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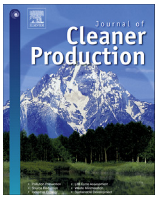

Options to make steel reuse profitable: An analysis of cost and risk distribution across the UK construction value chain

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ABSTRACT

Although steel reuse has been identified as an effective method to reduce the carbon and energy impact of construction, it is in effect only a marginal practice. A detailed analysis of the costs and risks of reuse in practice in the UK is lacking. We found that although there is a sufficient spread between the price of steel scrap and new steel, this difference cannot be captured by the demolition contractors. Rather, reused steel is somewhat more expensive than new elements, except in certain circumstances such as when the reused elements are available from a nearby site, or when testing elements can be avoided. Further, we show that neither the costs of steel reuse, nor the risks, nor its benefits are spread equitably throughout the construction industry supply chain: most of the substantial and capital-intensive changes required for the widespread adoption of steel reuse are concentrated on steelwork contractors and stockists. Based on this analysis, we suggest helping the emergence of a specialised stockist.

1. Introduction

The trends in ecologically-friendly construction aimed at reducing the impact of buildings have largely focused on the operational aspects: better insulation, better natural lighting, better ventilation. These have considerably lowered the carbon and energy footprints of newly-built or retrofitted buildings. Nonetheless, a large part of the whole-life carbon footprint of buildings is not associated to their use, but is embodied in the materials used for construction.

The study of operational emissions is thus insufficient to fully describe the impact of a construction (Ley and Samson, 2003; Choudhary, 2012). Moreover, current practices make it possible for constructions to be operationally carbon neutral. Further efforts should then look at the *embodied* carbon and energy required for building construction, materials production and forming, and material transportation. Depending on the material used for the frame, the strategies which have the highest mitigation potential are different (Nadoushani and Akbarnezhad, 2015).

Concrete framed buildings have relatively little scope for improvement, aside from the introduction of novel substitution cementitious materials (SCM) as the current production of SCM is almost wholly exploited (Snellings, 2016). Steel buildings, by contrast, offer an alternative route for carbon and energy savings: the steel elements of the building can be reused if buildings are deconstructed rather than demolished (Fujita, 2012). This is the case even when the elements have not been expressly designed for that purpose, a key focus of ongoing research (Durmisevic and Noort, 2003; Guy et al., 2006; Ness et al., 2015).

In this study, we concentrate on steel-framed buildings. Recycling steel only save approximately 50% of the energy and carbon over making new steel (Norgate et al., 2007), as the recycling of steel is an energetically expensive operation even using the best currently available technology (Milford, 2010). By contrast, steel reuse can play an important part in a global strategy for the efficient use of materials (Allwood et al., 2011; Allwood and Cullen, 2012; Zink et al., 2015). The carbon and energy embodied in structural frames can represent up to 29% of the life-time carbon footprint of commercial buildings (Nadoushani and Akbarnezhad, 2015; Dimoudi and Tompa, 2008). Although the embodied carbon for offices and dwelling is much lower, typically in the order of 8–13%, this fraction is set to increase as

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operationally carbon-neutral buildings are more commonly being constructed. Despite the consensus view of steel reuse as a potentially excellent strategy (Geyer and Jackson, 2004; Cooper and Gutowski, 2017), its practical implementation is fraught with difficulties. Thus, studies on the benefits of steel reuse tend to be prospective, focusing on *e.g.* the trade-off between design for deconstruction (Crowther, 2015) (thought to facilitate reuse) and carbon life cycle analysis (Densley Tingley and Davison, 2012). Indeed, the proportion by mass of elements reused from steel arising from demolition in the UK is low and declining (Sansom and Avery, 2014). This is due to a combination of factors, notably the decline of the reused steel market, now concentrated in a few niches such as farm animal sheds.

Studies of steel reuse practice tend to reflect the particular circumstances of the country where they are conducted, as in the work of Da Rocha about steel reuse in Brazil (da Rocha and Sattler, 2009), who identified steel quality to be a critical barrier. This barrier does not seem to the relevant to the UK, where the steel certification process is possibly *too* stringent. In Canada, Gorgolewski describes practical experiences with steel reuse and presents successful case studies (Gorgolewski et al., 2006). For example when the firm responsible for the design of a new building is also the owner of the building it replaces, keeping elements for reuse presents few difficulties. When there is strong integration in the supply chain, steel reuse is found to be practical, and most importantly cost effective. It is not clear this advice is generally applicable in the UK where the supply chain is highly fragmented.

Many previous studies of steel reuse in the UK list barriers extracted from interviews and establish a hierarchy (Vukotic, 2013; Kuehlen et al., 2014; Tingley et al., 2017). Cost and programme (the organisation and timing of the various operations in the design and build process) are always at the apex of barrier hierarchies, but there has not yet been a detailed reconstruction of the business case of steel reuse. A work from our team recently exposed the heterogeneity of the barriers to reuse felt across the supply chain (Dunant et al., 2017): the stockists and steelwork contractors are the ones whose operations have to change the most to accommodate steel reuse.

A business case for steel reuse in any country must fit in the context of the local construction value chain. This value chain is the added value from all the actors in construction as well as their share of the profit. In the context of this paper, we concentrate on the cumulative cost of a structural beam as it goes from semi-finished steel (or as deconstructed) to being erected on a construction site.

Suggesting effective steps to change the practice of the construction industry must be based on knowledge of the circumstances under which steel reuse can be profitable. In the particular case of the UK, using data acquired through interviews (Dunant et al., 2017), this paper attempts to demonstrate that:

1. In certain circumstances, steel reuse can be reliably shown to yield cost savings;
2. A general market for steel reuse has not arisen because the risks and benefits of it are not apportioned fairly among the actors of the supply chain;
3. There is an opportunity to introduce a specialised actor in the supply chain responsible for the acquisition, reconditioning and distribution of reused elements.

