themes helped to guide interpretation of the survey findings and provide direction for the interview phase.

2.4. Interview format and information retrieval

Twenty-nine stakeholders were interviewed in total: 22 of which were selected from the online survey, and 7 of which were approached separately, representing a wide range of backgrounds and experience. A short description of each interviewee can be found in Appendix (B). The interviews were conducted over the telephone or via web conference and typically lasted 45 – 60 min. Interviews were semi-structured in which a common set of prompts were prepared to build upon responses from the survey. Prompts included questions that intended to gain a better understanding of: the interviewee's background; typical supply-chain interactions; key influences in the design process; and existing considerations for sustainability and design for disassembly. They sought to understand the perceived value of the façade amongst other building elements; how different recovery strategies may align or conflict with the typical design process; existing appetite for specifying reuse and recycled products; suitability of existing designs for reuse and recycling; existing efforts to optimise recovery value at the façade's end-of-life; and previous experience of reuse. Additional prompts specific to the experiences of each interviewee were also prepared to maximise the quality of responses. All interviews were either recorded and transcribed, or transcribed during discussion. The themes emerging from the interviews were compared with the survey findings to develop a comprehensive understanding of the key challenges and opportunities, within and between stakeholder groups, to promoting high value recovery strategies for façade systems.

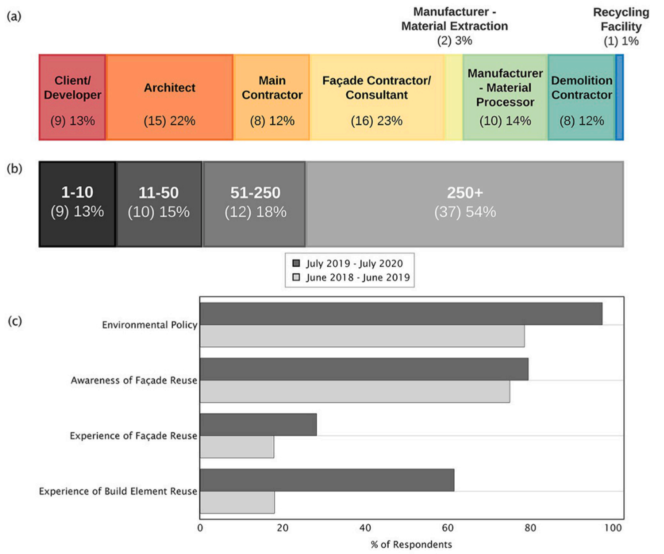


Fig. 2. Summary of respondents' background (a) position in façade supply-chain (b) number of people employed in company (68 total – 1 respondent did not specify) (c) previous awareness and experience in façade or build element reuse.

3. Results

The core survey results and emerging significant barrier and motivation themes from the survey are detailed first, followed by the qualitative interview results which are framed by the key emerging themes from the surveys.

3.1. Survey respondent background

The survey received 69 full responses. 75% of respondents were from the UK, 19% of respondents were from European countries outside the UK, and 6% were from the US and Asia. An overview of the demographics of the respondents and prior experiences of reuse is shown in Fig. 2.

90% of survey respondents had existing company policies related to sustainability. 75% of respondents in the first 13-month period had previously heard of the idea of façade reuse, compared to 80% of respondents in the second 13-month period. 64% of respondents registered experience of building element reuse in some form, compared to 25% of respondents expressing experience in façade reuse.

3.2. Survey results

3.2.1. Stakeholder willingness to consider reuse

Survey findings revealed that the willingness to consider reuse varied both between and within individual stakeholder groups. Fig. 3 illustrates the willingness to consider reuse for each respondent within their relative stakeholder groups and highlights 22 of the 29 interviewees that were later interviewed: 7 interviewees did not complete the survey prior to interview.

Individuals within each stakeholder group showed a wide divergence of responses in their willingness to consider reuse, particularly in the *main contractor* group. Based on the median values highlighted on Fig. 3, *façade contractors/consultants* and *demolition contractors* expressed a high appetite for reuse as a design and recovery strategy. The *main contractor* and *material processor* stakeholder groups emerged as least willing to consider façade reuse.

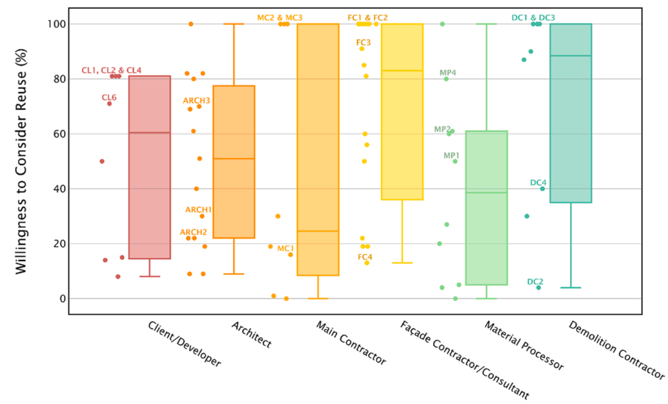


Fig. 3. Willingness of each stakeholder group to consider reuse. The top and bottom edges of each box represent the upper and lower quartiles, respectively; the median is indicated as a solid line inside the box; and the whiskers show the maximum and minimum value for each stakeholder group. 22 of the 29 interviewees have been highlighted by their interviewee reference.

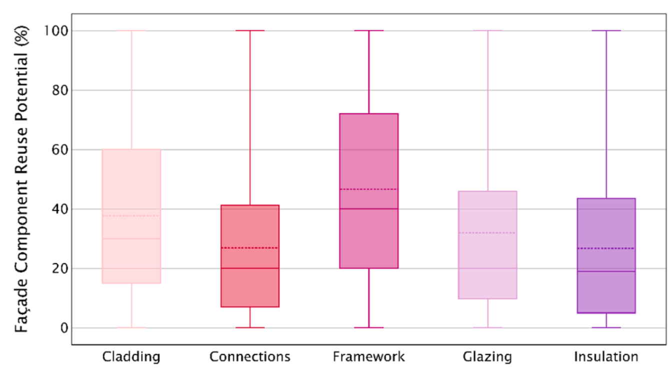


Fig. 4. Reuse potential (%) of different façade components as identified by survey respondents. The top and bottom edges of the box represent the upper and lower quartiles, respectively; the median is indicated as a solid line inside the box; the mean is shown as a dashed line inside the box plot; and the whiskers show the maximum and minimum values of reuse potential.

3.2.2. Perceived reuse potential of façade components

Survey respondents were asked to what extent they considered façade components to hold potential for reuse. In this context, reuse potential was interpreted by respondents to be in the form of direct reuse or closed-loop recycling. The reuse potential for different façade components as perceived by respondents is shown on Fig. 4.

Generally, framework components typically made of steel and aluminium, were considered to have a relatively high reuse potential. Insulation products, glazing and connections were deemed to have less reuse potential, with at least half of respondents suggesting reuse potentials $< 20\%$ for these components.

3.2.3. Perceived value and expected service life of building elements

Respondents were asked to rank building elements based on the perceived relative value, on a scale of 1 to 10, at their respective end-of-life. The load-bearing structure of the building was ranked as the most valuable building element (5.55), followed by the foundations (5.19), façade (4.47), and lastly mechanical and electrical (M&E) services (3.80). Subsequently, respondents were asked to provide estimates for the typical expected service lives (ESLs) of the same elements. A summary of the results is shown on Fig. 5.

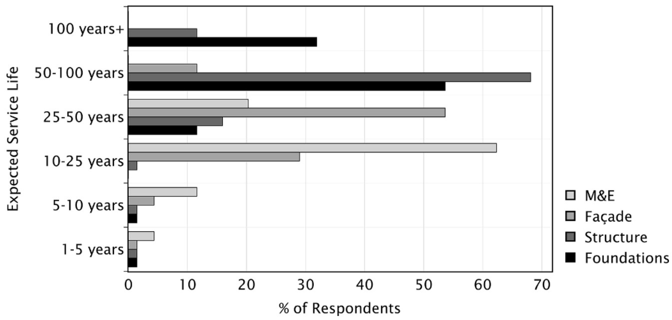


Fig. 5. Expected service lifetime of building elements as expressed by survey respondents (see appendix (C) for results in tabular format).

M&E services were deemed to have the lowest expected service life (ESL). The façade followed, with 88% stating an ESL of <50 years, and 35% stating an ESL of < 25 years. Meanwhile, 80% of respondents assumed that the structure has an ESL of >50 years. In a separate question, respondents were asked about the average rate of replacement in practice. 86% of respondents believed that the actual rate of façade replacement occurs at least every 30 years.

