

Recommendations for Implementing Circular Economy in Construction: Direct Reuse of Steel Structures

Sivaganesh SELVARAJ^a, and Tak-Ming CHAN^{b,*}

Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University,
Kowloon, Hong Kong.

Emails: ^asivaganesh.selvaraj@polyu.edu.hk; ^btak-ming.chan@polyu.edu.hk

*corresponding author Phone: +852 2766 6013; Fax: +852 2334 6389

Abstract

The principles of circular economy (CE) were well defined long ago, but adapting it to the construction sector is a long-winded and complicated task as several stakeholders are involved. This review article comprehensively analysed the existing technologies and managerial ideas. The barriers that impede implementing CE in construction are summarised and solutions to overcome them are suggested with practical aspects. An alternative direct reuse circular economy approach is proposed to further reduce embodied carbon emissions. An improved design concept called Design for Deconstruction and Reuse (DfDR) is suggested with the integration of interlocking connections for enabling the direct reuse of structural elements and increasing productivity. A strategy for practically integrating the various features of the direct reuse concept for implementing the circular economy in construction is proposed. More importantly, this article emphasised how steel structures can be a suitable solution for achieving a circular economy in construction. A potential take-back business model with a sustainable (self-driven) circularity mechanism is also suggested.

Keywords: Construction Sector; Circular Economy; Steel Structures; Design for Deconstruction and Reuse.

31 **Highlights**

- 32 • The barriers to circularity in construction are summarised in this review article.
- 33 • An alternative “Direct Reuse Circular Economy Approach” is suggested.
- 34 • It technically emphasises how steel structures can be a solution to circularity and reuse
35 concepts.
- 36 • A new strategy for integrating the features of the construction to create a circular economy is
37 proposed.
- 38 • A potential take-back business model with a self-driven circularity mechanism is suggested.

39

40 **Abbreviations:**

41	BIM	- Building Information Modelling
42	CE	- Circular Economy
43	DfD	- Design for Deconstruction
44	DfD/A	- Design for Deconstruction / Assembly
45	DfDR	- Design for Deconstruction and Reuse
46	DfMA	- Design for Manufacturing and Assembly
47	ECCS	- European Convention for Constructional Steelwork
48	EMF	- Ellen MacArthur Foundation
49	GRO	- Global Resources Outlook
50	ISO	- International Organization for Standardization
51	LETI	- London Energy Transformation Initiative
52	MiC	- Modular Integrated Construction
53	OECD	- Organisation for Economic Co-operation and Development
54	PROGRESS	- Provisions for Greater Reuse of Steel Structures
55	WGBC	- World Green Building Council

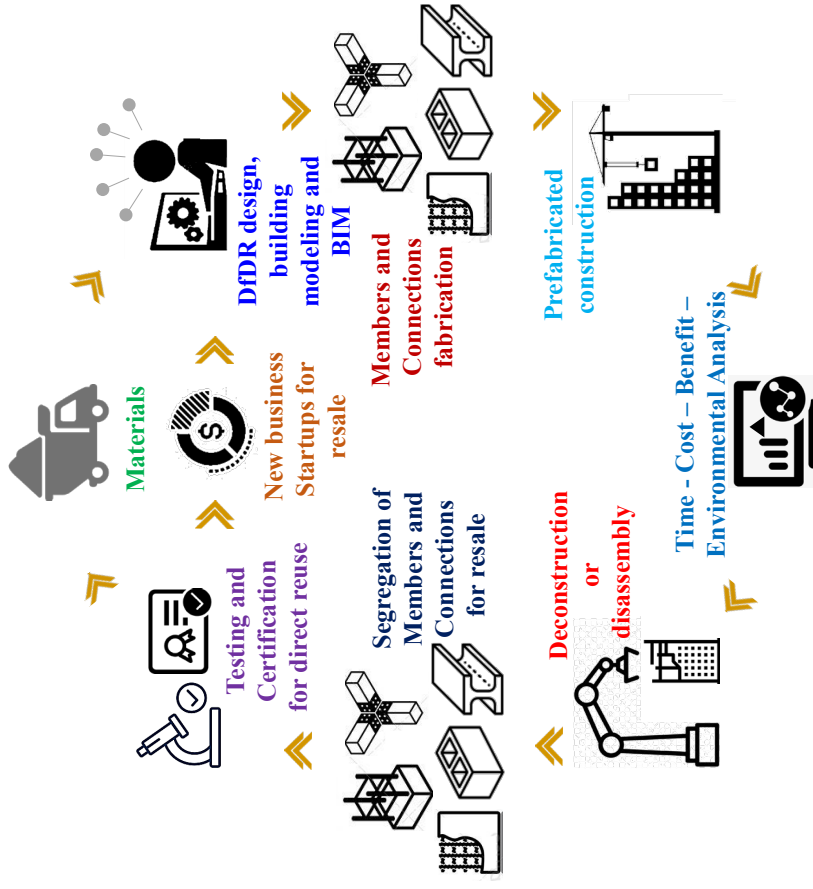
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57 **1. Introduction: Why Circular Economy?**

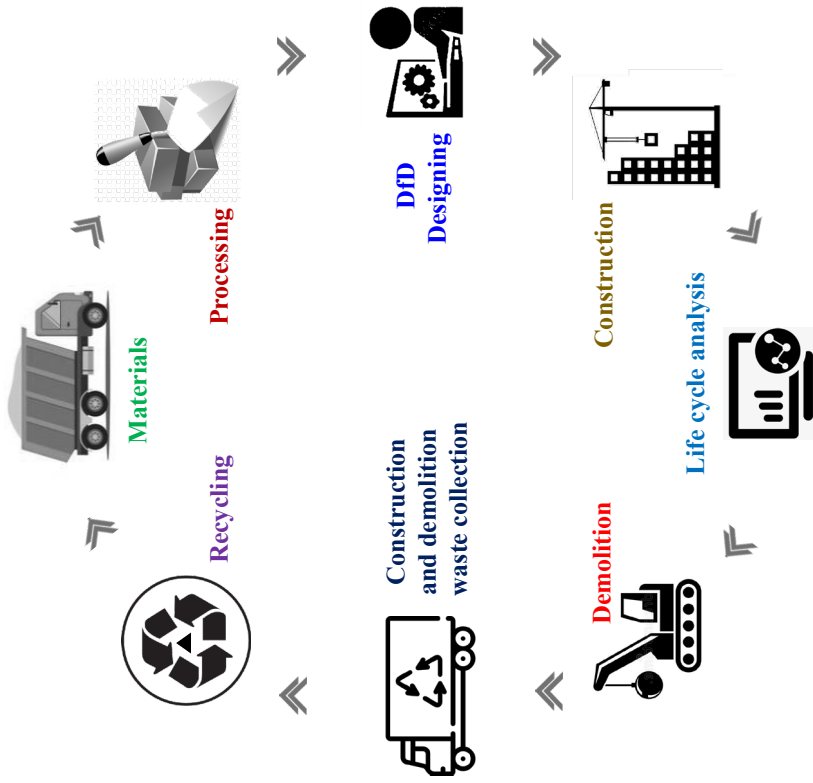
58 The construction industry takes the maximum share of 59% from natural resource extraction
59 (including metals, non-metallic minerals, gravel, sand, and crushed rock) and this will increase
60 significantly in the future due to infrastructure developments. The impact of the construction industry
61 on global energy-related carbon emission is 11% [1-2], in particular, producing cement and
62 associated activities contribute as much as 7-8% of global carbon pollution [3-4]. Therefore, it is a
63 high priority that the natural resource extraction for construction should be slashed down by