This is done by establishing a cost model describing how an erected steel beam is priced, and describing the risks faced by each actor when a construction project involves steel reuse.

2. Materials and methods

A quantitative survey of the costs of steel reuse is missing, in particular for the UK. Only scant published information is available on the pricing structure of new steel elements, even more so from reuse. This is in part because the information on the cost structure is fragmented across the supply chain, but also because such information is commercially sensitive. As part of a larger study on steel reuse, we have interviewed actors from across the chain about their experience of the topic, and have asked them to provide us what costing information they could disclose. By comparing the results, we were able to reconstruct the cost structure per tonne of fabricated and erected steel elements in the cases of new and reused steel.

2.1. Interviews

We interviewed 30 members of the value chain (Fig. 1): 10 client/advisers/architects, 4 main contractors, 12 structural

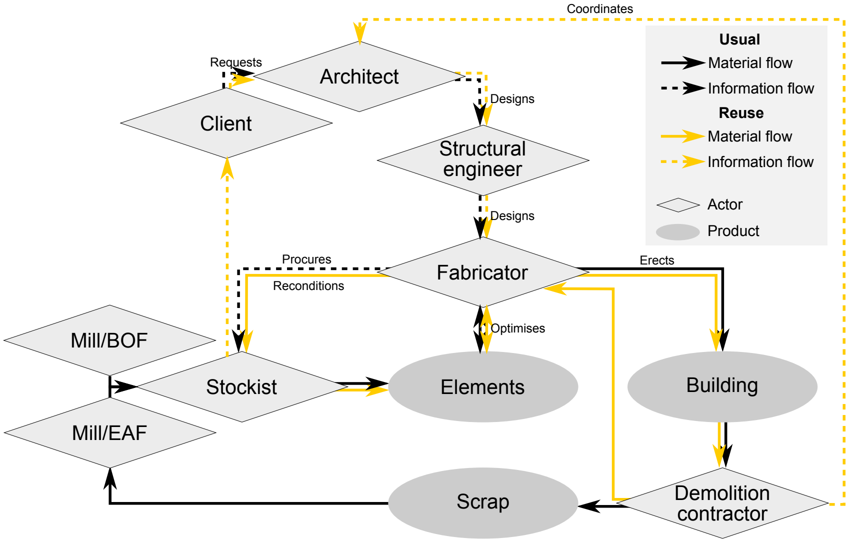

Fig. 1. How steel and information flow across the construction value chain. The central role of the fabricators and stockists is apparent. Figure adapted from Dunant et al. (2017).

designers, 1 steelwork contractor, 2 stockists, 1 demolition contractor. We conducted interviews in person where possible, or by phone as a fall-back. The interviews were conducted at the Department of Engineering of the University of Cambridge, the London offices of Cullinan Studio, or at the offices of those interviewed. The information obtained during interviews was verified by the interviewees who read their post-interviews reports. The interviewees had responded to our invitation looking for members of the supply chain with an interest in steel reuse. The detail of the survey and an analysis of the answers is given in the work of Dunant et al. (2017); importantly, the interviewed actors are representative of the construction industry in the UK.

The interviews consisted of questions relating to the role each actor played in the supply chain in general (delays, costs, legal requirements) and specific questions about reused steel, and fit to the actor's work flow. We also asked for cost estimations for each specific operations actors described. We asked about any case study involving steel reuse, successful or not. Some interviewees provided us with extensive information on a number of them, including pricing and plans. Much of this information was given in confidence, and in the cost reconstruction presented below, we show the maximum and minimum of all values we obtained.

2.2. Assumptions in the price reconstruction

To determine the price of some operations, we had to make some assumptions.

- We were told that the margin and operational costs of the stockist is 100 £/t: we assumed that this also applied to stockyards holding recovered steel elements as these are performed by similar companies with similar operations.
- From our own data, a database of 30 construction plans for office buildings and schools, we determined the mass of an average element to be approximately 340 kg (Dunant et al., 2018). This was used to translate prices per element to prices per tonne steel. .
- We were given a partial cost structure for fabrication: the percentages for the erection, administration design and the costs associated to the purchase of bolts and primer. The remainder is thus the fabrication operations, cutting, welding, *etc.*, as well as the margin of the fabricator, as these were the only elements unaccounted for.
- Using the costs for comparable operations in fabrication, assuming the average beam has two end plates and 0.5 m of welds per tonne of steel gives an estimation for the reconditioning costs. This estimation was found to be consistent with pricing offers from case studies.
- In principle, the cost for the fabrication from reused beams can be different from the costs for new beams. However, we found that the reconditioning in effect made the ‘reused’ beams as new, and therefore it is reasonable to assume that in the general case the costs are the same.
- The cost of transport can be very variable depending on the location. However, it only represents 1–3% of the total cost. The estimates used here are consistent with this fraction, which corresponds to the price per tonne expected given a full lorry and a 30–90 km drive. The cost per kilometre of a full lorry was given to us during interviews.

In all, these assumptions result in an error of no more than 10% of the total price. The total error is given by:

$$\text{error} = \sqrt{\frac{\sum \sigma_i^2}{n}} \tag{1}$$

With σ_i the standard deviation of the i^{th} operation's price, and n the total number of operations.

2.3. Price reconstruction

Every operation listed in the reconstruction was cited and priced by more than one actor. The values given were rarely the same, but typically within 20%. This does not imply that the information was wrong or imprecise but likely reflects slightly different circumstances for each actor. Rather than using a median price for each operation, we used the minimum and maximum cited values as bounds. Some prices given were relative (for example, the cost of transport was described to us as both between 1 and 3% of the total price, and £ 6 per kilometre for a full lorry). Since we tried to establish bounds rather than a single characteristic cost for each operation, there was no loss of information due to averaging costs. Construction costs are highly variable depending on location, design, *etc.*, we therefore believe that establishing *ranges* is a better representation of construction costs.