3.2.4. Reasons for façade replacement

Survey respondents were asked to weight the suggested reasons for façade replacement relative to one another for building refurbishment purposes on a scale of 1 – 6 (1 = least common, 6 = most common). Table 1 shows the average weightings of reasons for façade replacement across the supply-chain. Aesthetic (3.60) and functional performance-related (3.32) issues were considered the most common reasons for façade replacement. Fig. 6 highlights the divergence of relative weightings between the different stakeholder groups.

Table 1
Typical reasons for façade replacement as weighted averages across all stakeholder groups.

Reason for replacement	Average relative weighting
Aesthetic-related	3.60
Performance-related (due to component degradation)	3.32
Performance-related (to improve energy efficiency in-use)	2.29
To reduce maintenance costs in use	2.29
Driven by legislation	2.19
To accommodate structural changes	1.30

The large majority of the stakeholder groups including: clients/developers, architects, main contractors and façade contractors, indicated that seeking a new *aesthetic* was the primary reason for façade replacement. Material processors identified *performance* issues related to component degradation to be the most common reason for replacement. Demolition contractors proposed that seeking *reductions in maintenance costs* was the main reason for replacement, closely followed by *aesthetic-related* issues.

3.2.5. Barriers and motivations to reuse

In two separate questions, respondents were asked to state and explain: (i) the three main barriers; and (ii) the three main motivations, for adopting façade reuse design strategies. The absolute term frequency and TF-IDF of the themes that emerged from these responses have been grouped into 6 parent themes: behaviour, existing knowledge, supply-chain factors, and technical constraints from original façade design, financial factors, and governmental influence. The absolute frequency of barrier terms across the supply-chain is shown in Fig. 7(a). Several barrier themes relating to technical constraints that are imposed through the original design of façades emerged as significant. Uncertainties in *functional performance* ($F_j = 7.84$), lack of *education & awareness* ($F_j = 7.25$), *risk aversion* ($F_j = 6.68$), technical constraints originating from original limitations in *design for disassembly* ($F_j = 6.06$), and *a lack of information relating to the available materials* ($F_j = 5.97$), emerged as the main barriers to reuse across the supply-chain. The notion of limited *education/awareness* as a significant barrier to reuse was reinforced in a separate question, in which respondents were asked to rank the understanding of the concept of façade reuse ranging from not understood at all to very well understood. On average, respondents considered the idea of façade reuse to be 17.4% well understood.

The TF-IDF for each barrier theme in Fig. 7(b) shows that barriers related to *aesthetic, risk aversion* and existing *material selection* exhibit similar levels of importance across all stakeholder groups. Other barrier themes showed greater divergence between stakeholder groups. *Education and awareness* emerged as the most critical barrier for clients/developers. *Perceptions of old material* scored the highest TF-IDF score for the architect stakeholder group. *Logistics* were considered as the most critical barrier to reuse for façade contractors/consultants. Technical constraints related to *design for disassembly* and *functional performance* showed high TF-IDF scores for material processors. Uncertainty in *economic* feasibility accounted for the highest TF-IDF score for demolition contractors closely followed by a *lack of demand* for reuse products.

The absolute frequency of motivation terms across the supply-chain is shown in Fig. 8(a). Motivations relating to an improved understanding

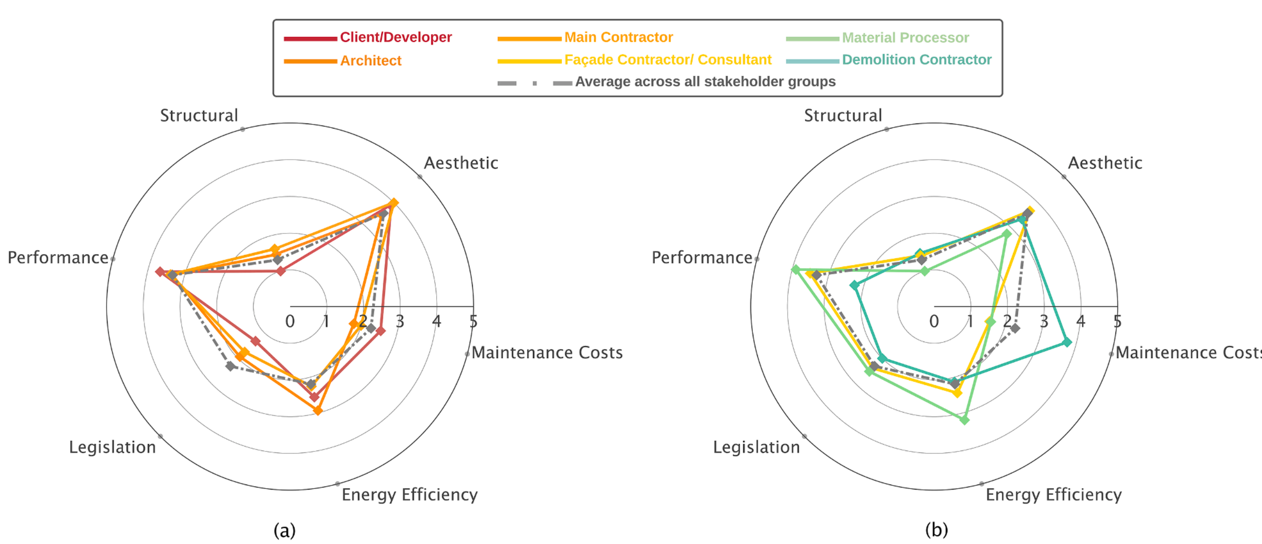


Fig. 6. Weighted ranking of typical reasons for façade replacement (see Appendix (C) for results in tabular format).

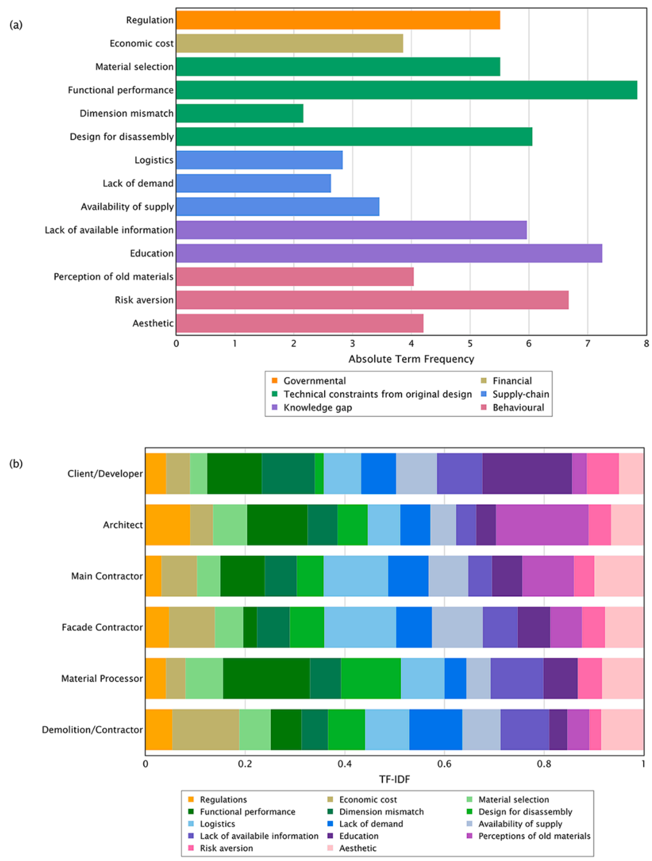


Fig. 7. Barriers to reuse listed by survey respondents (a) absolute term frequency of barrier themes across the supply-chain (b) TF-IDF, normalised by number of respondents in each stakeholder group, to indicate the relative importance of each barrier theme each stakeholder group.