64 developing alternative technologies such as direct reuse in construction to reduce the unsustainable
65 pressure on the environment. Governments and non-government institutions all over the world are
66 taking several initiatives in construction activities towards controlling exploitation by setting a “zero-
67 emission goal by mid-century” and developing low-carbon cement [3 and 5]. The policy documents
68 of the various countries [6] and associations including the World Green Building Council (WGBC)
69 also set a goal that “by 2030, all new buildings, infrastructure, and renovations will have at least 40%
70 less embodied carbon with significant upfront carbon reduction and by 2050, new buildings,
71 infrastructure, and renovations will have net-zero embodied carbon, and all buildings, including
72 existing buildings” [2]. In addition, the latest report by the London Energy Transformation Initiative
73 (LETI) [7] indicates that 50% of carbon reduction in the upfront carbon cycle (at the production and
74 manufacturing stage) is achievable through a fundamental change in the construction members'
75 development and process stage. Considering all the above, this review summarises the alternative
76 approach and way forward to reduce upfront carbon emissions from construction activities.

77 One solution to achieve upfront carbon reduction in the construction sector is to transit to a circular
78 economy [8-9] from the present linear approach (Take-Make-Waste method). The circular economy
79 is an evolved version of the recycle, reuse, and reduce concept as shown in Fig. 1a, where the natural
80 resource extraction will be reduced. The term circular economy in general “restorative and
81 regenerative by design and aims to keep products, components, and materials at their highest utility
82 and value at all times, distinguishing between technical and biological cycles” as defined by the Ellen
83 MacArthur Foundation (EMF) [9-12]. Although the Ellen Mac-Arthur Foundation pioneered the
84 circular economy concept for the construction sector and has published several reports since its
85 launch in 2010 to increase the awareness of the circular economy, several researchers and industries
86 have indicated that there are several technical and managerial barriers to implementation [13-14].
87 The potential benefits of the existing Design for Deconstruction (DfD) concept which aims to reuse
88 the structural members after their service life are not fully perceived by the industries due to the non-
89 availability of technologies for deconstruction over demolition.



(b) Direct Reuse Circular Economy Approach with alternative Design for Deconstruction and Reuse (DfDR)



(a) Traditional Circular Economy Approach with Design for Deconstruction (DfD)

92 Fig. 1. Circular Economy in Construction: (a) Traditional approach recommended in the existing
93 research articles and standards [9-12 and 19-30]; (b) Newly suggested Direct Reuse Circular
94 Economy Approach
95 The latest report from the Netherlands Government and IStructE [15-17] shows that the process of
96 building deconstruction is still based on cutting or breaking the structural members due to the
97 monolithic nature of the connections. The cutting and breaking of the structural member during
98 deconstruction make the reconstruction or reuse process more difficult as the structural member
99 requires repair work. Further, the cutting and breaking work creates more waste and delays the
100 process, eventually leading to higher costs. This indicates that the existing DfD technologies do not
101 create a closed-loop system for resources (enables reuse within the system), therefore, there is a need
102 for new technology and design concepts to reuse the structural members. This review article
103 discusses why the existing circular economy concept is not implemented, research gaps that need to
104 be filled, and how the structural members can be directly reused in new construction for a reduction
105 in carbon emission and a potential increase in construction productivity.

106 First, this paper discusses the challenges and barriers to implementing the circular economy in
107 construction, then provides potential solutions to the barriers in a practical method by addressing the
108 questions that were raised in the industrial survey [18]. The technical proposals, ideas, and
109 management strategies in the existing literature for implementing the circular economy in
110 construction are analysed (Fig. 1a) and a potential plan of action consisting of the improved circular
111 economy in construction with a direct reuse concept is proposed (Fig. 1b). After analysing the
112 barriers, a new strategy for practically integrating the various features of the direct reuse concept for
113 implementing the circular economy in the construction is proposed. A summary of the structural
114 design steps and checks that are required for the reuse of the building components is provided.
115 Overall, this paper emphasises the need for deconstruction over demolition and direct reuse of
116 structural steel members from old construction rather than recycling thus the upfront carbon footprint
117 is reduced. A novel structural design concept called Design for Deconstruction and Reuse (DfDR)
118 which is an improved version of DfD is proposed in this study. Technically, the DfDR is an updated

119 design method for structural components with interlocking connections that can be demounted after
120 a service life and reused based on the remaining design strength.

121 **2. Challenges and Barriers to Implementing the Circular Economy in Construction**

122 In general, the barriers to developing and implementing the circular economy in construction can be
123 classified into two categories, (i) management and (ii) engineering. To be generic, the first category
124 includes perceiving the risk in specifying reused structural members and the lack of reuse markets
125 and supply chains. The engineering barriers to reuse in construction are not only technical but also
126 the confidence in the contractors and builders on the reliability of the reused structural members.
127 Based on the conclusions from the number of studies [9-12 and 19-30], the barriers to be overcome
128 for implementing the circular economy in construction can be compiled as follows:

129 *Barrier 1 (Engineering): Preparing the used structural members for reuse may be expensive:*
130 Deconstruction of the building and preparing for relocated reuse might be expensive with the current
131 construction technologies. However, the reuse of the structural members at the same site with the
132 same or modified configuration will be cheaper than the relocated reuse. The non-availability of the
133 standard guidelines based on target-cost-investment analysis (or life cycle cost-benefit analysis) for
134 each structural material is an important barrier in business model creation [31].

135 *Barrier 2 (Engineering): Delay in deconstruction due to the complexity and irreversible nature of*
136 *structural connections:* The connections between the structural members in the existing construction
137 methods including the precast, prefabricated (with grouted concrete) and modular integrated
138 construction (MiC) structures (fully or partially welded) are mostly monolithic, therefore, it will not
139 be possible to disassemble or deconstruct the structural members for reuse [15-16]. Further, the delay
140 in disassembly will favour demolition over deconstruction and reuse, even if it is reused, the cost of
141 refurbishment will be higher than the original material [32].

142 *Barrier 3 (Engineering): Ambiguity on strength of the used structural members:* The structure is
143 deconstructed after its service life; thus, the structural members may have deteriorated (corroded,

144 reduction in sectional area, cracks, deformities, and damage), therefore, the contractors or the owners
145 sometimes both hesitant to use the reclaimed structural members due to the ambiguity on the strength
146 [33]. This uncertainty of the strength of the material leads to difficulty in assessing the whole
147 structure for insurance protection. Therefore, there is a need for non-destructive testing standards of
148 practice and certification schemes for the reclaimed structural members.

