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Toward Circular Supply Chains for Flat Glass: Challenges of Transforming to More Energy-Efficient Solutions

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Abstract: Even if flat glass is 100% recyclable, only 1% is currently handled in circular or closed-loop supply chains (CLSCs) in Sweden. This has an unnecessary environmental impact, indicating not only the potential for more energy-efficient solutions but also the challenges that need to be understood. The purpose of this article is to increase the knowledge of challenges in applying different types of more or less energy-efficient CLSCs for flat glass. Through a literature review, an overview of CLSC types, together with challenges in different areas, is provided. The CLSC types and challenges are corroborated in a flat glass context, including focus groups and expert interviews. Four CLSC types—two CLSCs based on remanufacturing, one on reconditioning, and one on reuse—are identified. A framework provides implications for both literature and practice. It contains 19 challenges—such as lack of large-scale actors, lack of material knowledge, lack of knowledge of customers' behavior, lack of promotion of flat glass CLSCs at many levels in society—in terms of both legislation and cost—and lack of business models—structured in four areas—material characteristics and quality, inefficient logistics systems, demand and supply, and means of control and costs. The least-applied CLSC includes almost every challenge and has a large upscaling potential, indicating the necessity of mitigating challenges. The framework identifies challenges not included in earlier flat glass literature. CLSC types are related to different challenge set-ups and different energy efficiency potentials, leading to expanded CLSC knowledge. One additional implication is that practitioners can identify potential CLSC types and understand their challenges from the perspective of several stakeholders. The participatory research methodology fills a methodological research gap within CLSC literature and provides important insights.

Keywords: circular supply chains; energy efficiency; flat glass; challenges; Sweden; construction waste

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1. Introduction

While supply chains have been described as forward chains to customers, scholars and practitioners have identified the need for implementing reverse supply chains in order to develop concepts such as closed-loop supply chains (henceforth, CLSC) (e.g., [1–3]) or circular supply chains [4]. Technological advancements have shortened the life cycles of products, which leads, in turn, to shortages of natural resources including energy [1]. The disposal of products as waste is a global problem, given growing landfills [5], and deviates from the UN 2030 Sustainable Development Goals. According to the frequently used definition of [6] (p. 10), CLSC is "the design, control and operation of a system to maximize value creation over the entire life cycle of a product with dynamic recovery of value from different types and volumes of returns over time." The goal of CLSCs is to extend the product life cycle or give it a second life cycle [3,7]. Driven by many different stakeholders' environmental sustainability requirements, e.g., [8], the application of CLSCs can lead to increased competitiveness [9,10]. CLSCs have the potential to reduce the usage of virgin raw materials, energy, and emissions [4].

Knowledge in the field of energy-efficient supply chain management and environmental sustainability is evolving [4]. Several knowledge gaps are identified, and a greater understanding of the link between supply chain energy efficiency and the circular economy as a relevant extension of current research has been suggested [11]. The need for research supporting CLSC managerial decision-making, e.g., understanding challenges, was identified in systematic literature reviews (SLRs) [12,13] and supported in the quest for more research on CLSC practices [7]. To concretize this, present research provides little managerial guidance on, for example, how to use existing knowledge and experiences when scaling up present CLSCs, identifying suitable loops for different materials, how to manage collaboration among stakeholders or transferring knowledge from a CLSC to another material. There is also a call for empirically grounded studies that address real-world problems in the area of CLSCs, as most studies are based on modeling approaches according to the SLRs of [8,12]. This gap can be reduced by applying participatory research methods and by more systematically involving practitioners [14]. The interaction and empirical input of practitioners who have experienced the problem investigated are necessary to gain in-depth information and understanding of a complex problem situation [15].

CLSCs are context- and material-specific [14,16], requiring industry- and material-specific studies [13,14,17]. This study focuses on CLSCs for flat glass, as this is a material with a very low recycling rate. It is, therefore, a suitable material for illustrating how managerial knowledge can be gained on how to scale up a CLSC, identify suitable loops, and apply the best strategies for taking advantage of knowledge from the CLSCs of other materials. Flat glass appears on the market as windows, doors, or façades [18,19]. Research studies on CLSCs for flat glass are lacking, as illustrated by recent SLRs on CLSCs: no articles mentioning flat glass were found [13,14,17]. The world market for flat glass is large, at 266 billion US dollars in 2020 [18]. This study was conducted in Sweden, a country with well-developed CLSCs for many materials. The selected geographic area also answers the call for European studies, as a majority of CLSC studies are Asian [12]. Flat glass appears as waste from demolition, at which point a large share is crushed with other materials and deposited in landfills [20], a practice that indicates a lack of knowledge of existing types of CLSCs for flat glass. This is illustrated by the up to 20,000 tons of flat glass that end up in landfills annually, meaning that only 1% of it is recycled in Sweden [21]. This is unnecessary as, theoretically, glass is fully recyclable an infinite number of times, as demonstrated by the 98% recycling rate for packaging glass [21]. Recycled flat glass not only conserves non-renewable natural material resources but also reduces energy required for melting and, thereby, decreases CO_2 emissions [22]. The low recycling rate for flat glass indicates that this material poses more significant or additional challenges than other materials—challenges that obstruct managerial decision-making and the application of a CLSC. *The purpose of this article is, therefore, to increase the knowledge of challenges in applying different types of more or less energy-efficient CLSCs for flat glass.*

By addressing the outlined research gaps in the methodology, an exploratory, qualitative, and participatory research approach, including several stakeholders, is applied. The contributions to the literature include a framework, including increased knowledge of existing CLSC types for the seldom-studied flat glass, together with the challenges that appear in these CLSCs. These are important points of departure for increasing energy efficiency and reducing the unnecessary addition of a fully recyclable material to landfills. The managerial contributions include the provision of practical guidance, with a focus on challenges, to support development toward more energy-efficient CLSCs for flat glass. A method for expanding CLSC knowledge for additional materials that addresses these methodological gaps is suggested. The remainder of the paper is organized as follows. A literature review identifies different types of CLSCs and categorizes the related challenges in various areas. The methods section details the steps in empirical data collection and analysis. Thereafter, the empirical findings from two focus groups and expert interviews are presented. The analysis develops the framework of challenges for different types of

CLSCs for flat glass. Finally, conclusions, contributions, limitations, and further research are presented.