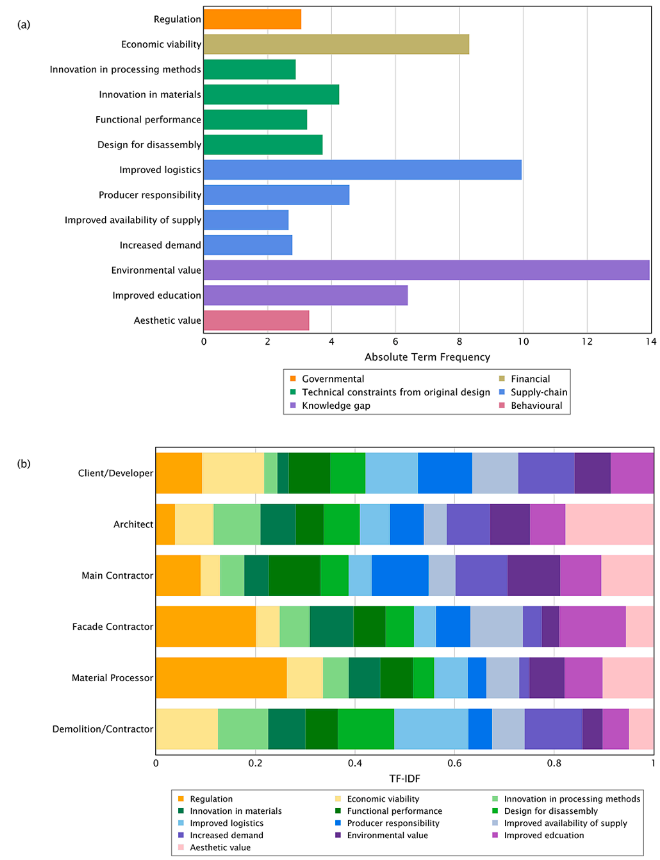


Fig. 8. Motivations for reuse listed by survey respondents (a) absolute term frequency of motivation themes across the supply-chain (b) TF-IDF, normalised by number of respondents in each stakeholder group, to indicate the relative importance of each motivation theme to each stakeholder group.

of the *environmental* value of reuse ($F_j = 13.95$), improved *logistics* associated with reuse ($F_j = 9.95$), and justifying the *economic* feasibility ($F_j = 8.31$) emerged as the most significant.

The normalised TF-IDF for each motivation theme is shown in Fig. 8 (b). *Functional performance* and *improved education* showed relatively equal weightings of TF-IDF for each stakeholder group. The relative importance of other motivation themes, as represented by their associated TF-IDF, varied significantly between stakeholder groups. Clients considered *economic viability* and *producer responsibility* to be key motivations for façade reuse. Attributing an *aesthetic* value to reuse designs and reclaimed material, accounted for the highest TF-IDF for the architect stakeholder group. *Increased demand* from clients and architects, was considered as one of the most critical stimuli for a reuse supply-chain by main contractors, together with *producer responsibility* measures. Considerations for existing and future *regulations* scored the highest TF-IDF weighting for façade contractors/consultants and material processors. *Improved education* exceeded the average TF-IDF of all motivation themes for façade contractors/consultants. *Design for disassembly, economic viability* and improved *supply-chain logistics* scored the highest TF-IDF for demolition contractors.

3.3. Interview results

This section summarises the key findings from the interviews. It is split into 7 sub-sections: the first details the existing design priorities related to sustainability, and the subsequent sub-sections are framed by the 6 parent themes that were identified in the survey findings. Many respondents switched between discussing existing practice and speculative future scenarios. Where possible, the authors have highlighted this difference when presenting the results. All interviewees discussed operations in the European context.

3.3.1. Existing design priorities related to sustainability

Several existing sustainability-related priorities emerged that can influence the design and recovery of façade systems. The unique priorities to each stakeholder group have been highlighted in Table 2.

Table 2 shows that while there is some degree of agreement about the opportunities for reuse across the different stakeholder groups, a wide variety of challenges exist.

3.3.2. Behavioural

The behavioural factors influencing reuse design strategies as expressed by interviewees have been summarised in Table 3.

3.3.3. Knowledge gap

Factors relating to a lack of awareness and available information on reuse design strategies have been summarised in Table 4.

Tables 3 and 4 highlight that whilst there is a growing demand for products with a high recycled content, it is often assumed that this must not compromise performance or design freedom. Reuse options present different knowledge-related challenges to recycled materials including a lack of awareness, lack of accreditation, and associated risk.

3.3.4. Supply-chain factors

The influence of the existing available supply-chain and available markets on reuse design strategies have been summarised in Table 5.

Table 5 shows that the responsibility of facilitating reuse largely falls

Table 2
Summary of the existing design priorities related to sustainability for each stakeholder group in the façade supply-chain.

Stakeholder group (abbreviation, number of interviewees)	Stakeholder-specific priorities
Client/Developer (CL, 6)	• All CLs expressed some awareness of quantifying embodied carbon however, provided few examples of its application in project work. • The majority of CLs expressed a lack of quantitative measures for justifying design for disassembly.
Architect (ARCH, 5)	• ARCH3 described the design process to be primarily centred around aesthetic and finishes. Sustainability and recycling criteria were described to often fall into the second stage of design development: designing for reuse and recycling is not a current priority. • ARCH4 described past experiences of selecting structural elements at a premium cost, partly for environmental reasons. • ARCH4 highlighted the influence of awards and other forms of recognition focused on sustainability and environmental impact as a driver for change. • 3 out of 5 of the ARCHs suggested that CLs are becoming increasingly aware of the commercial value of sustainability which ARCH4 described as a 'useful lever to justify greater capital expenditure within the project'.
Main Contractor (MC, 3)	• All MCs described their operations as largely driven by: minimising cost and risk in the façade system performance; client direction; logistics; and material availability. • MC3 described their level of influence in responsible material sourcing as 'limited by their later role in the design stage'.
Façade Contractor/Consultant (FC, 5) **Material-Processor** (MP, 6)	• FCs and MPs expressed little agency in the design specifications for materials: FC2 mentioned that they are 'not in the position to lead the design team in a different direction'; and FC5 stated that 'you have got to incentivise the CL and the ultimate building owner to come up with the idea and pass it through the procurement chain (to promote reuse)'.
Demolition Contractor (DC, 4)	• All DCs expressed that their operations are driven by: ○ CL brief in terms of specifications for material recovery and allocated time/programme; ○ maximising profit margins by balancing the time and labour costs to remove components with their market demand/value; ○ avoiding landfill taxes; ○ project type and location; ○ and the health and safety of workers.

Table 3
Behavioural challenges and opportunities associated with the application of reuse and recycled façade products.

Topic	Challenges	Opportunities
Existing perceptions of reuse and recycling	•Concerns of a compromise in performance and limitations on design freedom. •Several stakeholders detailed a 'negative social stigma'. FC3 proclaimed that 'everyone wants new.' •The majority of FCs and MPs felt that meeting the ARCH's visual intent was already challenging due to high expectations and limited flexibility in requests, particularly in the glass industry.	•Some MPs found that increasing their products' recycled content (RC) had increased their marketability. •DC2 claimed that functional obsolescence was often a perception.
Value of façade and aesthetic obsolescence	•The façade was described as an integral building element for CLs which they frequently seek to update. Aesthetic, performance, robustness, longevity, planning restrictions and age value were defined as the key influencing factors on specifying reuse due to their effect on the value of the client's asset: ultimately the building 'has to be a sellable commodity.'	•In rare circumstances, CLs accept a compromise in the aesthetic in favour of perceived age value or personal taste.

Table 4
Challenges and opportunities associated with the knowledge gap associated with reuse and recycled façade products.

Topic	Challenges	Opportunities
Lack of awareness and information on reuse products and recycled materials	• There was broad agreement amongst CLs and ARCHs that there is a lack of available information surrounding recycled content (RC) of materials. • Concerns over product availability which varies between materials: 'recycled post-consumer glass is very premature.' • MC1 recognised 'environmental benefits' as 'key opportunities' but questioned their accurate quantification to date.	• CLs, ARCHs and FCs called for better communication from MPs on the trade-offs of recycled products in terms of aesthetic, function, embodied carbon and cost. • Several CLs and ARCHs expressed willingness to adjust their acceptability criteria.
Awareness of impact of design decisions on end-of-life (EoL) design criteria	• ARCH1 suggested that designing for adaptability 'is often compromised by the drive for building efficiencies.' • CLs expressed low motivation to specify EoL design criteria in the client brief, thus deconstruction is not a key consideration for ARCHs, FCs and MPs. • MP3 described recent pushes for cradle-to-cradle certification to be a 'real challenge to get to work with the (existing) product range.' • DCs highlighted a disconnect between the design process and the ability to deconstruct. Further, they suggested that FCs 'design for build ability and maintenance but not for disassembly'.	• CL3 suggested that prioritising design for EoL would necessitate an attributable incentive 'that somehow assisted the idea of reduced carbon footprint.' • ARCH1 and ARCH4 called for better assessment methods to understand whole-life environmental impacts. • MP5 felt that 'until the environmental opportunities are quantified, and it comes into the performance specification for the design of the façade, we wouldn't be looking at reuse/recycling. It has to be driven by what we *have to* build into that design.' • MP3 suggested that the supply-chain is increasingly receptive, but not yet well-informed.