149 *Barrier 4 (Management): Uncertainty of circular economy business model for construction:* The
150 factors involved in the typical business models such as demand, supply, market running mechanism,
151 profit, coordination, integration, guidance, education, awareness, and information on reuse products
152 are lacking for developing a circular economy business model. The uncertainty about cost
153 assessment for the take-back (price to be paid by the scrap trader to the owner for the reclaimed
154 products) and resale of structural members (price to be paid by the contractor to the scrap trader for
155 reuse construction) is still an enduring problem [34-35]. Due to this market uncertainty, the
156 construction industries are ambivalent about investing in new projects designed with deconstruction
157 and reuse possibilities such as Design for Deconstruction (DfD), Design for
158 Deconstruction/Assembly (DfD/A), and Design for Manufacture and Assembly (DfMA). Some
159 companies in the Netherlands adopt the Design, Build, Maintain, and Remove (DBMR) concept and
160 reuse their structural members (store them in their yards and reuse them back) made of composite
161 and timber materials for new construction. However, the deconstruction technologies of the
162 composite steel structures are still based on cutting works and lasted for a few months (more than 2)
163 for a 5400 square meter building. This long duration of the deconstruction process interrupted the
164 traffic as well [36-37].

165 More importantly, coordination and integration between the stakeholders of the construction sector
166 are missing due to the following reasons and causing business uncertainty; (i) case 1 - how to
167 calculate the building future and life cost analysis when the structural components are of different
168 age (new floor slab, five years old beams, and twenty years old column) within the same building;

169 (ii) case 2 - who takes the liability when the damage or accident occurs in a mixed reuse environment
170 with structural components from various industries; (iii) in both case 1 and case 2 - how to calculate
171 the insurance premium cost for a new building with the used structural components of different life
172 and quality.

173 *Barrier 5 (Engineering): Lack of design tools and guidance that enables structural components reuse:*

174 The following are the technical questions that should be answered in the form of design specifications

175 Reuse cycles and Overall Structural Stability: For the structural member to be reused there should
176 not be any permanent deformation and the stress level should be well within the elastic limit. Though
177 the above statement related to design is straightforward (design with higher materials safety factor),
178 the key technical question remains, how many times the structural member can be reused?, what is
179 the stress limit that the structural member should be loaded at first use, second use (reuse cycle 1)
180 and so on? and is there a relation between the stress level in the structural members and number of
181 reuse cycles?. The next important thing is the connection tolerance, in the reuse environment
182 structural members are to be reused with different combinations of individual connector elements
183 (connecting different members), and there is a need for adequate tolerance in the connector element
184 dimensions and the effect of tolerance (slip) should be incorporated in the design. Moreover, the
185 design complexity increases while determining the structural stability of the overall building with
186 structural components of different ages.

187 Selection of the materials: As the structural members are expected to be used in many cycles (longer
188 than conventional methods), the durability of the materials should be longer and designed. Most
189 likely the highly durable materials can only be used in the reuse concept. The investment cost is
190 expected to increase owing to the use of highly durable materials, however in the long term due to
191 the reuse cycles, it will be a potential benefit. Therefore, there should be detailed design
192 specifications for the selection of construction materials with respect to the reuse design cycles,
193 climatic conditions, and loading criteria.

194 *Barrier 6 (Management and Engineering): Lack of Principles towards Construction Design*
195 *Sustainability:* The main principle for the reuse of structural members is not well received by the
196 designers and architects as there are many stages of implementation. The various stages of the
197 construction require a different set of design principles for standardisation, systemisation,
198 hierarchical relations between the structural elements, assembly and disassembly sequences,
199 connections, and material choice. The available design principles such as design for deconstruction
200 and assembly (DfD/A), design for manufacturing and assembly (DfMA), and the latest Design, Build,
201 Maintain, and Remove (DBMR) are in a nascent stage and require further improvement [15-17].

202 The above-mentioned barriers or in other words tasks involved in the circular economy are
203 interconnected to each other; therefore, the first task is to determine where to begin for a sustainable
204 circular economy so that closed-loop businesses happen naturally. Hence, the above barriers are
205 summarised in the form of four questions, and the answers are given in detail in the following section.
206 There are also other minor barriers indicated by the industries, and contractors [38-44], however,
207 they are not complicated and can be solved during the process of implementation.

208

209 **3. Potential Solutions for Reducing Upfront Carbon and Enabling Circular Economy in** 210 **Construction**

211 Improved suggestions to the existing principles of circular economy and ideas for overcoming the
212 above-mentioned barriers are given through the answers to the following questions:

213 *Question 1. Where to begin the circular economy for sustainability?*

214 *Question 2. How to integrate the various design and construction features for the direct reuse of*
215 *structural members?*

216 *Question 3. How to integrate the material producer, building contractor, owner, demolition*
217 *contractor, scrap trader, and government agencies to enable a new business model for taking back*
218 *(buy-back - green business model)?*

219 *Question 4. What are the quantifiable benefits of direct reuse strategies for various stakeholders of*
220 *the construction industry to impulse them to adopt a circular economy?*

221 **3.1 Answer to Question 1: Solution for Sustainability in Natural Resources for Construction**

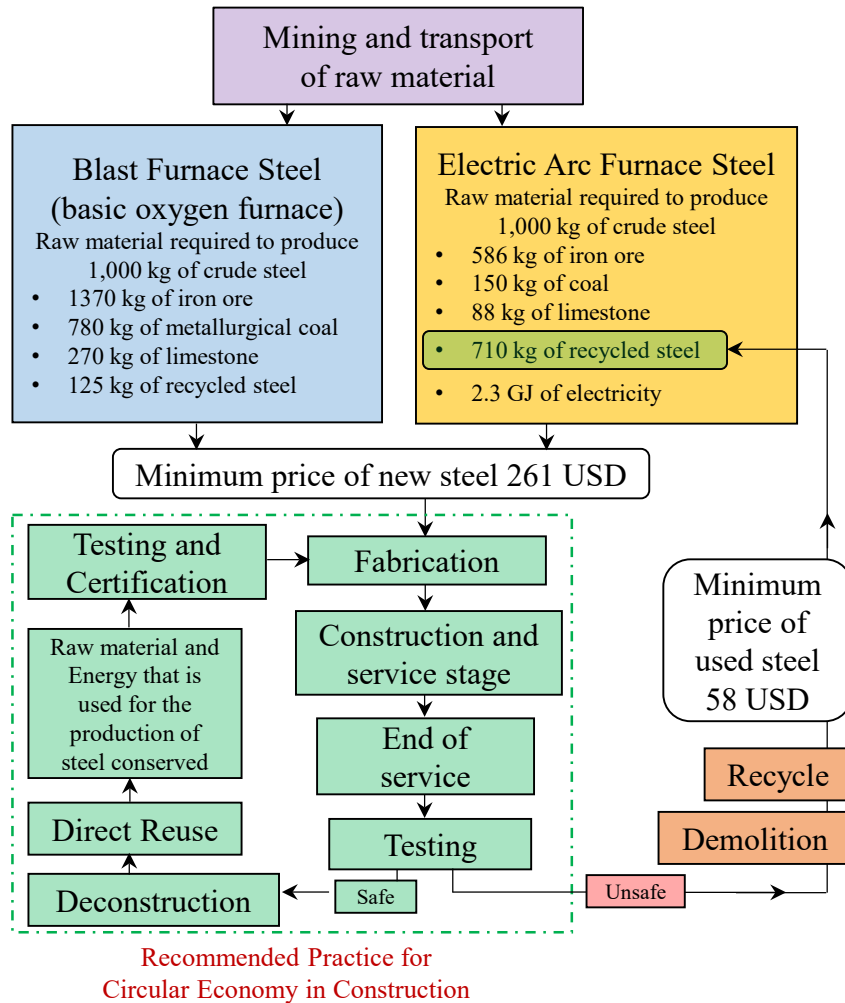
222 The circular economy should begin from the material level. Concentrated material extraction in
223 upper-middle-income countries is alarming due to the demand for building up new infrastructure.
224 Therefore, several countries have tabled resource efficiency policies to control natural resource
225 extraction leading to carbon emission control [45-50]. One of the main policies put up in the
226 inaugural meeting of the G20 resource efficiency dialogue is to implement “Circular Transformation
227 of Industrial Parks (CTIP)”, to prioritise the circular economy principles (such as reuse, recycling,
228 and reducing more) [51]. Although several steps have been taken by the construction industries to
229 reduce material consumption such as the use of high-strength materials [52-54], high-performance
230 structural members [55-58], and increasing the service life of the structure by refurbishment and
231 retrofitting [59-60], the demand for the natural resource is increasing due to global infrastructure
232 need.