2. Literature Review

The overall aim of this literature review is to provide a basis of the already existing knowledge on different CLSC types (Section 2.1) and the challenges in different areas. Four overall areas of challenges have been identified in the literature: those related to material characteristics and quality in Section 2.2, to inefficient logistics systems in Section 2.3, to demand and supply in Section 2.4, and to means of control and costs in Section 2.5. The literature search was conducted in the search engines OneSearch, Scopus, and Google Scholar, and was guided by keywords such as "reverse logistics", "closed-loop supply chain", "recycl*", and "recovery" (inspired by the SLR by [23], in combination with "glass". Further confirming the research gap, very few flat glass-specific scientific articles were found. Therefore, also "grey literature" in the shape of reports was included.

2.1. Different CLSC Types

A CLSC is more complex than a forward SC; it involves more actors who are potentially independent [6]. In the general CLSC literature, different CLSC types—characterized by, e.g., repairing, reusing, remanufacturing, and recycling—can be applied [8,24,25]. In their review of 254 CLSC articles, no fewer than thirteen different CLSC types, with the manufacturer, the distributor, and the customer as actors in the forward SC and the collector as the first actor in the reverse SC [12]. One example of a small CLSC type including few actors is the reuse of a product. Reconditioning is another CLSC type that involves a larger CLSC, going back to assembly, while remanufacturing (a third potential CLSC type) involves a CLSC going back to the manufacturer. Recycling is an even larger CLSC type, including more actors and going back before manufacturing to find an alternative to the raw material [12,24].

The types of CLSCs and the actors involved are only briefly noted in the flat glass-specific studies. Two CLSC types regarding re-melting include pre-consumer (CLSC1) and post-consumer (CLSC2) cullets (crushed glass), wherein the re-melting of pre-consumer cullets is mostly developed [20,22]. Melting cullets saves energy as compared to melting raw material; each additional 10% of cullets in melting results in energy savings of 3% due to the possibility to lower the melting temperature [22]. When it comes to describing actors, they note that CLSCs need collectors to reach the glass recycler. In a technically complex process, other materials are removed and different cullet sizes are produced, which are then transported to flat glass manufacturers, container glass manufacturers, or even glass wool manufacturers. In their study of a third CLSC type (CLSC3), reuse of intact windows, it was revealed that post-consumer windows are collected from demolition sites by a collector and transported back to window manufacturers, where they are disassembled and cleaned. Glass is assembled into new windows by adding new customized frames and a second layer to comply with higher energy efficiency standards, after which it is painted and tested before being transported to and installed in a new building [26]. The authors indicate that activities such as manufacturing and installation are outsourced, but they do not specify to whom. It is obvious that activities, rather than actors, are the focus in flat glass-specific literature. In terms of the lack of knowledge about actors, it is assumed that flat glass recycling is not primarily a consumer issue; therefore, here the first actor in the reverse SC is called the user, in line with the terminology in [25]. The user can be described as a supplier who possesses assets. The remaining actors are labeled as in the general CLSC literature.

2.2. Challenges Regarding Material Characteristics and Quality

The material's characteristics provide demands on the CLSC and are a central challenge in designing the CLSC [16]. Due to the lack of life cycle history, the quality of returned products varies due to, e.g., the environment in which they are used and user behavior [27].

The starting point for flat glass material characteristics is that it is particularly recyclable [21]. However, few products are designed for circularity [7]. Recycling is complicated by the fact that glass products contain several other materials. Windows consist of flat glass sheets, attached to wood or metal frames [26]. Multiple glass sheets improve thermal insulation. Windows can be treated, coated, and laminated to get the desired properties. Coating entails the attachment of a metal film to the flat glass, to reduce solar impact. Lamination entails that layers of potentially different types of flat glass are "glued" together [20]. Product characteristics are related to high-quality requirements of raw material [19], common for process industries [28]. As a result, the use of different quality classes is common when glass is breached into cullets. These classes differ, from pre-consumer cullets derived from breakage in glass production versus post-consumer cullets [22], to class A (zero contaminated cullets, mainly from pre-consumer glass), class B (contaminated cullets, such as from lamination, that can be used for glass wool), and class C (contaminated cullets that are not possible to remelt and therefore commonly end up in landfills). Contamination can cause damage, standstills, or production losses in glass production, as well as glass discoloration [19]. Therefore, trust must be built between suppliers of class A cullets and glass manufacturers [22]. The use of different cullet classifications is one example of a challenge due to lack of standardization. In line with this, the unstandardized sorting and marking practices for different glass qualities are described [21]. The challenges identified regarding material characteristics and quality are:

- High contamination risk for flat glass manufacturers;
- Windows are not designed for recycling—challenging to safely disassemble glass;
- Lack of flat glass material knowledge;
- Difficult to safely identify, mark, and sort different glass qualities.

