ECONOMIC AND ENVIRONMENTAL COMPARISON BETWEEN RECYCLING AND REUSE OF STRUCTURAL STEEL SECTIONS

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Abstract

It is generally agreed that product recovery strategies based on reuse are preferable to those based on materials recycling. Closing the loop higher up in the chain of value creation increases the environmental benefits but also offers opportunities for additional cost savings, so the argument goes. Nevertheless, reuse is not a widespread practice in the steel industry, which owes most of its environmental credentials to an extensive and self-sustaining recycling infrastructure. This suggests that there exist economic, technical or institutional obstacles that limit the extent to which reuse of steel products is feasible and profitable. In this paper we examine the obstacles that constrain the reuse of steel construction products and suggest possible ways to overcome them. An analytical model is developed to illustrate and compare the differences between recycling and reuse in supply loop systems. Our modelling approach allows us to derive some general results about the economic and environmental performance of both recovery options. The results emphasise how limiting factors, like market demand, product innovation and depreciation, can dominate the system performance. Finally, we discuss what institutional, corporate and technical changes are necessary to turn reuse into a viable option with growth potential.

1 INTRODUCTION

Steel is the most recycled material in the world [1]. The overall recycling rate of steel for France and the UK is estimated as roughly 50% [1,2,3], where recycling rate is defined as the percentage of yearly arising end-of-life scrap collected and reprocessed. In the UK, steel recycling from construction and demolition waste is a mature industry that achieves recycling rates considerably higher than this industry average [4]: Recovery of end-of-life steel from demolition in the UK is between 85 and 99%, depending on the steel product, making it the most efficient of all sectors [5]. Figures for other European countries are somewhat lower [6]. Structural sections, which are the focus of this presentation, are recovered from demolition waste with an estimated efficiency of 99% in the UK; 86% are currently recycled and 13% are reused in some form [5]. Whereas the recycling of steel components from construction and demolition waste is well established, the reuse of steel components from end-of-life buildings and other structures is neither widespread nor well documented. Deconstruction and reuse of construction components has only recently started to receive more attention; it is now identified as crucial for the development of a sustainable construction sector, and 'the challenge will be to increase the amount of steel re-used rather than recycled' [7]. Little quantitative research is available on the reuse of steel construction products and even less on how the economic and environmental profile of reuse compares with recycling of those products. The analysis we present in this paper is a first step towards closing this gap. For lack of existing research, our work has to cover the basic concepts before the research agenda can move on to more detailed and complex models. The systems approach of industrial ecology has been chosen as the analytical framework most appropriate for this task, and a general introduction to material and process flow models can be found in [8].

2 DESCRIPTION OF THE MODEL

Figure 1 shows the material flow and process model that has been used to derive our quantitative results about the economic and environmental impacts of section reuse and recycling. The system is driven by the demand for fabricated steel sections, which are used as components in buildings and constructions. There are three different paths to produce these sections: production from primary materials via the blast furnace / basic oxygen furnace (BF) route, production from scrap via the electric arc furnace (EAF) route and re-fabrication of end-of-life sections from deconstruction. BF and EAF sections are assumed to be perfect substitutes, but the reuse of re-fabricated sections may be constrained by factors such as limited market demand, technical feasibility or quality assurance. It may therefore not be possible to re-fabricate and reuse all of the end-of-life sections which could be recovered by deconstruction. End-of-life sections which have been recovered by deconstruction but cannot be re-fabricated or have been re-fabricated but do not find a market end up as scrap input for the EAF route instead [8]. End-of-life buildings and structures which are not deconstructed are demolished instead. End-of-life sections which are recovered via demolition either serve as scrap input for the EAF route or are landfilled and lost from the system.