233 *Appropriate material for reuse:* Due to the practical difficulty in the reuse of concrete structures
234 including heavyweight, monolithic nature, connection disassembly issues, damage during
235 deconstruction, and transport issues, steel structures are preferred over concrete for reuse applications
236 [61-63]. The latest report suggests that only 20-30% of the concrete components can be reused and
237 it concludes that the cost of reuse of concrete structures is high and it also creates a large amount of
238 waste during deconstruction [64-66]. The Green Guide to Housing Specification [67] also indicates
239 that concrete structures cannot be transported more than 240 kilometres for reuse as they are damage-
240 prone and heavy. On the other hand, the steel structures have been dismantled, re-erected and reused,

241 this trend is significantly increasing post-2000 [68]. The maximum safe and profitable transport
242 distance for steel components is 4000 kilometres which is 10 and 16 times higher compared to brick
243 (400 kilometres) and concrete (240 kilometres) products, respectively. Recently, Rios et al. [69] and
244 Sandin et al. [70] compared the reuse potentials of wood and steel buildings and reported that timber
245 structures are prone to connection damages due to the de-nailing process while the steel connections
246 with bolts are demountable without severe damage. Thus, steel structures are highly preferred or
247 adopted for the latest design principles of circular economy design such as Design for Deconstruction
248 (DfD), Design for Manufacture and Assembly (DfMA), and Design for Disassembly and
249 Adaptability (DfD/A), however, some precautionary tests and design assessments are necessary [71-
250 72].

251 *Direct reuse of structural steel members is more efficient than recycling:* The recycling process of
252 steel consumes energy, and natural resources, and emits carbon pollution. For example, on average,
253 1000 kilograms of crude steel recycling through the electric arc furnace route method requires 586
254 kilograms of iron ore, 150 kilograms of coal, 88 kilograms of limestone, and 710 kilograms of
255 recycled steel with 2.3 Gigajoules of electricity [73]. These raw material and energy requirements
256 will further increase if the conventional blast furnace and basic oxygen furnace methods are used for
257 steel recycling. Therefore, there is a necessity to fundamentally change the material usage pattern to
258 enable the circular economy in construction, which means the material recycling process
259 (reproduction or remanufacturing) shall be changed to direct structural member reuse for a potential
260 increase in productivity, profitability, and reduced material consumption in new construction [74-
261 75]. This process can be termed the “Direct Reuse Circular Economy Approach” and the difference
262 between the traditional circular economy and the newly suggested direct reuse approach is
263 graphically depicted in Fig. 1. The raw material conservation and cost savings comparison recycling
264 and direct reuse approaches for steel are explained in Fig. 2. The practice that can be adopted for
265 direct reuse of steel is also marked in Fig.2. The direct reuse of standardised structural members will
266 reduce the cost for quality testing as the sizes and shapes of the steel structural members will be

267 standardised. A similar proposal for the development of guidelines on the reuse of structural steel
 268 components is suggested by Bartsch et al. [76]. The proposal includes a summary of existing design
 269 guidelines for the reuse of steel, an evaluation scheme for old buildings, testing of old steel
 270 components, geometry measurements, and a design requirement. Finally, Bartsch et al. [76]
 271 concluded that the lack of design guidelines impedes the reuse of steel components.



272 Fig. 2. Raw material conservation and cost savings: Recycle of steel versus direct reuse of steel raw
 273 material requirement calculated from World Steel [73] and Cost of new and used steel (data from
 274 2000 to 2016) calculated from Dunant et al. [77].
 275

276 Moreover, there are potential cost savings in the construction if the steel structural members are
 277 reused directly. This is due to the cost difference between the new steel and the used steel members.
 278 The average price difference between the new and used steel over 16 years (2000 to 2016) is 340
 279 USD, with a standard deviation of 98 USD. The minimum price difference that occurred between
 280 the new and used steel is 203 USD (New steel price of 261 USD minus the used steel price of 58

281 USD equal to 203 USD) [77]. Thereby the difference in price between new and used steel (203 USD)
282 can be a threshold for transportation, storage, reuse quality assessment (non-destructive) cost, and
283 profit for the resellers. The above cost difference between the used steel members and new steel
284 members is explained in Fig. 2, boxed cycle tinted in green colour. If the new construction site (where
285 the deconstructed steel members are to be reused) is located near the storage yard or the existing
286 construction then the cost of relocation is cheaper thereby the cost of construction decreases.

287 Based on the above hypothesis, it can be concluded that steel structures can be a viable option for
288 implementing a circular economy in construction. In addition to the above information, there are
289 also other researchers [30, 78-84] who endorsed that steel is a viable option for achieving
290 sustainability in construction.

291 **3.2 Answer to Question 2: Integrating the Various Design Features for Direct Reuse of** 292 **Structural Members**

293 At first, a modified design principle for deconstruction and direct reuse is introduced namely Design
294 for Deconstruction and Reuse (DfDR), which is an improved version of the DfD, DfMA, DBMR,
295 and DfD/A, but the main difference is the use of new demountable interlocking connections to enable
296 direct reuse of structural members. The DfDR means, designing the structure for deconstruction with
297 simple assemble and disassemble sequences to reduce the construction cost, and time and increase
298 overall productivity. The interlocking connections introduced in the DfDR principle shall be defined
299 as “the module that joins two or more structural members by a simple locking mechanism”. The
300 DfDR will have a minimum number of bolts in the connections and eliminate welding and formwork
301 for concrete casting or grouting. In addition, in the DFDR concept, the interlocking components that
302 connect the structural members can be repaired easily by replacing and retrofitting the interlocking
303 elements. The Design for Manufacturing and Assembly (DfMA) concept can also be integrated with
304 DFDR for developing and fabricating the interlocking connection components. The demountable
305 interlocking connections shall be connected within a short time and reduce the use of large equipment

306 leading to cost and time savings. This reduced use of large equipment will also help to improve the
 307 city environment by controlling noise and air pollution.