2.3. Challenges Regarding Inefficient Logistics Systems

Inefficient logistics systems are described as another challenge for CLSCs [29]. The challenge of avoiding loops that are too large to achieve environmental, societal, and economic benefits is also identified [25]; for instance, long transport distances and geographically distant storage must be avoided for the sake of efficiency [30]. How the logistical flow is structured, means of transportation used, and location of storage are all challenges during the design of an efficient CLSC [14]. Construction, including demolishing [31] and renovation, is one of the most resource-consuming sectors, with significant material flows and high recycling improvement potentials [32]. On construction sites, both forward and reverse flows are unstructured, which often leads to inefficiency and sub-optimization [33]. Furthermore, regenerate, retain, and restore are put forward as important circular economy attributes in the construction supply chain [34]. Logistics service providers are the most natural choice of collector, since they possess relevant knowledge and can overcome the challenge of too-small volumes and gain economies of scale; thus, they can handle this activity efficiently [9].

Inefficient logistics systems—also called take-back infrastructure and logistics [19]—also exist for CLSCs for flat glass, where one challenge is the lack of cullet storage space [21]. CLSCs are characterized by demolished and refurbished properties neighboring each other and being similar to each other in terms of volume and size of windows, as this enabled a reuse CLSC (as well as a "purchase-to-order" situation) were studied by [26]. It is thought that such a situation is uncommon, as the real world instead consists of geographically and chronologically separated demolition (supply) and new construction (demand). This indicates another challenge: a need for consolidation and storage of windows, involving a "purchase-to-stock" situation. More specifically, a customer order decoupling point—i.e., the point that separates decisions concerning customer orders characterized by uncertainty from those customized by certainty [35]—must be established. The challenges identified regarding inefficient logistics systems are:

- Lack of logistics and recycling knowledge;
- Lack of storage space for windows to enable consolidation;

- Lack of storage space for cullets to enable consolidation;
- Complex international transports are required.

2.4. Challenges Regarding Demand and Supply

Uncertain volume of returned products can be challenging [27,28,36]. Demand for recycled products is often particularly uncertain [36,37], as a recycled or remanufactured product can be seen as new to customers [37]. Furthermore, demand is expected to differ across contexts [14]. Uncertain demand related to both time and volume were described [6]. Demand is affected by uncertain customer behavior that is difficult to capture and assess [14,31], which is a function of perceived environmental and price benefits combined with perceived quality [28] and risk sacrifices [36]. This is another aspect that makes CLSC management more challenging than that of forward supply chains [36]. The flat glass literature raises a central challenge regarding supply: the lack of availability of class A cullets [19,20]. If the manufacturer lacks visibility and predictability in terms of the supply of product returns, it is hard to efficiently plan the resources needed [26].

Uncertainties lead to unstable information flows [38]; thus, they must be identified and controlled in order to efficiently manage the CLSC. In construction, logistics information flows are generally unstructured and characterized by low information accuracy [32]. Uncertain timing and difficulties in predicting and forecasting (e.g., when returned products will be available) are challenges discussed by [10,36]. No flat glass-specific studies mention challenges related to information flows. The challenge identified regarding demand and supply is:

- Lack of supply of class A cullets.

2.5. Challenges Regarding Means of Control and Costs

Several studies discuss the close relationship between the means of control, such as regulation and subsidies, and the CLSC costs. For those looking to encourage demand, the lack of means of control in stimulating regulations, together with an absence of support through subsidies to make recycled products more attractive economically, was pointed out [8]. Additionally, challenges in construction in terms of regulations and high costs are shown [39]. Some challenges have been identified concerning means of control for flat glass CLSCs in particular, such as lack of promoting or supportive legislation [20]. However, recently improved EU legislation that forces demolishers to sort, handle, and transport glass separately, so that the option to combine waste glass with other demolition waste is no longer available, is discussed [21]. The lack of subsidies and the low taxes on landfills are also challenging, as higher taxes would function as an incentive to more recycling.

Furthermore, high costs are commonly reported as a challenge for flat glass CLSCs, as transportation to the recycler and then to the flat glass manufacturer is assessed as one-third of the total recycling cost [22]. However, this was questioned by [21]. Their recycling pilot study showed that a demolition project of 10–15 tonnes is enough to be profitable; instead, varying recycling costs are identified as a challenge. In addition, dependence on local enthusiasts is proposed [21]: without them, perceptions of high recycling costs easily spread and discourage CLSC initiatives. One challenge in post-consumer flat glass recycling was even found to be the perceived—not actual—cost disadvantage related to logistical costs in remanufacturing glass cullets [19]. The challenges identified regarding means of control and costs are:

- Low compliance with the new EU legislation;
- Lack of cost knowledge and business cases.

An overview of all challenges identified in the literature review can be found in Table 2 (Section 5.3).

3. Methods

To increase understanding, a qualitative research approach was applied [15]. Methodological research gaps further guided the chosen approach to data collection. This resulted in an approach characterized by participatory research methods in a Swedish setting. The overall method approach and its steps are illustrated in Figure 1.

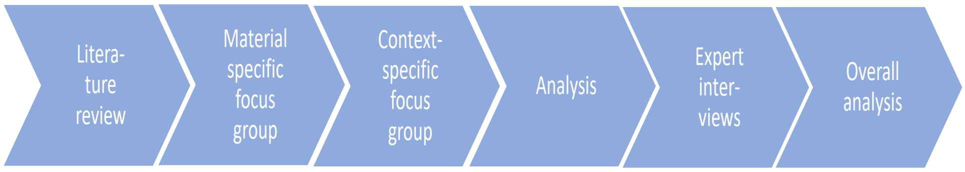

Figure 1. Overview of steps in method.