Table 5
Challenges and opportunities associated with the available supply-chain for reuse and recycling façade systems.

Topic	Challenges	Opportunities
Existing recycling infrastructure	• Existing levels of recycling were found to be dependent on material type and existing manufacturer operations. A clear distinction must be made between pre-consumer and post-consumer recycling; these terms were often used interchangeably by the supply-chain. • Some glass MPs detailed operations in pre-consumer recycling, however, experience of post-consumer glass recycling varied and was generally considered as unconventional. Fears in recycling post-consumer glass that might lead to production losses at a later stage arose from: potential contamination with other materials; managing different iron contents, which was considered challenging when dealing with glass from different manufacturers; and successfully achieving the required glass composition.	• CL1 expressed that they would be 'delighted to push the agenda to use post-consumer recycled glass. It is a niche industry and has the chance to take off rapidly once the motivations across the supply-chain are established.' • Post-consumer recycling of aluminium and steel products were described as well-established. This was exemplified by DC3 who proclaimed that the best-case scenario for a building with high recovery potential would be 'a metal sheet clad warehouse made of steel, concrete slab - every single item in that building can be recycled.' • MP4 detailed a key enabler in the success of recycling post-consumer aluminium was justifying the cost incentive and delivering performance assurance to customers. Demand for the recycled aluminium often outweighs supply. • MP5 concluded that it would be better to have a standardised composition for all individual glass panes manufactured across industry, to promote recycling.
Demand for Reuse products	• The majority of stakeholders believed that demand for systems and components for reuse was minimal. DC3 argued that 'the skill set (for dismantling) is there it is just a case of who wants the material? Where will it be reused?' • It was frequently found that stakeholders did not recognise their own role in stimulating demand for reuse products and recycled materials: they suggested that a change in approach from the CL or other stakeholder groups outside their own would be required.	• All CLs expressed high interest in reuse strategies to reduce embodied carbon in future designs. • ARCH4 described the idea of reuse as 'slightly like pushing at an open door'. • CL1: 'if it is client-led and client-driven, it is likely to happen, driven by cost and sustainability.'
Lack of reuse supply-chain, traceability and suitable logistics	• CLs and ARCHs were unaware of any take-back infrastructure or organised second-hand market/collection schemes. • Existing façade reuse experiences were material-specific e.g. traditional stone- or brick- work, and rarely multi-component systems. Experience of masonry reuse projects were described as highly labour-/cost-intensive leading to uncertainty in the practicality and logistical costs of reusing existing façade systems under the existing supply-chain. • MC1 felt that the 'fragmented' global nature of the construction supply-chain limited opportunities for recovery. • FCs expressed concerns over take-back and reconditioning schemes due to them necessitating a 'significant change to existing operations'.	• MP2 mentioned that a system of reverse logistics would require a 'whole new industry to be developed.' FC2 evaluated that 'products would have to be transported, adapted, refinished, stored and well-catalogued for the supply-chain to work efficiently.' • Several contractors and manufacturers called for on-site deconstruction sites. • Existing components with high-value that are salvaged for reuse are sold on directly to architectural salvage yards. DC2 emphasised that the 'industry *can* salvage the materials, they *can* be reused, but it needs to be a combined effort – someone needs to bring them all together.' • Some recognised examples of façade reuse for heritage purposes, have involved all actors working together to realise the reuse opportunity. • Some DCs suggested the use of existing technology such as embedded barcodes, to improve the traceability of parts, material grades, stress factors and life expectancy.
Existing influence on the demolition/ deconstruction process and existing market for reuse or recycled products	• Specifications for material recovery beyond the avoidance of landfill were described to fall outside the CL brief. Most CLs suggested the DC was responsible for selecting the best recovery route. • Influenced by the CL brief, DCs record recycling rates; typically at 96 - 98.5 wt% of each project. There is no requirement to specify the type of recycling. • DC4 mentioned that 'with current façades it's very difficult in the time frame that we're given on site to dismantle them and salvage them.' Deconstruction processes can be costly and time-consuming with limited access to original drawings that show fixing details to inform the demolition and deconstruction process. • MC2 and MC3 described the existing dismantling process as 'highly labour-intensive with a limited supply-chain for restoration' and 'lacking expertise'. • Façade materials were considered to be 'low value relative to other building elements based on existing (demolition) practices'.	• All CLs recognised that they *could* be 'better at articulating and specifying (recovery routes)'. • ARCH4 mentioned that reuse was more engrained within their current practice - 'where there is good fabric to be found, we will look for it', which necessitates working with DCs to determine the demolition sequence. • A mindset of avoiding landfill was found to be engrained in the demolition industry due to: the landfill tax; the CL-brief; and the market opportunities for salvaged components/materials, in which an additional '25% on top of the project value itself' can be obtained. • DCs' experience of salvaging building components were predominantly driven by architectural trends/importance, historic value and heritage. • DC4 mentioned that the development of 3D cloud-point surveys in the early design stages could help to recognise opportunities for reuse.

to the demolition contractor. As such, the take-back supply-chain for reusing façade products lags behind recycling infrastructure, and is largely limited to heritage components or façade retention projects.

3.3.5. *Technical constraints from original design*

The technical constraints originating from original system design have been summarised in Table 6.

Table 6 shows that apprehension in reuse designs largely stems from uncertainty in functional performance and lack of standardisation.

3.3.6. *Financial factors*

The supply-chain was described by CL1 as 'mainly driven by cost and not considering the holistic approach/wider impact'. The perceived financial implications of reuse design strategies have been summarised in Table 7.

Table 7 highlights that the financial feasibility of reuse design/recovery strategies is not well-understood, providing a limiting factor for CLs, FCs and MPs to invest in new business models and recovery infrastructure.

Table 6
Challenges and opportunities associated with technical constraints from the original design for enabling reuse and recycling of façade systems.

Topic	Challenges	Opportunities
Incompatibility in sizing	• Several stakeholders identified challenges in reuse due to a lack of standardisation and changing low-tolerance requirements for dimensions/fit, configuration and functionality.	• ARCH1 suggested opportunities for reuse for 'monotonous architecture' in international locations.
Experience and perceptions of functional obsolescence	• Many MCs, FCs and MPs highlighted the challenges in managing CL perceptions of functional obsolescence. Many CLs raised concerns over invalid warranties, which is particularly important for 'investment type buildings', where there needs to be a clear responsibility for performance assurance. • MCs emerged as largely driven by liabilities: MC3 highlighted that reuse projects would necessitate the 'client, design team and contractor to work together to share the risk'. • MCs and FCs typically offer a 12-year warranty for typical modern façade systems, with a design life of 30-years. • It was unclear as to whether expected failures of façade systems and components were from practised examples or perceived risks due to invalid warranties and uncertainty in actual service life figures. • New regulations for functional performance can occasionally force system obsolescence.	• MC3 called to formalise the process of testing and re-certification. Existing performance validation methods were described as basic PASS/FAIL verification assessments. • Some FCs and MPs believed that disassembling for component reuse and recycling would be more feasible than extending the system service life through reconditioning to enable system reuse.
Original design methods	• Changing design trends were described to have led to increasing the complexity of façade systems. MP3 highlighted that the existing design focus has been on longevity, not for disassembly. MP4 suggested that 'the more 'high-tech' a façade, the…less re-usable it is.' FC1 stated that 'façades at the moment are inferior in terms of recyclability.' • Existing systems were described to not be designed for 'rapid removal'.	• ARCH1 referenced the pilot project: 'Circular House', delivered by Ove Arup & Partners which utilised mechanical connections to enable better separation of systems for component reuse.

Table 7
Challenges and opportunities associated with the financial feasibility of reuse and recycling façade systems.

Topic	Challenges	Opportunities
Financial Influence	• The majority of FCs and MPs felt they did not have the financial flexibility to trial different recovery strategies without additional support. 'The current cost for deconstruction is not present in the CL's budget'. • MP1 proposed one remedy to incentivising reuse would be a leasing business model. The business model of leasing façades emerged from FC3 who felt that despite providing more incentive to reuse and recycle, as a company they would 'struggle to survive'.	• There were several calls to 'consider the economics and cost model' for different recovery options, including the necessary 'upfront capital investment in order to create a reuse / recycling supply-chain' and associated to help justify the business case and/or make recommendations for external government funding. • CL3 and CL5 proclaimed that they would be in the position to drive the demand for recycled or reuse projects by providing 'a financial bonus for over exceeding certain embodied carbon targets.'