To reconstruct the costs of reusing steel we have assembled all the information we have been given in the interviews on each operation according to the method in 2.3. Mainly two actors are responsible for pricing the elements: the stockist and the steelwork contractor.

Transport and handling.

Stockist
- Storage/administration
- The market price of steel elements
- The margin of the stockist
- A premium of uncommon sections

Steelwork contractor
- Connection design
- Administration
- Profit margin
- Fabrication operations: cutting, welding, drilling, *etc.*
- Materials, *e.g.* bolts, primer
- Erection of the elements

Further, in the case of reused steel, supplementary costs arise:

Demolition Contractor/Steelwork contractor Strike down costs (as opposed to demolition).

Steelwork contractor: Recondition costs, *e.g.* removing welds, shot-blasting, *etc.*

Testing.

3. Results

We show in this section that the price difference between used and new steel is lower than the difference between scrap and new steel. Nonetheless, this cannot be exploited due to different price structures between used and new elements. We give a price structure reconstruction, and we validate it looking at case studies.

3.1. Price spread between scrap and new steel

To assess the potential for cost savings of reused steel under the hypothesis that a serviceable element scheduled for scrapping could in principle be sold at a profit if it substituted a new element, we looked at the difference between the prices of new

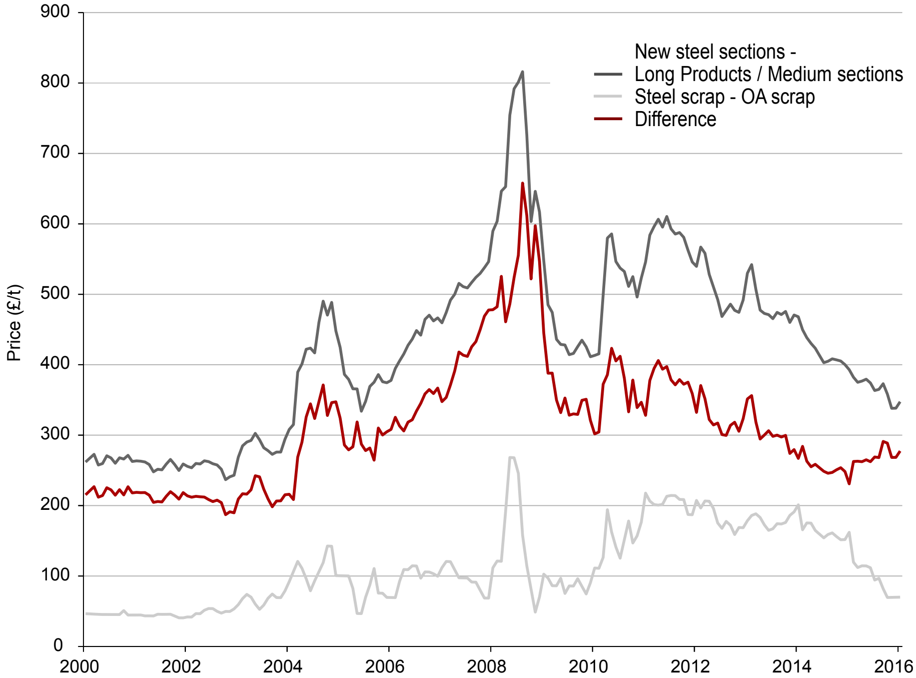

Fig. 2. Evolution of the prices of new elements, and OA grade scrap. The prices have been adjusted to 2016 Sterling. Historical data for the price of new sections from S&P Global Platt's http://steelbb.com, prices for OA grade scrap from Let's Recycle http://letsrecycle.com. The prices correspond to the European steel market, as paid in Pound Sterling.

elements and OA grade scrap (Fig. 2) in the European market, for transactions conducted in Pound Sterling. OA grade scrap is the highest value grade of scrap, and corresponds to demolition scrap from structural steel. The prices in Fig. 2 have been adjusted for the producer price GDP deflator to compare the evolution of the prices on a constant 2016 Sterling basis for the period from 2000 to 2016.

The difference between the prices of new and used steel has been over that period of 313 £/t on average, with a standard deviation of 90 £/t (Fig. 2). The minimum was 187 £/t. Therefore, steel reuse should be profitable if the cost of reconditioning and testing elements is not more than 187 £/t. We use the threshold of 187 £/t because stockists operate on a just-in-time fashion and do not hold stocks for sufficiently long periods of time to exploit higher average prices (Dunant et al., 2017).

This mechanism for enabling reuse — profiting from the difference in price between scrap and reused steel — does not reflect the practice of steel reuse. When a building is struck down and steel elements become available from its deconstruction, they are usually bought at the price of scrap. Although the elements have more *potential* value as reused steel elements, this cannot be exploited by the demolition contractors who do not have the facilities necessary to store the steel until a buyer is found, and neither do most stockists. Therefore, when the price of scrap and the price of new steel are *low*, there is an incentive for both the demolition contractor and stockists to sell and buy reused steel. The demolition contractor can get more value for the steel obtained from sites, and stockists specialised in reused style can build stocks at a low price.

3.2. Constituents of the price of a fabricated and erected steel element

Not all interviewees gave pricing information. None of them had a complete overview of what goes into the price of an element as designing, fabricating and erecting an element results from the collaboration of a number of specialists. The most detailed overall description we obtained was a breakdown of the fraction of the cost per actor. The total pricing was reconstructed partly from case studies, partly from summing up the known prices of operations, and partly from comparison with the known relative contribution of actors or operations. Relatively narrow ranges of values could be obtained for the cost of each operation and these are relatively independent of the circumstances.