Focus groups were conducted digitally (due to the COVID-19 pandemic) to collect insights from different stakeholders, applying a participatory research approach and more systematically involving practitioners. Two groups of stakeholders were identified as particularly relevant to involve: the material-specific glass stakeholders and the context-specific construction stakeholders.

The material-specific glass stakeholders were expected to have a deep knowledge of the material studied, potential and existing CLSCs, actors involved as well as deeper understanding of challenges. These stakeholders were expected to first: identify actors potentially involved in CLSCs for flat glass, resulting in some clarifications and language adaptation of the three identified CLSC types and actors from literature Section 2.1 (applying a deductive approach). Second, to validate and complement the CLSC challenges identified in literature Sections 2.2–2.5 as well as to offer a deeper understanding of them. The participants were recruited through convenience sampling [15] based on their long-term knowledge and collaboration with actors in the forward and reverse flat glass SC, and a snowball sampling which reduces the risk of omitting important respondents.

The context-specific construction stakeholders were also relevant to include. The context-specific focus group was held with construction stakeholders, similarly encouraged by [31,32], to understand central actors and decision-making at demolition/construction sites in a deductive manner based upon literature in Section 2.1, as well as to discuss and illustrate CLSC challenges identified in the literature review Sections 2.2 and 2.5 and revealed in the glass stakeholders' focus group. Furthermore, also these stakeholders are likely to assist in identifying experts. The sampling of participants for this focus group was carried out through close dialogue with the municipal department of business development using their existing local/regional construction network as a point of departure, with the aim of having several types of construction actors represented. Consequently, an indirect form of convenience sampling known as snowball sampling was used. The sampling for both focus groups was thus non-probability sampling [15]. A probing approach was utilized, starting with open questions about CLSC types and challenges, then suggesting the ones identified in literature and finally specifically probing those that were seldom mentioned, even if they were central to the general CLSC literature, such as challenges in the information flow.

Each focus group lasted approximately 90 min; they were recorded, notes were taken by at least two researchers and were later consolidated. The notes were then sent to the participants for respondent validation in order to increase the validity. The participants in the focus groups are shown in Table 1. Construction companies build new buildings, while property companies rent out buildings; the latter represent CLSC users. All participants have the potential to increase flat glass recycling rates.

Table 1. Participants in the empirical data collection (abbreviations for traceability).

	Type of Organization	Participant/Job Title
Material-specific/Glass stakeholders' focus group	Research institute	Flat glass project leader (RIPL)
	University	Professor in glass design (UPGD)
Context-specific/Construction stakeholders' focus group	Construction company 1	Project leader (CC1PL) Project responsible (CC1PR)
	Construction company 2	CEO (CC2CEO)
	Property company 1	Project responsible/owner (PC1PR)
	Property company 2	Project leader renovation (PC2PL) Property management responsible (PC2MR)
	Architectural company	CEO/architect (ACCEO)
	Municipality business development department	Business developer (MBD) Head of market and business development (MBH)
Expert interviews	Municipality-owned waste management company	Business developer circular economy (WMCBD)
	Glass material/recycling consulting firm	Owner/consultant (RCC)
	Window glass industry organization	CEO/glass expert (IOCEO)

Experts in recycling flat glass were interviewed, as shown in Table 1, to increase the reliability of the study, providing a third step of data collection involving triangulation [15]. The experts each have at least 20 years of experience in different positions with responsibilities related to glass recycling and complemented the local/regional representation of construction stakeholders with a national representation. This sampling was also a convenience, non-probability, snowball sampling [15], guided by recommendations from focus group participants. The experts were digitally interviewed individually for approximately 60 min each. Also in the expert interviews, a deductive, probing approach similar to in the focus groups were applied. Notes were taken by two researchers and consolidated, after which they were sent to the participants for respondent validation. All data collection was conducted in Swedish and translated into English. The participants demonstrated a broad understanding of the questions. This increased the validity of the study [15].

4. Empirical Findings

4.1. Glass Stakeholders' Focus Group

In terms of CLSC types and actors, there is a dearth of Swedish glass manufacturers and dedicated flat glass collectors. The same manufacturers found in the forward SC produce flat glass sheets, based on raw material and partially on a CLSC involved remanufactured pre-consumer cullets from window manufacturers. Window manufacturers engage in cutting, laminating, and assembling windows. Distributors can be glaciers, but this actor is not always included in the CLSC. When it comes to collectors in Sweden, only three actors were described: one handles cullets from car windows to produce glass wool; the second handles cullets from flat glass to produce household glass; and the third handles cullets from flat glass to recycle flat glass abroad. The quality classification using classes A, B, and C for cullets was applied.

A deeper understanding was gained of the challenge of high-quality requirements and the related fear of contamination in glass manufacturing. Even a slight contamination can result in a week's standstill in manufacturing. RIPL (see job title in Table 1) stated that it is difficult to transport post-consumer cullets back to flat glass manufacturers, due to the risk of metal contamination from containers; instead, big bags are used, which preserves the small scale of the recycling, which is a challenge. The risk of contamination means that sorting of flat glass must be carefully performed and thus remain labor-intensive, which is another challenge. As no tools are currently available concerning traceability of the product quality, the only trusted way is to take the cullets back from the window manufacturer to the same flat glass manufacturer who delivered it. *"One suggestion is a CLSC that recycles the glass to manufacturers less vulnerable to contaminations, into colored or patterned glass"* (UPGD).