3.3.7. *Regulatory factors*

Many stakeholders detailed limited external recognition for reuse design strategies. The influence of existing and speculative future regulatory schemes on reuse have been summarised in Table 8.

Table 8 provides evidence of the lack of existing regulation and certification schemes to promote reuse. The voices of the interviewees supporting the information presented in Tables 3-8 have been presented in more detail in Appendix (D).

4. Discussion

Based on the findings from this study, three key strategies for applying circular economy principles to façade systems at the design and recovery stages have been identified by the authors:

1 incorporation of design for high-value recovery at end-of-life as an early stage design parameter;

Table 8
Challenges and opportunities associated with the effects of legislative influence on reuse and recycling façade systems.

Topic	Challenges	Opportunities
Government and external certification	• ARCH4 highlighted competing factors between sustainability and other design constraints: 'some of the building regulations seem to be dancing around each other at the moment'. • MC2 questioned the effectiveness of existing certifications: 'BREEAM and other policies can help to assign credits for innovating - are they good enough? Are there specific counts for reuse?' • FC3 felt that 'few CLs would include specifications (for reuse) within the brief unless (externally) pushed'.	• Suggestions for external influence to aid the development of a recovery infrastructure included: certification schemes that better account for embodied carbon and whole-life carbon; specific regulations to limit façades to incorporating only a certain amount of virgin material; effective implementation of a design for disassembly policy; legislative incentives and tax breaks for reuse and recycled products or the ability to disassemble at the end-of-life; increased taxation for low-value recycling; legislation on quantities of virgin material allowed to market annually; and/or legislating minimum targets for the use of reused or recycled products through the government or local planning authorities. • MP5: 'Once it is a legislation, people have got to do it, the cost will end up on the cost of the new building. While it's not legislation then there's no real motivation to do it.'

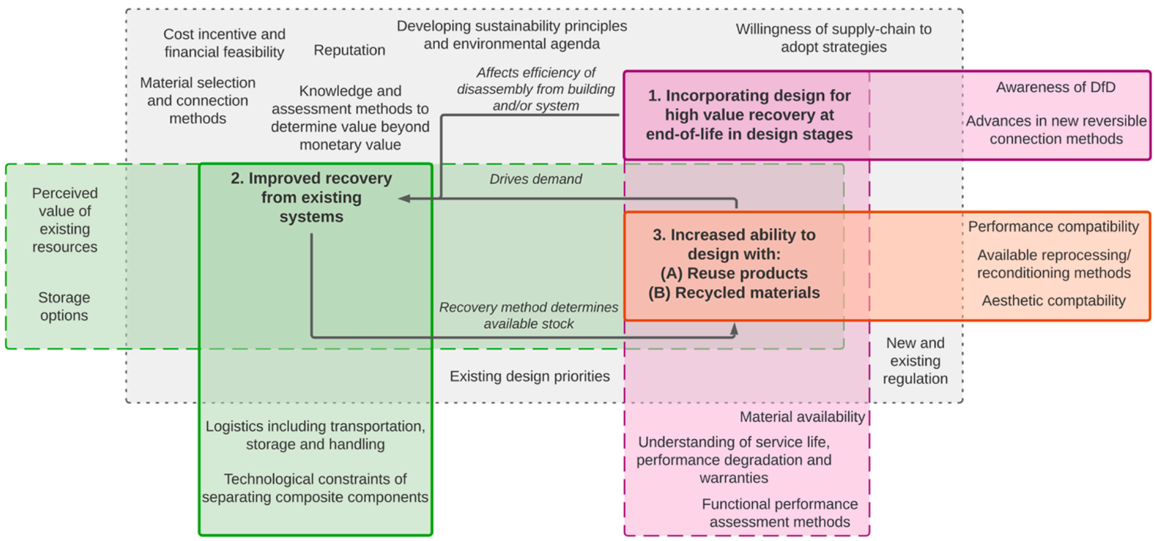


Fig. 9. Venn diagram summarising the unique (solid line) and shared (dashed line) influencing factors on the three key design strategies for applying circular economy principles to façade systems at the design and recovery stage as uncovered through this study.

2 improved recovery of systems, components and materials from existing systems; and
3 increased ability to design with reused products and/or recycled materials in new designs.

The influencing factors for each strategy have been highlighted on Fig. 9.

The unique and shared challenges of each design/recovery strategy are discussed in Section 4.1, and the key opportunities for developing circular design principles for façade systems are discussed in Section 4.2.

4.1. Overview of key challenges

Each strategy proposed in Fig. 9 presents a wide variety of economic, technological and risk-based challenges. The authors' interpretation of these key challenges based on the findings from this study have been summarised on Fig. 10.

The four branches of Fig. 10 are discussed in sections 4.1.1 to 4.1.4. Each branch requires equal levels of attention to ensure that any increase in demand for circular design strategies is met with an available supply of resources.

4.1.1. Designing for high-value recovery at EoL

Overall, the findings from the surveys and interviews provide support for the notion that evolving façade design has produced systems that are increasingly difficult to disassemble and re-process at their end-of-life (EoL). Awareness of design for disassembly (DfD) varied widely amongst stakeholders. Whilst some participants expressed a qualitative understanding of the ability to recycle different material groups, it was generally expressed that the design team frequently specify materials and interfaces for façade systems without knowing the impact on disassembly and the potential for components to be reused or recycled. The benefits of designing for high-value recovery are not currently recognised within the supply-chain and/or by external regulation/certification schemes. The supply-chain is thus not incentivised to formally include the deconstruction stage as an important factor in the original design process.

4.1.2. Recovery of existing systems and constituent materials

Driven by existing sustainability certification schemes, the avoidance of landfill is currently the only necessary condition for recovery set by CLs for DCs at the façade's end-of-life. Beyond CL aspirations, efforts to recover façade systems and their constituent materials are predominantly driven by market demand and avoiding landfill taxes, which at present favour recycling or down-cycling as opposed to reuse. MPs have been driven to develop the necessary reprocessing methods for recycling post-consumer metallic components by identifying the cost savings arising from utilising smaller quantities of raw materials. Post-consumer glass is not currently recovered for high-value recycling back to flat glass due to a *perceived* cost disadvantage originating from the logistical costs involved in recovering glass cullet at low contamination levels and a fear of unacceptable defects in the final product.

MCs and FCs emphasised their lack of willingness to consider system and component reuse strategies due to underdeveloped logistics and markets. Many systems would require evaluation and reconditioning processes which would incur costs for transportation to a willing contractor / manufacturer; careful handling; and storage. In addition, many FCs and MPs highlighted technological challenges in reuse (Table 6), due to the use of a broad range of materials and interfaces deployed in contemporary façade systems which inhibit efficient disassembly. A lack of demand and take-back infrastructure combined with negative perceptions of recovered/remanufactured products, and a limited ability to provide performance assurance from FCs, creates a self-sustaining cycle of façade products being perceived as low value at their end-of-life. This provides little incentive for DCs to optimise the recovery of systems, components and/or materials.

4.1.3. Designing with reuse products

Survey findings revealed that the façade often possesses a high value at the design stage relative to other building elements but is frequently considered as one of the least valuable elements at the EoL stage, preceded only by mechanical and electrical services. Aesthetic issues emerged as one of the most common reasons for façade replacement in the survey findings. This is consistent with the opinion held by the majority of stakeholders that the asset value of a building is closely related to the perception of the façade aesthetics. At the time of replacement, systems may still be functional but heightened attention on operational performance, negative perceptions around 'old' material and changing trends in architecture can limit potential for reuse. The allocation of warranties means that functional obsolescence is predominantly governed by the manufacturer-specified service life. However, many MPs and FCs recognised that façade systems can often outperform their warranty periods. The majority of ARCHs and FCs implied that the uniquely-sized, performance-orientated nature of