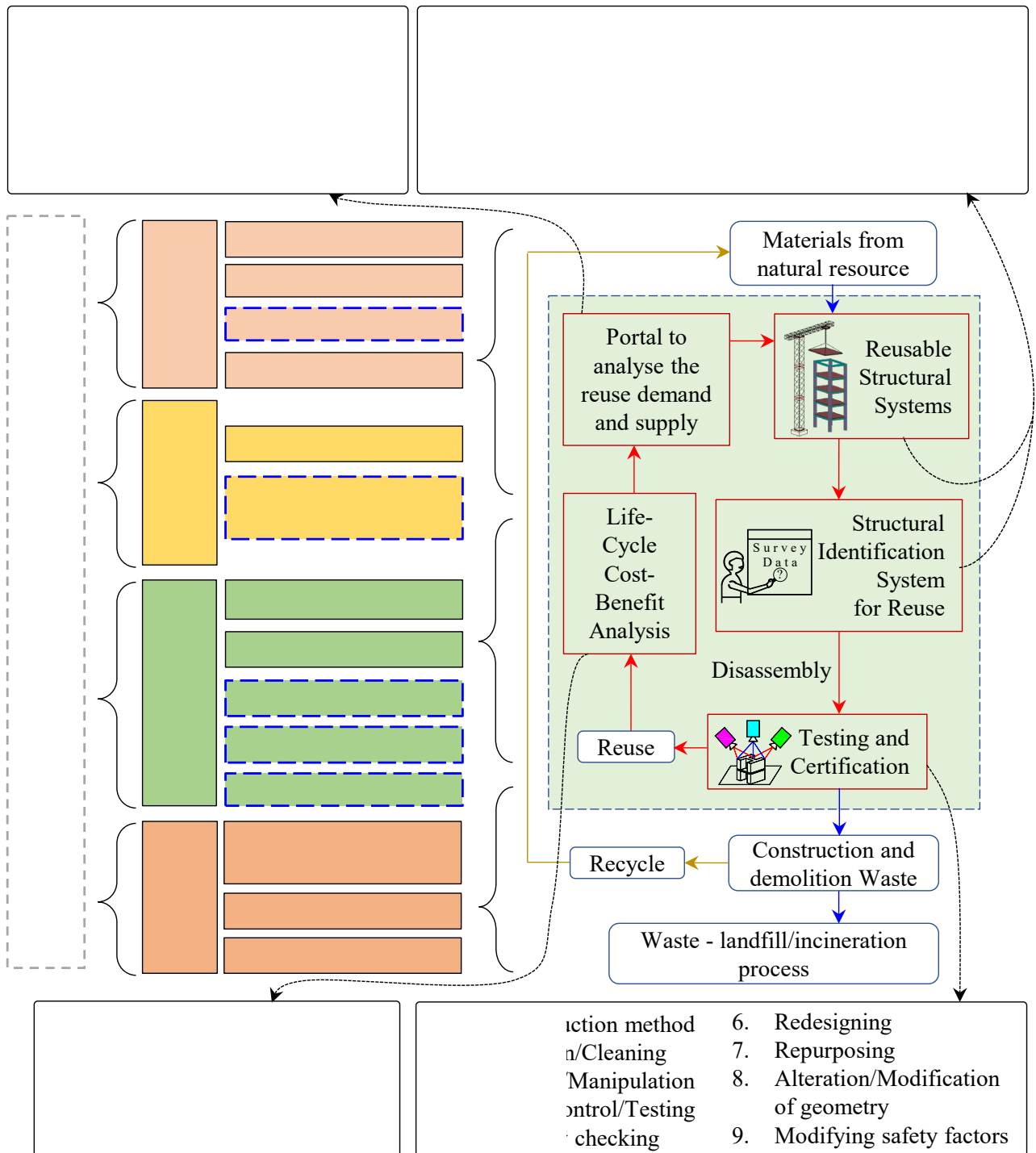


Fig. 3. Overall concept and features of the Direct Reuse Circular Economy; Expected carbon reduction in various stages of the construction [7 and 64]

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 309
 310
 311

312 The overall concept and features of the direct reuse circular economy are shown in Fig. 1b and 3.
313 Figure 3 also depicts the anticipated amount of carbon reduction in the various stages of the
314 construction according to WBCSD [64]. The main five components of the circular economy are
315 tinted in green colour in Fig. 3 with flow paths. Starting from the design of reusable structural systems
316 with DfDR principles, then building construction (assembly), and next identifying the structural
317 members for direct reuse. Structural member identification and separation process with
318 documentation will help to create a take-back market. This identification process should be done at
319 the design process or the existing building site for ease of transportation and integration with the
320 reuse market. After disassembling the structure and before the next use (first reuse), the structural
321 member may be modified or redesigned or altered and tested, and certified, finally, the whole
322 properties of the structural member shall be documented. The modification and redesigning process
323 includes (i) calculation of the remaining strength of the structural member; (ii) determination of a
324 number of potential reuse cycles; and (iii) connection dimension tolerances. These redesign
325 processes with reduced resistance factors are to be repeated until the structural members reach their
326 non-refurbishable stage [85-86].

327 *Design for reuse:* The comprehensive summary of the currently available interlocking connections
328 for steel structure are summarised in [61 and 87]. Though several researchers have proposed,
329 developed, and demonstrated interlocking connections with simple assembling features, the
330 possibility of adopting them for the newly proposed DfDR design principles is analysed. Indeed, the
331 latest state-of-the-art papers also demanded new design guidelines and reliable interlocking
332 connections between modules [30, 88-89]. The design principles that are used for analysing the reuse
333 characteristics of the existing connections are according to the ISO standards for Design for
334 disassembly and adaptability [19]. The definitions of the design principles in ISO 20887:2020 are
335 summarised in Table 1. The analysis for reuse is simple if the connection has the ability to achieve
336 the required qualities in Table 1 (principles of ISO 20887) then it will be noted as qualified otherwise
337 it will be noted as not suitable. Based on the simple interpretation of the authors, it can be concluded

338 that most of the existing connections are not directly reusable due to geometric tolerances or the
 339 members requiring alterations/significant modifications before reuse, which will lead to a higher
 340 price for the reuse components than the new ones. In addition, the report by ECCS indicated that the
 341 design for reuse with current interlocking connections leads to more numbers of bolts and more
 342 weight of steel [71-72]. Therefore, future research must be towards developing directly reusable
 343 structural members and their associated interlocking connection components, similar
 344 recommendations were also given in the recent review articles [30, 88-89]. Further, the potential
 345 strategies that can be used to develop interlocking connections to achieve direct reusability are
 346 compared with the existing strategies in Table 2. As the reuse process in the construction circular
 347 economy is a repeated process until the final service life of the structural member, the integration
 348 between the design, identification, and testing processes shall be planned at the policy-making stage.