The values for all individual operations or group of operations in £/t are reported in Table 1. As the calculated difference between reuse and new steel is lower than 187 £/t, steel reuse should be profitable. However, this simple analysis does not take into account whether any profit can be captured or whether it will be lost. For example, the cost of striking down, here attributed to steelwork contractors, are borne only if the deconstruction of the old building is commissioned by the same actor commissioning the new one. In general, the deconstruction or demolition cost will be paid by the previous owner to demolition contractors, who will then sell on the steel at the cost of scrap. The costs of storage are included in the operating margins. These can be highly variable, and depend on location. Stockists specialised in reuse commonly have access to cheap land. Nonetheless we expect this uncertainty not to affect the results presented in this paper.

When taking into account the cost structure, the spread which would be shared between the stockist and the demolition contractor is 9.42% of the element price when the price of scrap and the price of steel are both low, but only 2.72% when the price of steel and the price of scrap are both high. Importantly, we find that if the price of steel goes *down* we should expect reuse to become more prevalent. This result is supported by the anecdotal evidence we obtained from interviewing stockists and demolition contractors. The potential profit margin does not seem to be exploited as steel reuse only happens in rare circumstances. The price structure of an element is illustrated on Fig. 3.

Table 1
Overview of the maximum and minimum costs of various operations necessary for the fabrication and erection of used and new elements. Prices are in £/t, displayed rounded to £ 5.

Operation	Reuse element		New elements	
Operation	min	max	min	max
N — *Distributor (new steel)*	–	–	530	750
– Margin	–	–	110	110
– Steel	–	–	400	600
– Premium for rare	–	–	20	40
O — *Distributor (used steel)*	200	300	–	–
– Margin	110	110	–	–
– Steel	90	190	–	–
R — *Fabrication (recondition)*	220	370	–	–
– Shot-blasting	15	55	–	–
– Removing welds	–	25	–	–
– Removing end plates	85	120	–	–
D — *Striking down*	120	165	–	–
F — *Fabrication*	500	700	500	700
– Administration	50	65	50	65
– Design	55	80	55	80
– Bolts/primer	25	35	25	35
– Erection	120	165	120	165
– Cuts/Welds/Drills/Shot-blasting	248	355	248	355
r, T, t — *Testing and transport*	210	250	20	25
– Testing	145	175	–	–
– Transport	65	75	20	25
Total	**1130**	**1620**	**1050**	**1475**
Reused steel carry			– 1130	– 1620
New – Scrap spread			+185	+185
Spread			**105**	**45**
Spread (relative)			9.29%	2.78%

3.3. *Case studies*

We verified the general validity of our pricing estimations by comparing reconstructed costs with overall prices paid. Structural engineers have given us the overall price they expect to pay per element for fabrication and erection. Further we were given overall decompositions of the relative costs from each actor. Using these data, we compared our reconstructed cost with the overall prices structural engineers are charged for elements (1600 £/t to 1900 £/t in London for multi-storey offices or housing). We obtained a good agreement, indicating the cost estimations for the different operations are reasonable.

Data in literature, *e.g.* from 1996 gives 2077 £/t for ‘Steel studs, doors, frames, ceiling grid’, when converting given values to 2016 pound Sterling. This value is an average of structural elements and high-value items. It is consistent with the upper-bound of estimations. Similarly Guggemos and Horvath (2005) give for structural steel elements 1292 £/t translated to 2016 pound Sterling, which is consistent with our lower bound. The large variation between the circumstances of individual projects should be captured in our estimated range. Importantly, none of these assumptions affects the price structure given in this work.

To further verify our results, we have compared them with case studies described to us during interviews and found in literature. These are briefly summarised on Table 2. In general although detailed pricing information is missing we could only apply our pricing model to the circumstances of each case.

We have verified the hypothesis that all successful reuse case studies described in interviews (and some found in the literature) could be explained by substantially lower costs of the reused steel. A small summary of the case studies is found in Table 2. The summary of this analysis is illustrated in Fig. 4. In all cases, the operations necessary to recover, recondition, and reuse the steel were accounted for in the breakdown detailed above. The ‘Guillemont park’ case study was not successful. There, elements of a partially-built building were proposed for reuse but could find no buyer. This case study is an example of the viability of reused steel being low outside of favourable circumstances, particularly when the steel prices are relatively low. The RHS Hyde hall reuse option was also chosen due to costs. The Honda station had to be decommissioned due to changes in the building codes — nonetheless is it a successful example of a building which was constructed, deconstructed, stored, and reconstructed.

We find that the upper estimate for the cost of reused steel in all the successful case studies is lower or very close to the lower estimate of new steel. It is therefore very likely that in all these cases reusing steel was profitable. When reusing steel, other costs may be incurred, notably design and insurance costs, but these did not prevent reuse in many cases. These results indicate that the design with reused steel elements is probably not significantly

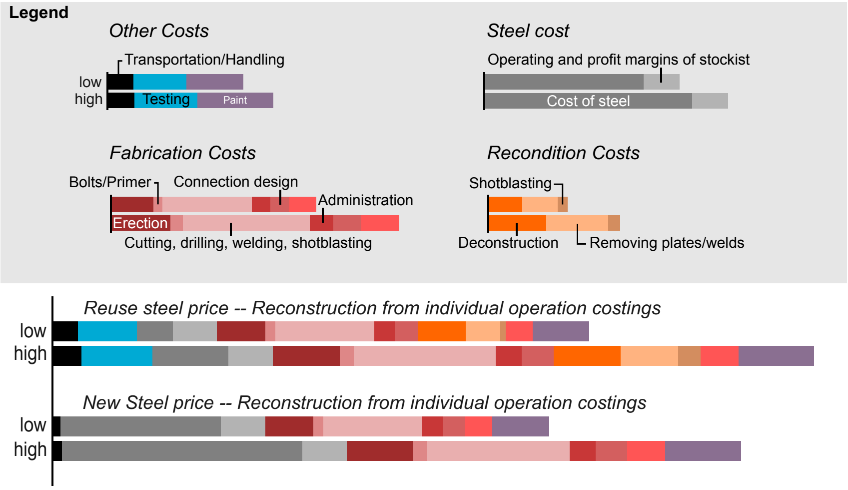

Fig. 3. Comparison between reconstructed new steel prices, by summing individual costs, and from information about the overall structure. Reused steel prices are reconstructed only summing the prices of individual operations.