4.2. Construction Stakeholders' Focus Group

The second focus group confirmed many of the findings identified in the literature review, such as the recycling rate being close to zero. Addressing the lack of CLSC, CC1PL explained that one local actor handles recycled construction material, including windows, on a very small scale; here, a reuse CLSC of intact windows is identified. CC1PR argued, *"even if we would want to purchase recycled windows, there is no large-scale actor on the market."* CC1PL, CC1PR, and CC2CEO described how demolishers, potentially those lacking flat glass-related knowledge, have an important role as decision-makers in recycling for larger demolition projects, while demolition on a smaller scale is handled by the construction companies themselves. The CLSC including the re-assembly of intact windows [26] was not recognized.

A deeper understanding was gained of the challenge of lack of storage space. *"The local recycler's storage would probably drown in windows if used on a larger scale,"* said CC1PR. Sorting is carried out by the actor who performs the demolishing. The process is complex, unstandardized, and lacking in traceability; therefore, it is knowledge-demanding and takes too long to be performed by expensive carpenters. Furthermore, sorting requires space that is seldom prioritized on small construction/demolition sites (PC2PL). Participants also confirmed lack of knowledge on how windows can be recycled. PC2MR stated: *"there may be damages on single windows among thousands in demolition; still, we discard all of them."* The architect ACCEO explained that they can increase the amount of recycling in new construction, *"which we have done, on a small scale, by including recycled glass in complementary buildings. However, windows are not designed for recycling."*

Few challenges related to uncertainties in demand and supply were identified. One explanation for this can be the current low recycling rate. MBD elaborated on the uncertainty in demand: *"decision-making about recycling is often carried out in layman boards of condominiums, with an unclear composition of behavior and knowledge."* A lack of marketplaces was mentioned by MBH—a challenge related to information on timing and volume. MBD also identified a lack of predictable business models as a challenge. PC1PR described challenges related to costs: "*Every time recycling is discussed, it includes which actor should carry the costs.*"

4.3. Expert Interviews

The expert interviews confirmed the CLSC types (except for the reassembly of intact windows CLSC) in Sweden. IOCEO confirmed the pre-consumer CLSC involving class A cullets at window manufacturers being taken back to the glass manufacturer on dedicated/adapted vehicles as return transports after delivering glass sheets. All other CLSC types contain small volumes or merely project volumes, as in remanufacturing.

The challenges identified in the literature and in the focus groups were supplemented with deeper insights. None of the experts problematized long transportation distances, but as there are no Swedish flat glass manufacturers, *"international transports, crossing different borders, have their own challenges"* (RCC). All experts mentioned contamination risks as having a large impact, resulting in the safe recycling only of pre-consumer cullets. RCC suggested that lack of knowledge is compounded by a lack of contacts and networks, which is valid for several actors. Deeper insights were also offered into the cause of the cost challenge: *"The municipalities that I know calculate in an unfair way, so recycling is much more expensive than landfills"* (WMCBD). All actors confirmed the lack of legislation promoting recycling: "*The EU legislation demanding separation of glass has been valid for over a year, but it has low compliance.*" WMCBD stated "*The industry organization of waste management could be* *more involved in recycling. However, glass comes low on their agenda."* IOCEO commented on the lack of legislation: "*recycling is not very high on our action plan either; we are lagging behind, and we have a responsibility.*"

Only a few of the challenges were disputed by the experts, such as the challenge of a lack of recycling actors: "There are recycling actors in both Europe and Sweden. Or do construction stakeholders just think about local reuse of intact windows and not about remanufacturing?" (WMCBD). Relying on local enthusiasts was another challenge that was disputed: "If CLSCs should function on a higher system level, local enthusiasts are not enough and not sustainable. Legislation and financial incentives are much better" (WMCBD). IOSCEO added that more than one actor taking action is needed: "we need to collaborate; no one is against recycling."

5. Results and Discussion

The analysis begins in Section 5.1 by summarizing the identified CLSC types for flat glass and their energy efficiency potentials. Then, Section 5.2 elaborates on the four areas of challenges identified in the literature and complements them with a detailed understanding of empirically identified flat glass-specific challenges. Next, Section 5.3 ties the study together and fulfills the purpose by elaborating a framework of the identified flat glass-specific challenges in different types of CLSCs.

5.1. CLSC Types, Actors Involved and Energy Efficiency Potential

Unlike some general models of CLSCs [12], in a flat glass CLSC, the manufacturer is represented by two different actors: the flat glass manufacturer and the window manufacturer. This is analogous to part manufacturer and product manufacturer [25]. In the reverse flow, the first actor is outsourced by the property company (e.g., a demolisher); the addition of this actor means that the activities and challenges identified the literature as occurring at the user can appear/occur with the demolisher, which influences the distribution of responsibility and of the potential actions among actors. Altogether, this inclusion entails the involvement of more actors and more complex flat glass CLSCs than seen in general CLSCs.

Four CLSC types for flat glass were identified (see Figure 2). This is significantly lower than in general CLSC literature, where the recent extensive SLR identified 13 types of CLSC [12]. CLSC1 involves the flow of pre-consumer class A cullets [20,22]; it was described in the glass stakeholders' focus group. Here, CLSC1 is termed 'remanufacturing', in line with the logic of [25]. The glass manufacturer and the window manufacturer are the actors involved in this CLSC. CLSC2 is the larger remanufacturing CLSC of post-consumer class A cullets [20,22]; this CLSC has the most included actors, going all the way forward to the collector and all the way back to the flat glass manufacturer, and it also has the largest potential for increase [21]. Due to the number of activities needed in CLSC3 [25], this CLSC is termed 'reconditioning' instead of reuse here, in line with the suggestions of [12]. However, this CLSC was not confirmed empirically. CLSC4, here termed 'reuse', represents a local loop of intact post-consumer windows without any re-assembly; it includes the demolisher, the collector, a local distributor, and a new user. CLSC4 was not identified in the literature but was described in the construction stakeholders' focus group. The landfill/glass wool flows [21] are linear and therefore are not CLSCs.