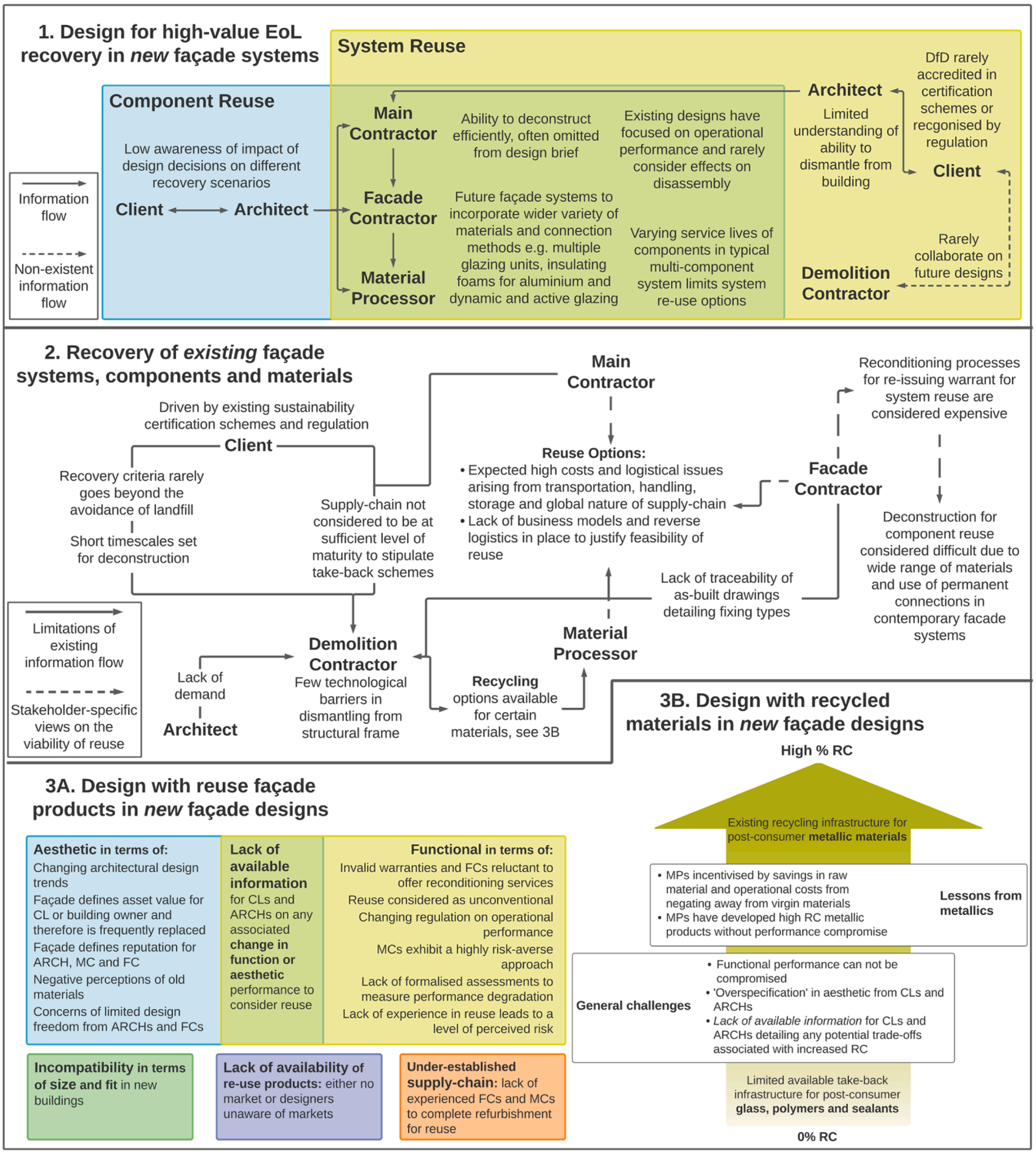


Fig. 10. The unique and shared challenges of incorporating circular economy principles in the design and recovery of façade systems that were established through this study. The information flows between stakeholder groups are mapped and the key challenges are listed as text.

building envelope design would inhibit their compatibility and design freedom in new projects. In addition, the current supply-chain for reuse was described as under-established: many CLs and MCs felt that other stakeholders would be unprepared to adapt to the different technological deconstruction processes and necessary business models; other stakeholders anticipated higher costs for reuse design strategies, despite detailing few experiences of direct façade reuse other than for heritage components and listed façades; and none of the respondents were aware of stockists of façade systems for reuse. Buying new materials was considered to be more efficient that dealing with 'old' materials. To some extent, the lack of experience and case studies demonstrating reuse strategies creates a degree of perceived risk.

4.1.4. Designing with recycled materials

The interviews revealed that it can be difficult for stakeholders in the design stage to understand or get access to the information on the recycled content (RC) of materials from MPs. Many CLs, ARCHs, MCs and FCs assumed that there would be a compromise in aesthetic and/or performance when increasing the RC of material products. The aluminium MP described how they have effectively managed this common misconception by offering a high RC product that possesses the same functional and aesthetic properties as primary products. Interviews with glass MPs revealed that in many instances, an increase in RC alone with a cullet of a known composition would not affect the final product. With the right take-back infrastructure in place, often a product of similar technical and visual quality can be achieved. However, gaining access to glass cullet with a known composition and limited contamination (e.g. from coatings and interface materials) was considered challenging, leading to limited capacity in the utilisation rates of post-consumer recycled glass. It is important to note that there was some disconnect between the views on the aesthetic finish of high RC materials expressed by stakeholders involved in the design stages, and the expected acceptability as perceived by MPs and FCs. Past experiences of the MPs and FCs working alongside ARCHs and CLs have brought about a fear of moving away from perfectly uniform visual quality. However, several CLs and ARCHs admitted an over-specification for glass. Some, went as far as to state that it would be desirable to have some visual differentiation for high RC products on projects with a sustainability-focus. Thus providing evidence of a new appetite for high RC materials and products that may allow for compromise in other design factors.

4.2. Development of shared opportunities

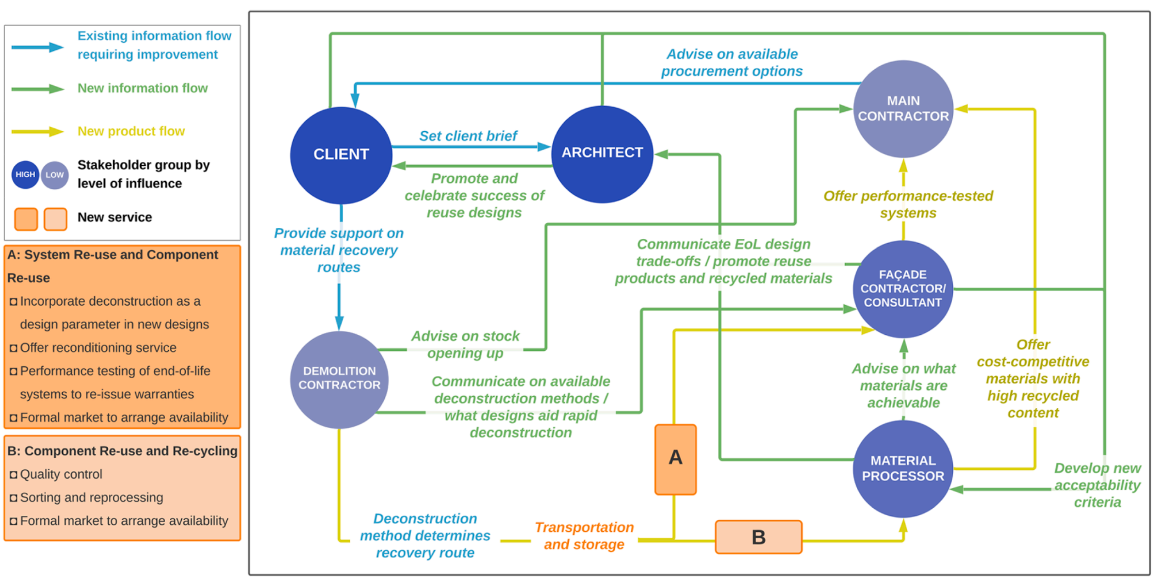
The successful implementation of reuse as a design strategy will necessitate a reform to the existing supply-chain which provides incentives to all stakeholders. Each stakeholder in the façade supply-chain expressed different priorities, which was made evident in the high divergence of TF-IDF of recognised barriers to, and motivations for, reuse for each stakeholder group (see Figs. 7 and 8). The key priorities expressed by interviewees have been developed into key influencing factors on the operations of each stakeholder group in Fig. 11.

Fig. 11 also highlights the new information, product and services flows between stakeholders that could support supply-chain reform. The potential benefits arising from these new flows are shown in Fig. 12. The benefits will depend on initial façade system design: in some instances, seeking recovery for re-conditioning/adaption for system or component reuse will be more viable, whereas in others, due to constraints in the initial design, service life, and a lack of fully-developed technological processes, recycling may be the most feasible option.