Table 2
Case studies used for the verification.

Case study Success?	Description
Guillemont Park Camberley 2004 **No**	Five, 3-storey buildings, grid 9 × 9 m, 14,000 m^2; 107 tonnes the almost unspoilt floor beam available for reuse; Price of steel scrap was high so proposed buyer price wasn't profitable for demolition contractor
Carrwood Park Doncaster 2008 **Yes**	1800 m^2 portal-framed building constructed using 82 tonnes of reclaimed structural steel from an old warehouse; Refurbished
Blue Steel Building Leeds 2005 **Yes**	14,500 m^2, Poundstrecher facility refurbished and extended. Became a Carlsberg facility.
BedZed London, 2001 **Yes** (BioRegional Development Group, 2002)	Structure of workshop area of the building made using steel sourced from temporary works at Brighton railway station; No testing, material costs neutral compared to new steel, second hand steel price 300 £/t.
740 Rue Bel-Air Montreal, Quebec, 1990s **Yes** (Gorgolewski et al., 2006)	325 roof steel joists were recovered, 65 were reused, the rest was sent to recycling or reuse; All elements were tested, including X-rays and chemical tests; Reuse on-site
Relocation of Leigh Rd, 9 Cambridge Ave. (Segro) Slough, 2015 **Yes**	Relocation of the building 1 mile away; Reused: steel structure, glazing, staircases, loading doors, precast beams, planks, curtain walling, fencing, lift, balustrades; Not reused: bricks, cladding, roof.
Sainsbury Mezzanine Kent, 2010 **Yes**	Roof disassembled, new floor added, roof re-assembled; Structure: shot blasted, not painted, not fire protected, only connections tested.
RHS Hyde Hall Essex, 2014 **No**	An option for reuse was developed, and rejected on the basis of cost.
Honda Central Swindon, 2005 **Yes**	Honda steel warehouse deconstruction, storage (for 18 months); Re-erection in different location (cladding not reused).

more expensive than design with new steel and that it is possible to find cost-effective solutions to insure buildings made with reused steel.

Even when steel reuse is profitable in the aggregate, the supplementary costs in the form of the striking down and reconditioning all fall on the steelwork contractor. Although these operations are charged for, they imply a risk in the form of a loss of profit opportunity. Similarly, although stockists could hold reused steel, this does not mesh well with their usual operations.

4. Discussion

The high volatility of the price of steel should cause difficulties for the construction industry. However, this is not the case as the structure of the contracts is now ‘cost-plus’, with the clients paying for the price of the steel at the rate which is current at procurement. The stockists therefore have just-in-time operations and hold little stock. If the structure of contracts was different, stockists might hold steel stocks to maximise their benefits by buying the steel when its price is low. Currently, the cost structure of steel reuse as described here is a key barrier to its widespread adoption. This structure reflects the distribution of risks associated with steel reuse.

In the cost structure described above, the costs of storage and the delays which may be incurred from reusing steel have not been accounted for explicitly. We expect them to be very variable depending on the location. These costs would be incurred by the stockist in general. In this price model, they are assumed to be within the ‘operating and profit margins’ of this actor.

4.1. Costs for different scenarios

The cost structure described in Section 3.2 will prevent steel reuse from happening (Fig. 5) if the difference in price between new elements and scrap in not captured. Indeed, when reused steel elements are put into direct competition with new ones, reused steel is expected to be more expensive, all other things being equal. The cost of a reuse element C_{reuse} is:

$$C_{reuse} = O + R + D + T + F \tag{2}$$

With O the price of used steel from a stockist, R the cost of reconditioning and testing, D is the cost of deconstruction, T the price of supplementary transport and handling, N the price of new steel, and F the fabrication costs. The cost of deconstructing rather than demolishing cost cannot be avoided in certain circumstances. For example, deconstruction rather than demolition is mandatory in dense urban environments. Demolition contractors usually sell the steel to small/medium-sized stockists at the price of scrap. This is in contrast to the cost of a new element:

$$C_{new} = N + F + t \tag{3}$$

With t a reduced price for transport and handling, owing to a more streamlined operation. In the abstract, the savings potential of reused steel is in principle therefore obtained by:

$$P = N + t - R - D - T - O < 0 \tag{4}$$

With P the expected savings which are negative in this case, as reused steel is more expensive than new steel according to our cost reconstruction. Further, the value of O can never be lower than the price of scrap, as a stockist holding used steel will never sell it on for less than that value. Higher scrap prices therefore tend to increase the disadvantage of used steel: it is always easier for demolition contractor to sell the steel for scrap, and with high prices, this is also a profitable strategy.

However, a number of specific circumstances can change the cost structure. The most successful scenarios for steel reuse have markedly lower costs compared to new steel. The following strategies were the most commonly reported in our interviews. In each case, some of the costs were abolished due to the special circumstances of the project:

1. Testing of individual elements may not be required
2. Transport costs can vary depending on the project
3. Sub-assemblies which are reused do not need to be re-fabricated
4. Reused steel can be procured at low costs

Further, the fabrication costs for new and reused elements may be different depending on the project. However, the similarity of operations mean that *on average* the costs will be similar.

The three archetypal reuse cases illustrated on Fig. 5 are described in more detail below. They are:

1. Partial structure reuse,
2. Reinforcing old structures,
3. Reusing elements from a demolition site,

Partial structure reuse. The most cost-effective strategy is partial structure reuse (or in some cases whole buildings). In this case, the reconditioning costs are considerably reduced ($R \rightarrow r$), there is no cost for the steel already in the structure other the opportunity cost which is the scrap price, and the fabrication is simplified ($F \rightarrow f$).