In line with the recommendation on the power of inner circles—i.e., avoiding loops that are too large to achieve environmental, societal, and economic benefits [25]—CLSC1 and CLSC4 ought to be prioritized. However, in current practice, the lack of class A cullets [19,20] and the matched availability and demand of certain windows limit the use of these CLSCs, creating a need for all types of CLSCs. Furthermore, the window manufacturer seems to play a critical role, as it is included in three of the four CLSCs and also could potentially handle two different products (both class A cullets and intact windows).

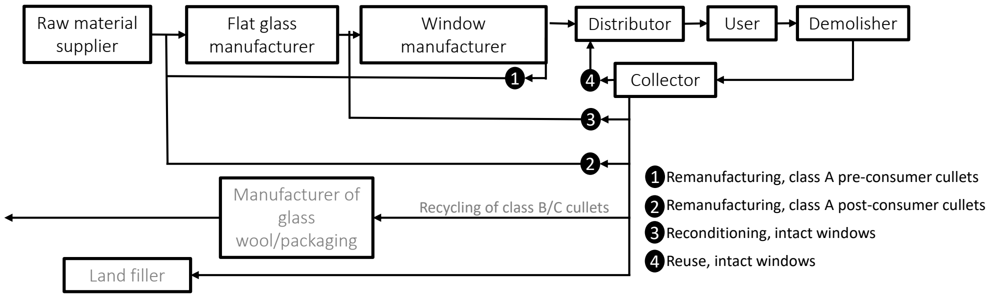

Figure 2. The four CLSCs identified for flat glass.

All four loops represent better solutions from an environmental and energy efficiency perspective as compared to the forward supply chain. However, there are differences between the loops when it comes to energy efficiency. Melting a high share of cullets at flat glass manufacturers means a more energy-efficient solution as compared to melting virgin raw material [22], which is valid for CLSC1 and 2. Furthermore, as no Swedish flat glass manufacturers have been identified, these loops mean longer transports. Therefore, it is critical that also the transport is carried out in an energy-efficient manner. As no re-melting is carried out in the local CLSC4, this is likely to be the most energy-efficient loop.

5.2. CLSC Challenges for Flat Glass

On an overall level, all the challenges identified in the literature were present except for the dependence on local enthusiasts, which was empirically disputed.

Unique material characteristics and the high contamination risk [19,22] are central challenges to CLSCs for flat glass. CLSCs are further challenged by the fact that windows are not designed for recycling [7] and discussed by construction stakeholders, which complicates safe disassembly and influences practitioners' reluctance toward recycling. Earlier studies have shown that lack of material knowledge results in inefficient sorting and marking practices [21]. The challenge of uncertain product quality [22,27,28] was considered important in both focus groups; this issue was clarified as the lack of standardized marking of different flat glass qualities and the challenge of tracing the properties of different glass types. In addition to this, no producer responsibility exists for flat glass. The high contamination risk means that material characteristics is a root cause of other challenges.

Challenges related to inefficient logistics systems [19,29] were identified both in the literature—e.g., the lack of cullet storage space [21]—and in empiry—e.g., intact windows need on-site storage space. Lack of space for on-site sorting by the demolisher was identified by construction stakeholders. This challenge physically complicates sorting and, in combination with its labor-intensity and its execution by non-recycling professions (such as demolishers and carpenters), makes it de-prioritized. This is another example of challenges generating new challenges. Moreover, earlier studies have shown that lack of logistics knowledge combined with lack of recycling knowledge results in inefficient collection [9]. The empiry further support this: knowledge is lacking on a societal level, due to an unawareness of what happens to the glass, but also on a more local level, due to the lack of expertise networks. Construction stakeholders expanded on this, as local recycling actors can only operate on a small scale. The glass stakeholders added that transportation can currently only handle small volumes in big bags, as standard containers are neither adapted to nor clean enough for glass, which preserves small-scale logistics systems. For both windows and cullets, storage space and locations are needed to enable consolidation and large-scale logistics systems. Other challenges identified in the literature, such as longer transport distances [30] and selecting appropriate means of transport [14], were also mentioned in the empirical data, since international transports are required, and adapted vehicles are currently only used between the flat glass manufacturer and the window manufacturer. Lack of knowledge and of recognition of large-scale CLSC actors was identified in the empirical data as a CLSC challenge that was not found in the literature.

This challenge was mentioned by most construction stakeholders; however, the experts disagreed, as such actors exist abroad. This indicates the potential for professionalized recycling actors or collectors, whose entrance into the Swedish context can mitigate such challenges—which can solve other challenges, such as the lack of class A cullets.

Due to the current low recycling rate of flat glass, several challenges related to demand and supply, such as uncertainty in timing and volume [28,35], could not be confirmed either empirically or in the flat glass-specific literature. Related challenges, in the form of unstructured information flows with low information accuracy, are mentioned in the construction CLSC literature [33]. It can be expected that more such challenges appear when the recycling rate increases [6]. The uncertainty of customer behavior [14,31] was confirmed in the construction stakeholders' focus group, revealing a reluctance to "offend" or underestimate the customer; this makes recycling risky and also indicates a challenge in encouraging customers to demand recycled windows. The lack of marketplaces, which was empirically identified by construction stakeholders, indicates existing uncertainties and no easy ways to find information about supply and demand for recycled windows, facades, or cullets. A lack of supply was identified in the literature as a lack of class A cullets [20] and was empirically identified as a contamination-avoiding strategy, as almost only pre-consumption cullets are recycled.