4.2.1. Improve take-back infrastructure, logistics and innovation in new products

Many stakeholders indicated that the main barriers to reuse and high value recycling lie in the lack of take-back infrastructure and supporting business models. Some lessons can be learned from MPs that represented the aluminium industries where the environmental and cost benefits of recycling post-consumer metallic components are successfully driving a take-back reuse and recycling supply-chain. To increase the market demand of recovered products, new and existing manufacturers have an opportunity to evaluate, and where appropriate, market the benefits of different recovery scenarios for façade systems and develop reconditioning operations / better separation methods to support reuse and/or high value recycling. Simultaneously, FCs/MPs would be encouraged to take greater levels of ownership and responsibility in recovering façade products in instances where there is not an immediate direct match with client demand. DCs unanimously stated that together with greater support from CLs, increased demand from FCs and MPs would incentivise them to salvage and, in some instances, store recovered components with increased confidence that they can sell them on at a viable price.

The most appropriate recovery route for components from existing façade systems will vary between projects. For example, unitised systems were mentioned as holding good potential for system reuse



Key influencing factors on the operations of each stakeholder group

CLIENT	ARCHITECT	MAIN CONTRACTOR	FAÇADE CONTRACTOR/ CONSULTANT	MATERIAL PROCESSOR	DEMOLITION CONTRACTOR
Asset value	Sustainability policy	Value engineering	Aesthetic design intent	Internal operating costs	Health & safety
Global client approach	Functional design intent	Cost	Functional design intent	Raw material costs	Market demand
Reputation	Reputation	Legislation	Cost	Environmental cost	Skillset of workforce
Investor	Legislation	Reputation	Reputation	Supply-chain pressure	Legislation
Certification schemes	Aesthetic design intent	Risk	Risk	Reputation	Time / programme
Planning authorities	Project type / budget	Planning authorities	Legislation	Legislation	Labour & equipment costs
Tenant	Typical approach of practice			Supplier differentiation	Project type e.g. full demolition, retained structure etc.
Legislation					
Wider sustainability agenda					

Fig. 11. Stakeholder map highlighting the existing influencing factors on each stakeholder's operations; new information flows; and new product flows and services required for a take-back supply-chain within the façade industry.

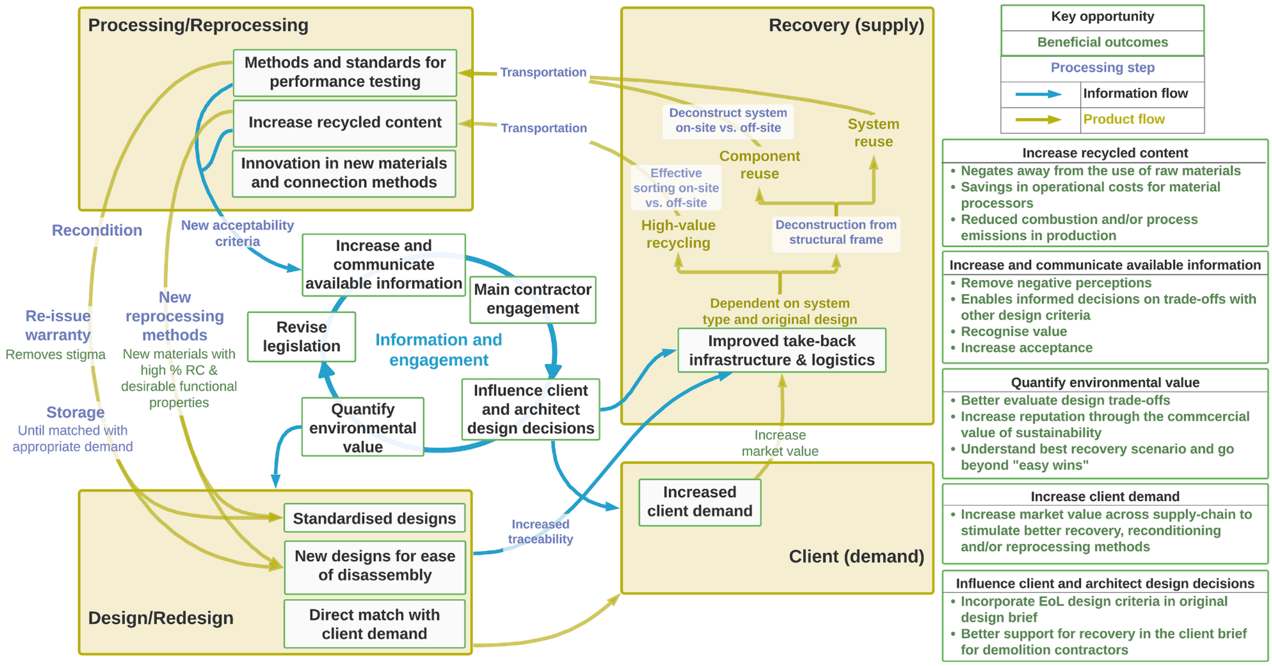


Fig. 12. Development of key opportunities to promote high value recovery options across the façade supply-chain.

however, DCs emphasised that they rarely have access to the original construction drawings to enable efficient deconstruction. It emerged that DCs are dependent on FCs and MPs to establish a clear disassembly sequence that explicityl assesses disassembly and potential for reuse or recycling. Enhanced traceability of material properties and fixing types through component labelling systems that are supported by BIM, such as those researched by (Rose and Stegemann, 2018), could act as a useful precursor to supporting reclamation and reuse strategies. Existing demolition audits undertaken by DCs could provide a useful tool to understand the components arising from refurbishment and demolition projects. FCs and MPs highlighted their need for support from CLs to invest in developing new business models and systems of reverse logistics that seek to obtain and utilise salvaged components in new designs. It was suggested by several stakeholders that a leasing business model, such as that previously researched by (Azcárate-Aguerre et al., 2018) could give more incentive to manufacturers and downstream companies to incorporate design for deconstruction principles. This could distribute the responsibility of functional performance across the supply-chain more evenly, and therefore mitigate against the premature obsolescence of systems that comes about from expired warranties and a lack of ownership. Typical warranties issued by manufacturers are often much shorter in lifetime than the expected service life, suggesting opportunities for improved assessments that quantify the existing performance of façade systems beyond categorical PASS-FAIL assessments. This would enable the identification of any necessary reconditioning to return systems to their original or improved function. The subsequent deployment of performance evaluation processes similar to that for new systems would enable manufacturers to re-issue warranties to MCs, CLs and building owners to alleviate concerns of system deterioration and associated risk in investment decisions. Simultaneously, FCs and MPs have the opportunity to work with CLs to develop new acceptability criteria specific to recovered products. Protocols for non-destructive testing and recertification have recently been developed for structural steel components in an effort to facilitate the reuse of steel structures (Coelho et al., 2020; SCI, 2019).

Where re-certification is not possible, deconstruction for component reuse may be a more viable recovery option. This would enable components with long service lives to be effectively reused without being limited by their parent system service life. Deconstruction units on-site, financed by the client/developer, were proposed by several MCs and FCs to aid efficient deconstruction and minimise transportation costs. Components could then be reconfigured for new system types that comply with relevant standards. For example, metallic and monolithic glass components which are less susceptible to degradation, could be incorporated into new systems with improved fixing technologies that enable future reuse.

All CLs and ARCHs expressed a growing interest to incorporate fully recycled products. Some, conveyed a willingness to accept a compromise in aesthetic, and others, expressed a willingness to celebrate an alternate aesthetic in favour of enhanced environmental credentials. This contrasted with many perceptions expressed from MPs and FCs. This disparity suggests that there is an opportunity for downstream stakeholders to take the lead in innovating to bring products to market that incorporate higher quantities of post-consumer materials. Increasing and communicating the availability of these products, will enable ARCHs to more readily incorporate them in new designs and alleviate an element of risk for MCs. Greater support from CLs and ARCHs through increased understanding, flexible specifications, embodied carbon targets and/or financial incentives, is required to encourage MPs to search for more efficient ways to recover systems and/or components post-application.

4.2.2. Increase available information and communications with supply-chain

Previous research has found that flexibility in design and early commitment to reuse as a design strategy are key factors in the successful implementation of the reuse of structural steel and timber elements in practised examples (Gorgolewski, 2008; Gorgolewski and Morettin, 2009). In the present study, CLs were found to hold a key influential role in initiating the façade supply-chain to develop reuse design strategies. As a stakeholder group, they expressed a high willingness to specify reuse and more responsible sourcing of materials in future projects where they are available, on the premise of reductions in embodied carbon on new projects. *Education and awareness* and *perceptions of old material* scored the highest TF-IDF score for the CL and ARCH stakeholder group, respectively. Increased knowledge transfer across the supply-chain as highlighted in the inner core of Fig. 12, emerged as a key enabler to allow for MPs, FCs and DCs to have more autonomy and influence over different façade design options and create specifications that have positive impacts on responsible sourcing and/or disassembly. MPs and FCs need to clearly document and communicate any associated trade-offs of reuse products and recycled materials including: aesthetic and functional performance; procurement times; maintenance; environmental impact and cost. These should be communicated with the design team and MCs in the early design stages, when CLs and ARCHs have more flexibility in the project vision, to allow a value-based judgement to be made and incorporated into the client brief/design specification. This would encourage designers to search for innovative ways to procure and use reuse products and/or recycled materials, and subsequently celebrate their success. In addition, clear communication of the benefits and value of reuse products or recycled materials across the supply-chain will ensure that reuse and recycled options survive the value-engineering processes in later design stages.