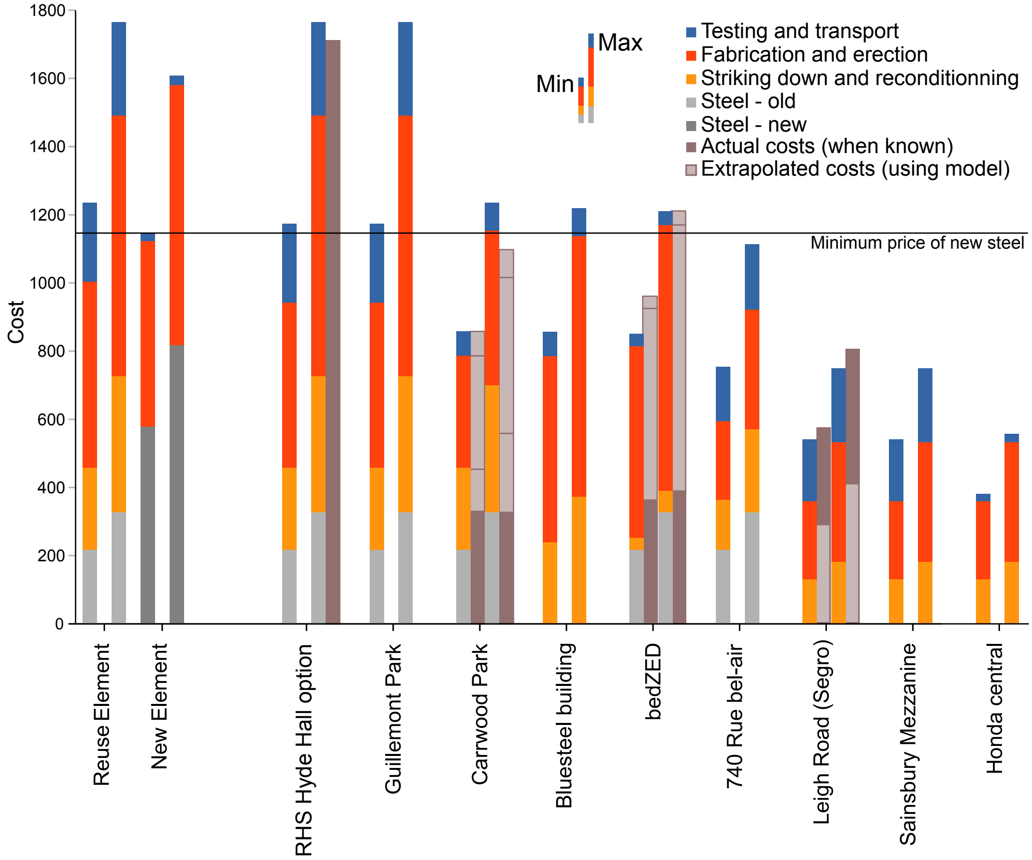

Fig. 4. Reconstruction of reused structural steel costs per tonne for successful and unsuccessful case studies and reconstructed baseline costs for new and reused steel (four leftmost bars). In all other cases, the circumstances of the project allowed a lowering of the cost. Limited information means that the real costs could only be partially verified for projects. Hollow bars mark extrapolation using the model from this paper, whereas the full sections marks costs which could be verified.

$$P = F + N - O - r - f \tag{5}$$

Depending on circumstances, there may be testing costs. This is different than the simple extension of an existing building: in the case studies we looked at, the buildings (such as the Segro building, the Honda terminal) or parts of structures (the Sainsbury mezzanine) were disassembled, checked and reassembled, sometimes after a period of storage. In the latter case, the owners must have incurred storage costs, but we have assumed they were negligible.

Reinforcing old structures. Old structures which are partially reused can significantly change the cost structure. These circumstances can occur in the case of listed buildings or when demolition would have been particularly costly, difficult, or dangerous. As plans and specifications are only rarely accessible, there is usually considerable uncertainty concerning the properties of the steel reused. The British Constructional Steelwork Association (BCSA) handbook of historical steelwork (Bates, 1984) gives the grades and mill marks for older elements. Guidelines specify the safety factor one should apply when reusing older frames. To reach these safety factors, existing elements are reinforced. About $\frac{1}{3}$ of steel is therefore needed compared to a new construction and the useful life of existing elements is increased. However the price of fabrication is increased by a factor 3, because most of the fabrication of the reinforcing elements, in particular the welding, is done on-site. The potential savings are then:

$$P = N - \frac{1}{3}(N + 3F + t) \tag{6}$$

In this case, the embodied carbon in the frame is increased overall, limiting the environmental usefulness of this practice.

Reusing elements from a demolition site. A possible case of reuse which may seem marginal but should be encouraged because it brings benefits at little cost is reusing some elements of a building scheduled for removal for the replacement building. In this case, arrangements can be made and those elements which are easy to preserve stay on site for the erection of the new building. The savings are then:

$$P = N - r - O \tag{7}$$

However, this will only apply to a relatively small part of the new structure. Further, for this reuse case to happen, it is necessary that the owners of the demolished and new buildings coordinate, whereas they would in many cases never meet.

4.2. Risks

Motivated clients and architect can try to push for reused steel in their projects due to the environmental benefits it can bring. Indeed, the risks faced by clients and architects are, like the costs, minor. As shown in the analysis above, there can be significant savings, depending on the project. But although there can be significant upsides to reused steel for these members of the supply chain, this is not the case for other actors (Table 3).