An absence of means of control in terms of regulations [20] and subsidies [8] promoting recycling were confirmed by construction stakeholders, who did not ask for more regulations than the existing ones in construction. This was accompanied by a discussion around which authority on what level should act to promote recycling: the state, the municipality, the local waste management company, the industry organization, or other authorities. Hence, no clear "leading" actor exists to take responsibility for further development. In contrast, the experts indicated low compliance with the new, more recycling-stimulating EU regulation. The high costs [22,38], varying costs [20], and profitability opportunities [21] indicate another challenge that was viewed differently by different actors. In light of unknown costs, decision-makers are guided by assumptions [19,21], while the experts revealed that established, simplified ways of calculating costs do not favor recycling. The construction stakeholders confirmed the little knowledge on costs, further encouraging information from studies that focus on assessing the "business case" of CLSCs. Finally, the lack of predictable business models—who should pay whom for what?—was described by construction stakeholders but was not found in the literature; this is another challenge that prevents larger-scale recycling.

5.3. Challenges in Applying Different Types of CLSC for Flat Glass

The analysis in Section 5.2 results in the identification of 19 flat glass-specific challenges that form the basis for the framework presented in Table 2. The sources generating each challenge are also presented. The challenges that were identified in literature (general or flat glass-specific literature) are written in bold font. The challenges that were identified in the three different empirical studies—glass stakeholders focus group, construction stakeholders focus group, expert interviews—are written in italic font. The many challenges identified in this category confirm the need to involve empirical studies rather than applying the common modelling approach [8,12]. In particular, it is obvious that the CSFG generated many flat glass-specific insights. Those challenges that are identified both in literature and confirmed empirically are written in bold italic font. Furthermore, the framework outlines which challenges occur in the applied types of CLSCs, thereby showing the set-up of challenges in each type of CLSC.

Table 2. A framework for flat glass-specific challenges.

Challenge Area	Flat Glass-Specific Challenges	Sources (Literature/Empiry)	In CLSC		
Material characteristics and quality	***High contamination risk for flat glass manufacturers***	Flat glass literature/glass stakeholders focus group, expert interviews	1	2	
	Windows are not designed for recycling—challenging to safely disassemble glass	Flat glass literature/construction stakeholders focus group		2	
	Lack of flat glass material knowledge	Flat glass literature/construction stakeholders focus group	1	2	
	Difficult to safely identify, mark, and sort different glass qualities	Flat glass literature/glass stakeholders focus group, construction stakeholders focus group	1	2	
Inefficient logistics systems	*Lack of space for sorting on already-crowded demolition sites*	Construction stakeholders focus group		2	
	Labor-intense sorting gets de-prioritized	Construction stakeholders focus group		2	
	Lack of logistics and recycling knowledge	General literature/construction stakeholders focus group, expert interviews		2	
	Lack of adapted large-scale containers	Construction stakeholders focus group		2	
	Lack of storage space for windows to enable consolidation	Flat glass literature/construction stakeholders focus group			4
	Lack of storage space for cullets to enable consolidation	Flat glass literature		2	
	Complex international transports are required	General literature/expert interviews	1	2	
	A general lack of professionalized, large-scale actors/collectors	Construction stakeholders focus group		2	
Demand and supply	*Lack of knowledge about customer behavior and demand*	Construction stakeholders focus group		2	
	Lack of marketplaces/unavailable information flows	Construction stakeholders focus group		2	
	Lack of supply of class A cullets	Flat glass literature/construction stakeholders focus group	1	2	
Means of control and cost	*No leading actor for promoting CLSC*	Expert interviews		2	
	Low compliance with the new EU legislation	Flat glass literature/expert interviews		2	
	Lack of cost knowledge and business cases	Flat glass literature/construction stakeholders focus group, expert interviews		2	
	Lack of business models	Construction stakeholders focus group		2	

CLSC1 is practiced by glass manufacturers who prioritize smaller and safer volumes from pre-consumer CLSCs over post-consumer CLSCs. CLSC1 faces challenges but has succeeded in mitigating these challenges. Challenges related to material characteristics, the high contamination risk [19,22], actors without flat glass knowledge, and lack of marking practices are mitigated, and the same actors as in the forward supply chain are involved in a very "closed" CLSC. Furthermore, due to the involvement of few actors and thereby few locations, the logistics system becomes less complex, and several logistics-related challenges can be avoided. As no Swedish flat glass manufacturer exists, international transports are required. Without any volume assessments, refs [20,22] suggest that this

CLSC is well-developed. Still, a lack of such pre-consumer or class A cullets prevails [20]. It may be the case that CLSC1 is already fully explored and that the potential for increased recycling is limited.

To address the lack of class A cullets, the far more challenging CLSC2 needs to be upscaled. CLSC2 entails a set-up of almost every challenge identified, which makes its current low recycling volumes unsurprising. As CLSC2 currently only contains project volumes, the challenges are not mitigated. However, CLSC1 has managed to mitigate flat glass-related challenges, and it should provide lessons to learn and solutions to transfer to CLSC2. As can be seen in Figure 1, many more actors need to be involved in CLSC2, which makes the logistics system more complex. Furthermore, as collaboration among all stakeholders is preparatory for achieving sustainable CLSC, CLSC2 is more challenging simply as it includes most actors. Challenges related to demand and supply as well as to control, promotion, and cost also appear in CLSC2. It is a challenge in itself that the further upscaling of CLSCs, and hence increased recycling rates for flat glass, must take place in the challenging CLSC2. This loop, however, shows energy saving potentials.