349 Table 1. List of Design Principles used for analysing the Direct Reusability of the interlocking connections
 350 proposed in the literature [61 and 87]

Design Principle	Definition according to ISO 20887
Adaptability	Ability to be changed or modified to make it suitable for a particular purpose
Fixity	Ability to modify the connection's boundary conditions
Expandability	The ability of a design or the characteristic of a system to accommodate a substantial change that supports or facilitates the addition of new space, features, capabilities, and capacities
Refurbishability	Ability to restore the aesthetic and functional characteristics of a product, building, or other constructed asset to a condition suitable for continued use
Simplicity	Quality of an assembly or system that is designed to be straightforward, easy to understand, and meet performance requirements with the least amount of customization
Versatility	Ability to accommodate different functions with minor system changes
Convertibility	Ability to accommodate a substantial change(s) in user needs by making modifications
Accessibility	The ability for ease of access to components for disassembly, refurbishment, replacement, or upgrade
Direct reusability of members*	Ability to directly reuse the structural members at the same site or the relocated site
Direct reusability of connections*	Ability to directly reuse the connection component (if any) at the same site or the relocated site

351 Note: * New definitions for the DfDR concept

352 Table 2. Redesign, direct reuse, and building decarbonisation strategy suggestions for future interlocking
 353 connections

Description	Connection Concepts from Existing literature	Suggested Strategies
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Connection components in super-structure	Expendable connections - To be sacrificed or recycled	Interlocking connections – Should be designed for direct reuse
Foundation components (piles and footings)	To be sacrificed or not to be reused or to be recycled	Part of the foundation components like pile caps or pier caps can be recycled.
Structural components	To be reused after alterations	Should be designed for direct reuse
Non-structural components	To be sacrificed or not to be reused or to be recycled	To be sacrificed or not to be reused or to be recycled
Limitations of the geometry	Member dimensions and spacing between them to be standardized - will lead to constrained building design with fewer options for flexibility in the plan.	The interlocking connections should have a geometric tolerance for future adaptability and expansion in the structure, however, within the strength of the connection components.
Material	Regular material grade to be used	No strict limitations on the materials as the connections, and members are to be mostly designed within the elastic limit.
Joints	Bolts and Screws to be used - indeed it recommends using more bolted connections. The suggested reuse design options will increase the number of bolts and screws leading to an increase in the construction time in the case of tall structures.	Minimisation of bolts and screws by using interlocking connections. However, a minimum number of bolts may be used for rigidity.

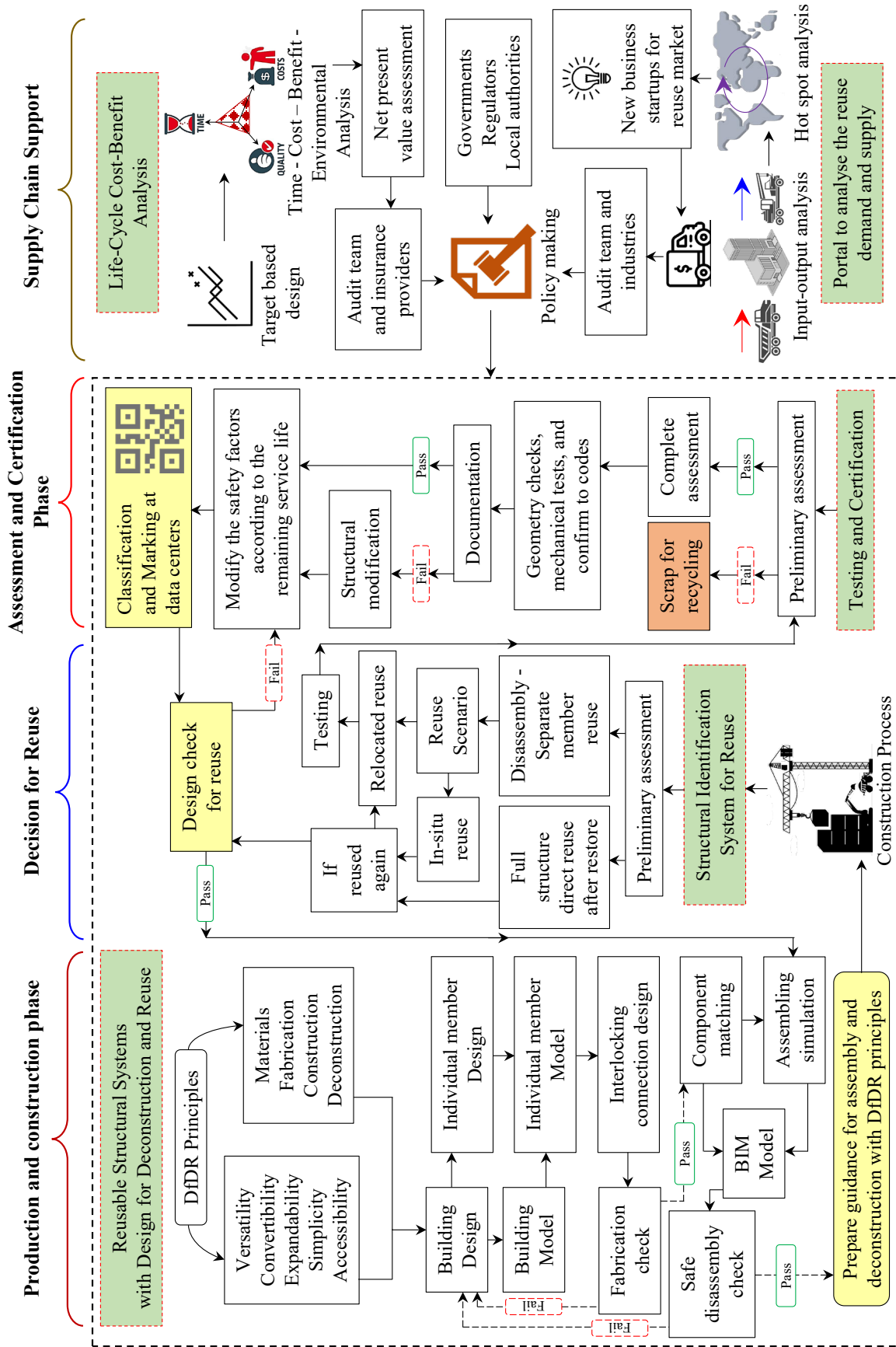
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355 *Potential Integration Strategy for Direct Reuse in Circular Economy:* An integration of different
356 phases of circular economy in construction is shown in Fig. 4 in the form of a flow chat. Practically,
357 the circular economy for construction can be divided into four main phases, such as; (a) Production
358 and construction phase; (b) Decision for reuse; (c) Assessment and Certification Phase; and (d)
359 Supply Chain Support. The first three phases indicated in the dotted line in Fig. 4 are technical, while
360 the fourth phase is management. The integration process of each phases is explained below:

361 *(a) Production and construction phase:* The process starts with material extraction and the design of
362 reusable structural systems with DfDR principles. The DfDR design process involves the selection
363 of material, fabrication, construction, and deconstruction methods to achieve versatility,
364 convertibility, expandability, simplicity, and accessibility. Then the whole building is to be designed
365 by individual member design and modelling, in another way the building model can be used for
366 determining the geometry of the individual member. After the individual member design and
367 building modelling, the interlocking connection should be appropriately designed. In addition to the
368 strength and stiffness criteria, the interlocking connection shall be designed for simple fabrication

369 and assembly sequence. Therefore, the interlocking connection model should be checked by the
370 manufacturer for fabrication feasibility check, if passed, the interlocking connection will be checked
371 for component matching and assembly simulation, and functional characteristics using the building
372 information modelling (BIM) technique, and finally, the connection component will be checked for
373 safe disassembling process. The safe disassembly process is an important step in the interlocking
374 connection design as any drawback in design will lead to the collapse of a whole structure during
375 deconstruction. If the interlocking connection passes the final safe disassembly check, then the whole
376 building design report shall be prepared with guidelines for construction. If the interlocking
377 connection design fails at the fabrication feasibility check or safe disassembly check, then the whole
378 design process from building design should be repeated by iteration process until safety is achieved.