Similar to (Dunant et al., 2017), the steelwork contractors and stockists face the most important obstacles to implementing steel reuse. However, these risks are not the same as the barriers which

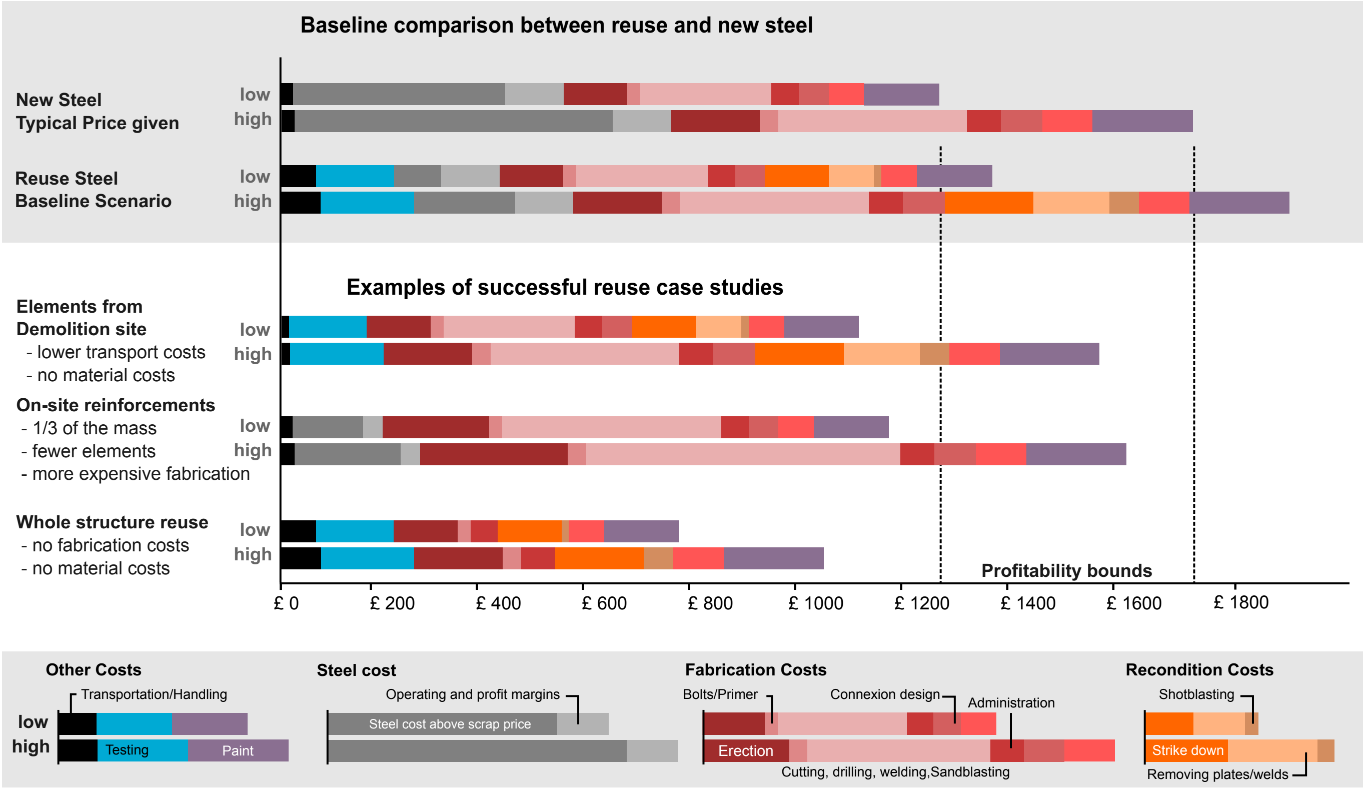

Fig. 5. Comparison between common cases of successful steel reuse. The three most common scenarios of successful steel reuse are detailed: the reuse of elements left on-site from the demolished building — on-site reinforcing of used structural elements which are kept — the reuse of a complete structure.

Table 3
Cost and risks associated to reuse for all the actors of the supply chain. Costs and risks are marked with plusses from very likely, very expensive (+++) to quite unlikely, fairly inexpensive (+).

Actor	Source of Costs		Prominent Risks	
Client	– Possible delays	(++)	– Procurement	(+)
	– Price differences	(+)		
Architect	– Possible delays	(++)	– Procurement	(++)
	– Price differences	(++)		
Designer	– Longer design times	(+)	– Time overruns	(+)
Fabricator	– Production line tied up	(+++)	– Procurement	(+++)
	– Reduced margins	(+)	– Time overruns	(++)
			– Fewer clients serviced	(+)
			– Fewer optimizations	(+)
Stockist	– Storage space tied up	(++)	– No just-in time model	(+++)
			– Change in norms	(+)
			– Lack of demand	(+)
Demo Ctor	– Time on the worksite	(++)	– No buyers	(+)
Other Ctors	– *No specific costs*		– *No specific risks*	

they cite as preventing reuse. Rather, they are the operational consequences of some of the barriers. Steelwork contractors describe as barriers the quality of the steel and whether they can establish trust with used steel elements suppliers. The risks associated are opportunity costs and fewer revenue streams. For stockists, the principal cost is land. All the risks they face are associated to that: the stocked steel may never deliver a profit depending on circumstances. Further, stockists would need to change their operations, which would imply capital costs to build extra storage capacity.

During interviews, it became apparent that it was frequently the steelwork contractors which determined whether a reused steel project would proceed or not. For example, the BEDZed experiment led to the formation of a company which would procure steel from yards and provide it for fabrication (BioRegional Development Group, 2002). As the steel had been bought at the expense of the spin-off company, when the steelwork contractors refused it on the grounds that it was not up to their standards, the spin-off was almost bankrupted. Steelwork contractors face a strong disincentive to work with reused steel: the reconditioning then fabrication of elements is complex, taking approximately one and a half as much labour and time as fabrication from new elements. In an industry where the deadlines are very tight, this is a problem. The processing of reused steel will tie up 1.5 times the production capacity needed for the equivalent new steel. Depending on the work programme, only half the number of clients can be served, increasing the dependency of the steelwork contractor and reducing the opportunities to form new business relations. This problem is compounded by the stop-start nature of a number of projects: flexibility is required as the production lines shift from the needs of one project to another.