4.2.3. Justify the environmental motivation

There was a high degree of uncertainty across the supply-chain on the best approach for reducing whole-life carbon. FC4 posed the question: 'should we actually be replacing (the façade) and making it more thermally efficient because that in turn reduces its carbon factor during the lifetime, or do we take an old façade and put it on another building?' Existing research suggests that the contribution of embodied GHG emissions to the building lifecycle is not insignificant. It has been found to increase up to and beyond a ratio of 1:1 (embodied: operational) over a 50-year period (Röck et al., 2020). MPs verified that increased recycled content can often result in a decrease in embodied emissions for most materials, including aluminium and glass, due to a reduction in the GHG emissions generated in the combustion and/or processsing stages of manufacture. Interviewees in this study expressed some uncertainty about the accuracy of embodied carbon assessments and stated that they are not regularly considered in new build and construction. Voluntary environmental product declarations (EPDs) produced by manufacturers provide a measure of the embodied carbon of products, along with other environmental indicators. CLs and ARCHs have an opportunity to action their willingness to better account for embodied carbon on new projects, by consistently requesting EPDs from manufacturers. This, in turn, will better translate the benefits of low embodied carbon products and increase their competitiveness.

Design for disassembly principles do not frequently take high priority in the design brief: all stakeholders mentioned that the benefits of designing for reuse would need to be quantified to justify its inclusion. Alongside life-cycle assessments, more formal environmental assessments specific to multi-component systems, are required that better evaluate the benefits and trade-offs from material selection/connection methods and different design options with the ability to optimise recovery (Beurskens et al., 2016; Durmisevic et al., 2017; Hartwell and Overend, 2020). These have the potential to define the value of recovered systems/components after their first use. Considerations for service life are essential to ensure that designing for disassembly is balanced with designing for longevity.

4.2.4. Legislation

Legislation and certification schemes were factors that were only occasionally mentioned amongst stakeholders but were considered to have a significant influence on business operations across the supply-chain. There was broad agreement across the supply-chain that sustainability-measures are largely driven by the client brief, which is driven by compliance with external legislation and certification schemes such as BREEAM and LEED. These were found to largely prioritise operational efficiency, thus leading to some uncertainty over the most effective way to achieve sustainable designs. Several new forms of legislation proposed by interviewees are detailed in Table 8. One CL emphasised the importance of making recycling and reuse obligations product-specific, to avoid the supply-chain focusing on 'quick-win' high-wt. % building elements such as structural components. New forms of legislation that considers whole-life carbon accounting could increase the level of influence of MCs, FCs and MPs in recommending suitable products to the design team, who themselves would be incentivised to look more creatively at how they can reuse recovered/refurbished products in new designs. In turn, DCs would be motivated to salvage components in response to the increased demand.

4.2.5. Recognising financial opportunities through pilot projects

There is a preconceived idea that cost will create a significant barrier to higher value recovery options. Despite a growing interest in the areas of reuse and recycling, there are very few examples to showcase the potential benefits in the context of façades. Experiences of circular design involved: the direct reuse of brick and masonry façade products, driven by the aesthetic value of the products and/or planning authorities; and recycling on a material level. One sole example of the reuse of contemporary façade systems was referred to by one MC involved with the 1 Triton Square, London, refurbishment project where the curtain walling units were removed, re-glazed with new glass, and fitted with new seals. The lack of examples of practical disassembly of systems and components for reuse means that the upfront capital investment and subsequent associated costs to initiate and grow a reuse supply-chain remain unknown. Thus, it emerged that the business case for façade reuse and/or legislative financial support is not well-understood. Service-based business models, that consider logistical costs, reconditioning and/or deconstruction, were mentioned with mixed enthusiasm by FCs. Arguably, any reduction in sales of new products could be offset by the increased revenue through the provision of services and enhanced manufacturer reputation for those that opt to take greater responsibility for their products beyond their warranty period.

5. Conclusions & recommendations

This study set out to understand the key challenges and opportunities in advancing circular economy principles in façade design, through an online survey and series of semi-structured interviews with several different stakeholders in the façade supply-chain. Based on the findings, the following conclusions and recommendations can be made:

1 Interviewees unanimously expressed a need for new ways to communicate the value of reuse with the supply-chain, to offset the demand for "new". Environmental-related drivers for façade reuse emerged as the most prevalent. To date, due to existing legislation, operational efficiency has taken priority in the design stages. Altered perceptions of environmental value are required to help the supply-chain to consider implications of design on end-of-life recovery, alleviate premature obsolescence, and, in some instances, stimulate greater flexibility in the desired aesthetic. Developments into the metrics of embodied carbon and designing for disassembly specific to façades, with service life considered, would help to develop a more holistic understanding of environmental value, and ensure that wasteful supply-chains are not being created on the basis of operational performance alone.
2 Functional performance was emphatically considered as uncompromisable by all stakeholders. This exemplifies the risk-averse nature of the façade supply-chain, particularly MCs, who are ultimately responsible for the performance of the façade over the warranty period. To overcome this, new testing procedures that evaluate system performance; new reconditioning methods to mitigate system/component deterioration; and ongoing revisions to acceptability criteria, are required. This would enable performance assurance and supporting warranties which act to remove the perceived high level of risk associated with specifying reuse.
3 Where system reuse is not possible, due to sub-component degradation, more research is required to alleviate the existing technological constraints of disassembly for component reuse. A key enabler for component reuse for new systems lies in the ability to

obtain materials that are undamaged by fixings. This requires research and development on viable disassembly techniques for existing designs, such as adhesive connections and laminated glass. In addition, research and innovation is required into new designs that facilitate disassembly and encourage reuse. This may involve standardising designs; incorporating more design redundancies for adaptation; creating systems with fewer components; and/or designing reversible connections that enable rapid deconstruction.

4 Clients/developers emerged as the key stakeholder group influencing decisions at the design stage. They indicated growing enthusiasm for specifying higher percentages of reused products and recycled materials in new designs. It is therefore vital that there is increased training and dissemination of information on the availability of these products from the supply-chain. It emerged that the clients/developers could use the information from (1) and (2) to include specifications for reuse and designing for deconstruction in the client brief. This would help to ensure that the architect's design intent is not compromised by the late adoption of reuse strategies when there is less flexibility in the vision of the project. In addition, it will encourage façade contractors and material processors to search for new ways to incorporate reconditioned components in new designs and in turn, stimulate their demand and market value. Consequentially, demolition contractors would have an enhanced motivation to salvage at high value. Increased supply-chain collaboration in this way is essential, to ensure that all actors are informed, engaged and prepared to take ownership.

5 The majority of stakeholders were unaware of an existing take-back infrastructure for façade reuse. Despite clients/developers recognising their influence on material recovery routes, they rarely expressed motivations to apply their influence in support of reuse. In order to increase the available stock of recovered components, clients will need to better support the supply-chain with the necessary finance and reasonable timescales at the refurbishment/demolition stage, to avoid a future limited supply of recovered products. More examples of reuse in practice through demonstration projects would help to identify the economic feasibility of different recovery scenarios, based on logistical costs and savings from avoiding sourcing primary materials and energy-intensive production processes. Greater realisation of the benefits of reuse or high-value recycling, would provide motivation for the supply-chain to develop new business models and the necessary supporting infrastructure and logistics for recovered products to be fed back into the most appropriate stream, in a manner that provides incentives for all relevant stakeholders. All recovery routes must continue to be investigated in order to avoid settling for the easier, but potentially less environmentally friendly option.

6 In the absence of a functioning reuse market, well-considered government regulation and/or revisions to certification schemes to evaluate whole-life environmental impacts more holistically, are required. These have the potential to divert the client brief away from the status quo of prioritising the operational performance of products, utilising virgin material resources and low-grade material recycling.

CRediT authorship contribution statement

Rebecca Hartwell: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization, Project administration. **Sebastian Macmillan:** Methodology, Supervision, Writing – review & editing. **Mauro Overend:** Conceptualization, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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