CLSC4 has a small set-up of challenges, as it avoids challenges related to material characteristics. As the window remains intact, identifying different flat glass qualities becomes simplified. CLSC4 also includes a logistics challenge in the lack of window storage space, as intact windows are bulky. Demand and supply challenges are mitigated by not promising an assortment to customers, but simply offering available windows, often in a "batch" of similar windows from demolition. Supply is simplified, as the local recycling actor is known and information flows are simple. However, it is difficult to learn about all the relevant challenges, as CLSC4 is only established at a small, local scale.

6. Conclusions, Contributions, Limitations, and Further Research

This study set out to increase the knowledge of challenges in applying different types of more or less energy-efficient CLSCs for flat glass, as well as increasing understanding around the low recycling rates for flat glass in Sweden. The framework developed, as presented in Figure 2, shows a large number of existing challenges related to different types of CLSCs for flat glass. One interesting note is that most challenges identified in the empirical study are related to the design of the CLSC, such as lack of large-scale actors, lack of material knowledge, lack of knowledge of customers' behavior, lack of promotion of flat glass CLSCs at many levels in society—in terms of both legislation and cost—and lack of business models. Furthermore, in contrast to the current study, the literature focuses more on control challenges, such as uncertainties in timing and volume—challenges that the actors in the empirical study have not yet experienced.

This study expands the recent CLSC design study [12] to a flat glass context. The unique material characteristics of flat glass, as well as the inherent high contamination risk, currently outweigh its excellent recyclability and energy-saving potentials, entailing challenges that generate additional challenges in other areas. The study, hence, has responded to the call for understanding the link between supply chain energy efficiency and a circular economy [11]. Challenges related to lack of material, logistics, recycling, demand, and cost knowledge prevail in every area, entailing an overall challenge in the lack of professionalized actors found in CLSC2 with the largest upscaling and energy efficiency potential. The increased knowledge of challenges related to different types of CLSCs revealed that the more-frequently applied CLSC1 had very few challenges, while CLSC2 was characterized by almost every challenge identified.

The selection of a methodology inspired by participatory research methods increases the potential managerial contribution of this study as it addresses the need for research that supports CLSC decision-making as called for [13]. The categorization of challenges into areas such as material characteristics and quality, inefficient logistics systems, demand and supply, and means of control and costs offers a structure to the challenges that need to be mitigated and reveals how different challenges relate to each other. The overview of different types of applied CLSCs supports practitioners in understanding, identifying, and developing different types of CLSCs. Furthermore, connecting the CLSC types to different set-ups of challenges, as presented in Table 2, also supports managerial decision-making, for example, by shining a light on the need to develop business models and to secure the increased need for storage space to decrease potential resistance with the implementation of CLSC2. This new knowledge provides a point of departure for enabling a higher recycling rate of flat glass, with potentials to improve environmental sustainability and energy efficiency.

The framework of challenges specific to flat glass is a contribution to the CLSC literature—in particular, it expands the knowledge of CLSC challenges into an area in which few scientific articles have been published. The empirical study involving different stakeholders and experts adds several challenges, related primarily to logistics systems and to demand and supply, to the earlier material focus of the flat glass literature. It also illustrates how knowledge from studies of other materials provides insights into operation and control, while new challenges related to design (which might be more material-dependent) also exist.

The study also offers methodological contributions emanating from the research gaps identified by [8,12] calling for real-world, empirically grounded studies and suggesting participatory research methods and more systematically involved practitioners [14]. It was seen that the data-collecting parts of the study (material-specific and context-specific focus groups and expert interviews) were important for generating material- and context-specific knowledge about the challenges of applying different types of CLSCs. This methodological approach is suggested for expanding CLSC knowledge to additional materials.

A limitation of the study can be seen as the sampling of respondents in the empirical studies. Sampling was affected by the exploratory, qualitative research design and a lack of material-specific literature. Therefore, no attempts to generalize the findings are made. The identification of areas for future research is another contribution of this study. Studies furthering this work are recommended in order to mitigate identified challenges. For example, the lack of professionalism in collection, identified as a core challenge in CLSC2, might be mitigated by broader studies. Knowledge transfer regarding different challenges for different types of CLSCs and their potential solutions from CLSCs with other materials, which are addressed by recent EU regulations on the sorting of construction waste (such as plastic and metals), could be incorporated. Similar CLSCs for flat glass in other geographic settings could also be incorporated to provide an even deeper understanding of how the geographic context can influence the challenges that might arise in different CLSCs. In both cases, actors on different levels—including states, municipalities, and potential industry organizations—need to collaborate, in line with the suggestions of [28], to address the challenges identified and, thereby, enable an increase in the use of CLSCs. Few logistics-related challenges were found in the flat glass literature, while several were identified empirically. As for any type of supply chain, developing efficient logistics systems for CLSCs of flat glass requires careful logistics considerations to create value and to avoid overly high costs. Costs can be reduced by using contemporary technologies, such as automation and digitalization of logistics processes as outlined by [2]. In addition, it would be interesting to proceed with further studies of flat glass in the field, such as test beds or investigations of how contemporary digitalization tools can enable marketplaces for the supply and demand for flat glass. Business models for circularity, which is another path of deeper research on flat glass, were suggested by [26]. Finally, participants in the construction stakeholders' focus group indicated a desire for accurate cost-related information, potentially identified as business cases spread broadly among stakeholders; this is another potential avenue for further research.

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