379 *(b) Decision for reuse:* The structural member identification system, testing, and certification
380 processes are interrelated in the implementation of the construction circular economy. When the
381 DfDR-designed building completes its first service life, a preliminary investigation will be conducted
382 to categorise the building's stability and need, to decide whether the full structure can be reused or
383 disassembly is required. If the full building can be reused directly, then it will only be restored and
384 refurbished. For a disassembled separated member reuse, in the case of relocated reuse the structural
385 members will be tested and certified whereas, for the in-situ reuse of structural members, they will
386 only be checked for structural design. In the case of the reuse of reused full building (after the first
387 reuse), it has to be checked for the factor of safety and stability check by technical experts.



388

389

390

Fig. 4. Potential Practical integration strategy between various features for direct reuse in the circular economy

391 *(c) Assessment and Certification Phase:* In the testing and certification process, the deconstructed
392 structural members are first assessed preliminary for visible failure, deformation, and aesthetics. The
393 structural members with visible significant failure shall be directly scrapped, and the other members
394 should be further checked for a comprehensive assessment. The comprehensive assessment process
395 involves non-destructive testing to identify the defects (corroded, reduction in sectional area, cracks,
396 deformities, and damage) [90-92], material characteristics (tensile strengths, yield strengths, and
397 density), geometry imperfections [93-95], and conformity to codes (according to the building
398 standards). Later all the test results shall be documented for reuse and future preliminary assessments.
399 If the test results are not satisfactory, then the structural member should be repaired (altered or
400 strengthened) and the member design has to be changed for the altered geometry perhaps by reducing
401 the reduction factor [76 and 86]. If the testing results are satisfactory and according to the standards,
402 then the structural member design may only be modified for the remaining service life. Finally, the
403 ready-to-reuse deconstructed structural members are to be classified and marked at the data centres
404 for sale and reuse. More detailed discussions about the testing methods and overall framework for
405 the classification of structural members through testing and certification for reuse are available in
406 various documents [71-72]. It should be noted that the testing and classification procedure is
407 location-specific (varies with country) due to the loading and weather conditions. After the
408 classification and design check for reuse, the structural members will be checked again for
409 assembling and component matching with the full structure as shown in the integrated flow chart Fig.
410 4. Further, it should be noted that the cost for the non-destructive quality assessment process can be
411 equalised by a difference of cost between the new steel and reuse steel as depicted in Fig. 2.

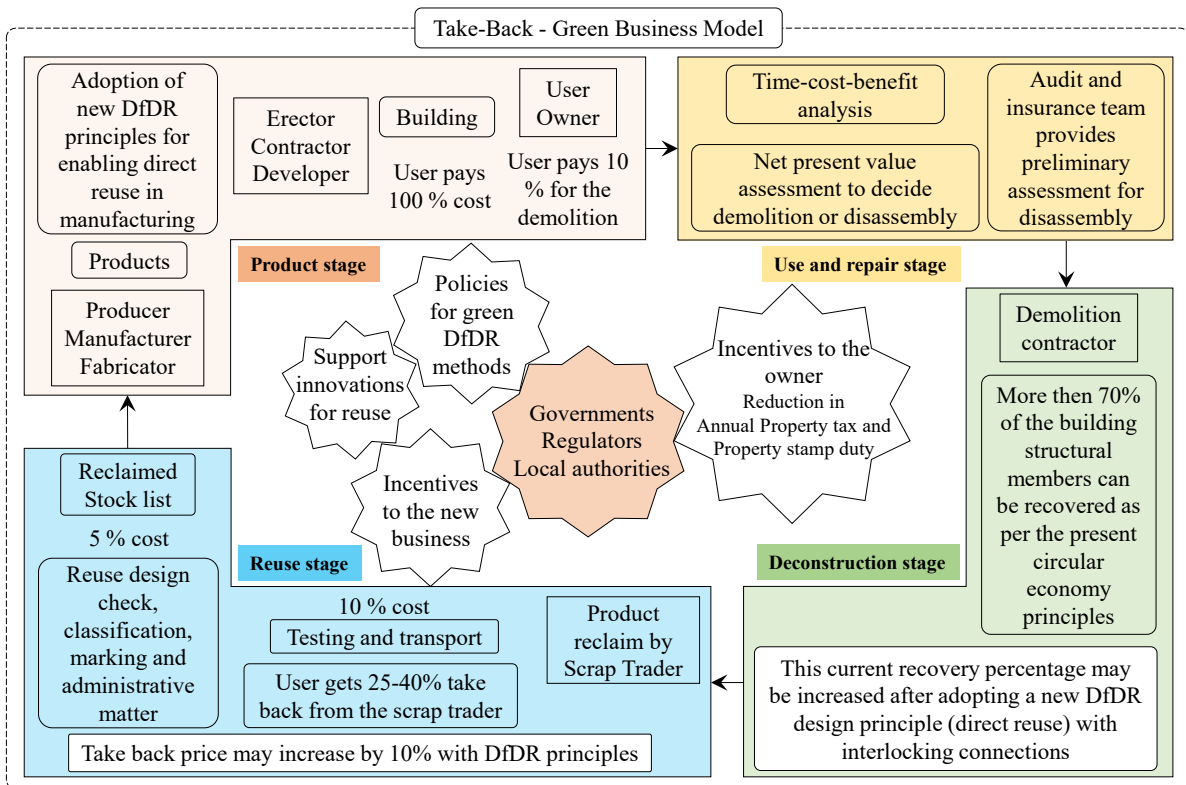
412 The fourth phase “supply chain support” is a support system for enabling the circular economy, it
413 includes various management-related activities and technical surveys. This phase is further explained
414 in the next section with a new business model.

415

416 **3.3 Answer to Question 3: Integrating the Stakeholders for a New Take-Back Business Model**

417 Various researchers over the decade specified that the integration of stakeholders for a reuse business
 418 model is the most complicated task in achieving a circular economy [9-12, 20-29]. This was also a
 419 response to the interview questions put to the contractors, owners, fabricators, engineers, and
 420 architects [38-44]. This section attempts to suggest a holistic approach for the new take-back
 421 business model and the necessary tasks to be carried out to tackle the uncertainties.

422 The possible take-back business model for the reuse of building structural members with the
 423 integration of various stakeholders and a self-driven mechanism is shown in Fig. 5. The main driver
 424 of this take-back business model is the government regulatory policies as shown in the fourth phase
 425 of Fig. 4 and Fig. 5. This circular economy business model loop starts at the product stage where the
 426 building structural members and products are designed using DfDR principles for multiple reuses.
 427 The critical aspect of this stage is convincing the user or owner to use reusable structural members
 428 for construction. This can be done by promotion and mandate schemes by the governments.