Stockists, unless specialised in reused steel cannot introduce the new practice in their operation seamlessly. The turnaround time for an element in a large stockist's operation can be as short as 48 h, following a just-in-time strategy. By contrast, a specialisation in reused steel implies owning large stockyards and the turnaround is counted in months or years. A stockist maintains a list of most common sections and sizes and usually has fairly accurate forecasts on the immediate needs of the market. Prices in the new steel market can vary daily, whereas the reused steel stockist invests over the long term, trying to buy his stock when the value of scrap is low and selling when the price of new steel is high. Therefore, although the service provided are the same (sell the required sections in the amounts required by the clients), the operations when dealing with reused steel and new steel are completely different. It is therefore not in general possible for a stockist to start holding reused steel.

The demolition contractors do not usually have the infrastructure to store large quantities of reuse elements. They thus cannot perform the role of the stockists. As the market for reuse elements is not liquid, it is considerably easier for them to sell all steel for scrap, independent of its state.

Coordination within the supply chain can produce good outcomes. This happens despite the generally unfavourable distribution of risks and costs. We present below circumstances in which successful reuse happens.

4.3. *Partial reuse and extending the life of structures*

Although steel reuse is most frequently understood as the reuse of steel elements to construct a completely new design, in practice, reuse occurs frequently within the context of extending the lives of existing structures. All the expertise required for assessing and designing with reused elements is commonly used when old steel structures are refurbished. The strength of the old frame is assessed, either by an engineer relying on historical knowledge of construction practice or by a material laboratory which will perform tests on a coupon; the structural engineers will design the new extension of the building taking into account the existing inventory of steel.

The cost structure described in this paper explains why this is frequently cost-effective: considerably less steel is required, even when costly reinforcements are added on-site. Although the new structure will thus in general be heavier than a completely new design, the environmental savings are important. Crucially, the practice of extending the life of existing steel structures has the important side benefit of spreading the know-how required across the supply chain for successful steel reuse. Finally, this practice does not represent a break with common practice, meaning there are no particular barriers to it which need to be overcome.

Design for deconstruction has long been proposed as a solution to increase the potential of steel reuse. Our analysis shows that it would work in two ways: first the cost of deconstructing buildings would go down, increasing the potential cost savings from reusing steel, and second by standardising connections, which would also reduce the costs of reconditioning the steel. As shown in this work, the price difference between elements from used and new steel is small. Therefore, systematic design for deconstruction may help reuse by making used elements more attractive (Cullen, 2017). Alternatively, new automatic surveying techniques would help procurement and reduce costs (Yeung et al., 2015).

4.4. *A potential for a new actor — specialised stockists*

Providing steel ready for fabrication is the usual role of stockists. They usually function as brokers, buying steel in bulk when ordered and where it is the cheapest and selling it at short notice to the steelwork contractors. However, a long-term operation could exploit the fluctuations of the price of steel and scrap to maximise profit, provided it could hold large amounts of steel for long periods. Such operations exist, but are usually specialised in preparing steel from specific provenance. One such example is Cleveland Steel and Tubes which uses the unused pipes from pipeline projects. This stockholder is successful in the steel reuse market because they own large stocks of steel, which they obtained at relatively low cost, can provide special elements very fast, and own large stockyards where the storage is cheap.

It is not possible in general to sell used steel to steelwork contractors unless it has been tested and conditioned to be ready for fabrication. A reused elements stockist should then be associated with, or be, a specialist steelwork contractor who would recondition the steel so that it could be sold competitively with new steel. Due to inherently long holding times, the fabrication process for the reconditioning would not induce opportunity costs, and would be optimised for the specialist operations required.

Conversely, other actors, in particular the fabricator could take on the role of stockists. As they bear the opportunity costs of steel reuse, they could better manage this by doing reconditioning of beams when their fabrication lines are idle. This arrangement would be cost-effective if they could acquire the storage space required to also function as a stockist. Land being expensive in general in the UK, this solution may only work regionally.

5. Conclusion

A detailed reconstruction of the costs and risks associated to reused steel across the construction supply chain in the UK showed that although steel reuse is not much more expensive than using new steel, the distribution of risks make it frequently difficult to implement. Nonetheless, as the challenges of global warming become more pressing, the pressure to implement such strategies will grow.

We identified a number of options for the market to become more favourable to steel reuse, both from private-sector investment and public policy. Key amongst them is the restructuring of the supply chain to include stockists who hold steel for long periods of time. Conversely, the fabricators could take on some of the function of the stockists, which would allow them to hold and recondition steel from reuse without incurring opportunity costs.

Finally, we found an empirical explanation for the anecdotal evidence that reuse is favoured by low prices of steel: the potential cost savings for reused steel goes up when the price of steel goes down. This is because although the price of new steel and scrap tend to move together. Should the price of steel remain low in the long run, steel reuse should become more prevalent, as selling steel for scrap offers insufficient returns.

The following aspects of reuse could be improved through regulation:

1. Standardising the certification of reused beams would reduce the testing costs
2. Pre-demolition surveys would help uncover options for reusing parts of buildings or elements.
3. Incentives could be provided to favour design for deconstruction.

Finally, to allow for a market for reuse elements to take off a number of steps should be taken:

1. Stockists and steelwork contractors should work together so that reused steel elements are indistinguishable from new steel elements when they reach the fabrication stage.
2. Capital investments are necessary for stockists to be able to manage large stocks of reused steel and condition it for fabrication.
3. The volume of elements potentially available for reuse can cover large proportions of the overall market. However, due to a lack of transparency and programme constraints, nearly all the steel is currently scrapped, even when buildings are deconstructed. Complete plans of structures should be kept so that a precise inventory can be made before demolition.

Although we believe that specialised stockists could make the best use of the opportunities opened by the reorganisation of the supply chain, the specific functions they would perform (certification, long-term storage), could be taken on by existing actors as a means to diversify their businesses.

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