429 Fig. 5. A possible practical take-back business model with a sustainable (self-driven) circularity
 430 mechanism
 431

432 After the service life of the building at the used and repaired stage, the audit and insurance team
433 assess the building and suggests suitable disassembly procedure. The audit team also assesses the
434 net present value of the building and suggests the owner for a return on investment for deconstruction.
435 With the current technologies, more than 30% of the structural members can be recovered from the
436 existing building for reuse (according to the case study by ARUP – (WBCSD [64])). This recovery
437 percentage may increase significantly with the use of proposed DfDR principles which will enable
438 the reuse of full member and connecting components whereas the current technology in Europe
439 suggests [36-37, 71-72] sacrificing the connection/joint components. In the deconstruction and reuse
440 stage, new business startups will be created for scrap trading, testing, and certification of reclaimed
441 structural products and marketing the reclaimed products. It is expected that the new business startup
442 may need to invest 55% of the total building cost, 25-40% for payback to the owner/user, 10% for
443 testing and transport, and 5% for administration. The pay-back price to the owner may increase by
444 10% as the quality of the DfDR-designed structural products is expected to be high and they will be
445 designed with an objective of direct reuse. The above investment values are interpreted from the
446 resale and reuse cost of steel buildings by Dunant et al. [77]. After this stage, the
447 producer/manufacturer/fabricator will refurbish the reclaimed structural members for reuse. The
448 refurbishing process includes modification of the structural member, design check, component
449 matching check, and assembly simulation check as shown in Fig. 4.

450 As mentioned earlier, the government has to act as a mediator for the circular economy and facilitate
451 the required policies for making the direct reuse business sustainable. The following are the
452 observations obtained from the various government policies [18, 96-98] which were adopted to
453 encourage business opportunities, the same may be followed for integrating the stakeholders of the
454 construction circular economy; (i) Support the talent demands; (ii) Public-private partnership; (iii)
455 Digital market: The business-to-business exchange (manufacturer - owner - demolisher - reuse seller
456 and logistic manager), between each stakeholder, should be streamlined and accessible to the public
457 to match the demand and supply; (iv) Facilitating the new business by technical analysis at local and

458 global levels; (v) Standards for testing and certification of construction reuse components; (vi)
459 Policies and incentives by the governments: (vii) Continuous governance and assessment. The
460 bottleneck barrier for the circular economy is mainly the cost of the reused product, the government
461 should assess, control and regulate it (act as a mediator). The price of the reused product (reclaimed
462 product cost + deconstruction cost + storage cost + testing cost + logistic cost + profit margin) shall
463 not exceed the price of the new product. Though the path to a circular economy is clear, the barriers
464 can be broken only after several implementation trials and reviewing at a local level.

465

466 **3.4 Answer to Question 4: Quantifying the Benefits of Direct Reuse Strategies to Various** 467 **Stakeholders to Impulse them to Adopt a Circular Economy**

468 The quantity of the benefits of reuse strategies can be assumed equal to the damage done by the
469 existing unfavourable technologies to the environment. The benefits of a circular economy are
470 eventually the number of business and job opportunities but beyond that, it is all for reducing the
471 carbon emission and construction waste. There are two types of carbon emission in the building
472 industry, one is embodied carbon (known as upfront carbon) which is created during the
473 manufacturing (material extraction and fabrication), transportation, construction practices, and waste
474 reprocessing; next is the operational carbon that comes from energy, heat, lighting of the building.
475 The operational carbon varies depending on the building functions (office, hospital, school, and
476 residential) while the embodied carbon is measured to be an average of 11% of overall global carbon
477 emission and 49% of the total carbon emission in the construction industry [2-4]. A significant
478 amount of carbon emission comes from the waste reprocessing stage. A recent case study by ARUP
479 on various types of buildings indicated that the total embodied carbon savings can be in the range of
480 12% to 68% with the reuse technologies [64]. These embodied carbon savings can be achieved at
481 various stages of the construction project, importantly, 50-55% of the expected embodied carbon
482 savings can be done at the product manufacturing stage itself as shown in Fig. 3 according to WBCSD

483 [64]. In addition, the newly suggested interlocking connections may also increase the speed of the
484 construction with reduced equipment usage, this will also reduce the embodied carbon in the
485 construction stage. As the structural members are to be directly reused with the DfDR design
486 approach, the cost for refurbishment or retrofitting will be less contributing to the profit of the owner
487 and contractor. This also reduces the embodied carbon or energy used for
488 maintenance/repair/replacement/refurbishment. The introduction of interlocking connections will
489 help to improve the disassembly progress leading to 5% additional savings in embodied carbon.

490

491 **4. Some Practical Limitations of the Circular Economy in Construction**

492 Though the applicability and adaptability of the circular economy in the construction field seem to
493 be on the verge of a breakthrough, there are some practical limitations. These limitations are due to
494 the service and operational features of the structures.

- 495 1. The large size columns (more than 1 meter in cross-sectional dimension) at the basement level
496 of the apartments, bridge piers, wing walls, and deep piles cannot be designed with structural
497 reusability features as they are not easy to be demounted and relocated.
- 498 2. The interlocking connection components will have a tolerable gap for ease of assembly and
499 disassembly. These gaps can be filled with adhesives (epoxy resin grout) to avoid seepage
500 and later the adhesives can be removed with release agents like spray [99]. However,
501 sometimes these epoxy resins may react in acidic or alkaline conditions, therefore the
502 interlocking connections cannot be provisioned at the water treatment plants, water tanks, oil
503 storage, and thermal power stations.
- 504 3. The reusable structural components when used with the importance of buildings where more
505 people gather may be designed with higher material and load safety factors and it should be
506 monitored. Considering the fabrication difficulties for larger-size interlocking connections

507 for heavy loading in tall structures, the applicability of the reusability may be limited to mid
508 to low-rise structures.

509 In addition to the above limitations, the readers are recommended to read the lessons learnt from the
510 listed case studies in the IStructE document [17] for decision making.

511

512 **5. Conclusions**

513 The World Green Building Council called for immediate action to reduce the embodied carbon in the
514 construction environment by at least 40% by 2050 to avoid the future catastrophic event of climate
515 change. To support the action plan, this review article proposes an alternative direct reuse approach
516 to implement the circular economy in construction. The following are the potential proposals from
517 this article

- 518 1. A new technical design concept named “Design for Deconstruction and Reuse” (DfDR) is
519 suggested as a solution to the technical barrier for facilitating deconstruction over demolition. It
520 highlighted how the upfront carbon can be reduced by introducing the demountable interlocking
521 connections with the DfDR concepts.
- 522 2. It also technically highlighted why steel structures will be more suitable for implementing the
523 circular economy in construction over other materials. The research gaps that impede the reuse
524 of existing buildings are also summarised.
- 525 3. It is suggested that future research should focus on developing directly reusable structural
526 members and their associated interlocking connection components. A concept for the
527 development of each structural connection is also summarised.
- 528 4. A new framework for integrating the various sectors of construction is suggested as a solution to
529 the managerial barriers.
- 530 5. A policy plan for a take-back (reuse) business model is suggested with a self-driven market
531 approach.

532 The proposed “Direct Reuse Circular Economy Approach” with potential practical integration
533 strategy will be tested by the authors through the government-funded research grant titled “Achieving
534 the Circular Economy in Construction through Deconstruction and Reuse Technologies for Steel and
535 Composite Structures” and improved for implementation.

536 **Data Availability Statement**

537 All data, models, and code generated or used during the study appear in the submitted article.

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541

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