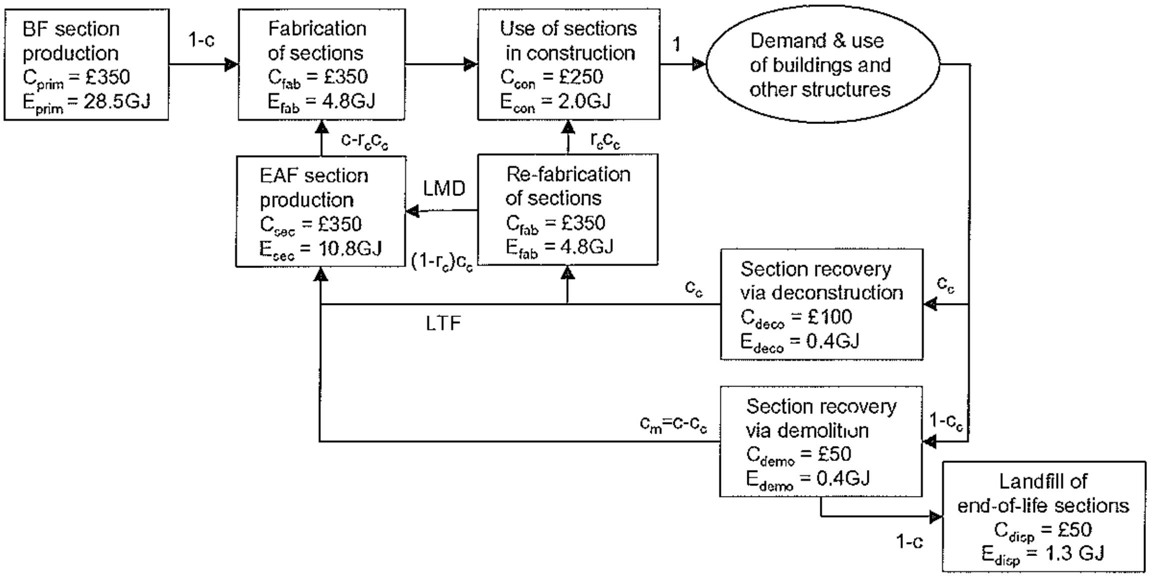

Figure 1 Material flow and process model for a closed-loop production and consumption system of sections (cost and energy consumption of the processes are given per ton of output)

Each process in the production and consumption system is characterised by its economic cost C and its energy consumption E per ton of material output. Energy consumption has been chosen as the most meaningful one-dimensional proxy for the environmental impact of the process. For this first analysis production cost and energy consumption of all processes are assumed to be linear functions of the output quantities, i.e. they have constant returns to scale. Fabrication and re-fabrication are taken to be identical processes. For confidentiality reasons it is very difficult to obtain accurate information about production costs. Some economic values were therefore derived from output prices assuming that the high competition in the section market results in very thin profit margins. In general all figures from Figure 1 should be taken to represent the right order of magnitude rather than to specify precise values [5].

Recycling and reuse of the recovered sections is modelled in a closed-loop fashion, i.e. recovered end-of-life sections are recycled into or reused as sections again. It is further assumed that the system is in a steady state, which means that all its material flows and stocks are constant over time. The energy consumption per ton of output of such a closed-loop system in steady state is identical with the results produced by the ISO 14041 allocation methods described in [10]. There, the energy consumption of the BF and EAF routes are calculated separately but turn out to have the same value due to the debits and credits of the allocation procedure. Using an expanded system like our model avoids the need for allocation and thereby makes the underlying assumptions more transparent. The analysis of production and consumption systems which are not in steady state or where end-of-life products are recycled or reused in open loops to replace products other than the original lie outside the scope of this presentation and will be treated in subsequent publications.

All material flows in Figure 1 are normalised to the flow of fabricated sections entering the use phase, which is therefore set to unity. Since the system is in steady state, the input of primary sections into the system equals the loss of end-of-life sections from the system via landfill. In this first analysis we avoid unnecessary complexity by ignoring scrap inputs into the BF production route or primary inputs like directly reduced iron (DRI) into the EAF production route, thus the analysis focuses on the principal interactions between the system components. The parameters that determine the sizes of the material flows are the reuse yield r_c, the component recovery rate c_c, and the material recovery rate c_m or the total recovery rate $c = c_m + c_c$. The component reuse rate follows as $r_c c_c$, and the resulting material recycling rate is $c - r_c c_c$. The economic and environmental performance of the system is now quantified via the total economic cost and the total energy consumption of the system respectively. We distinguish between two cases, limited technical feasibility (LTF) where only $r_c c_c$ of the c_c deconstructed sections are re-fabricated and re-marketed and limited market demand (LMD) where all c_c deconstructed sections are re-fabricated but only $r_c c_c$ find a market. The flow constraint modelled by r_c applies before re-fabrication in the LTF case and after it in the LMD case. Total economic cost and energy consumption for the LTF case are:

$$\begin{aligned} C_{LTF} &= (1-c)(C_{prim} + C_{disp}) + (c - r_c c_c)C_{sec} + C_{fab} + C_{con} + c_c C_{deco} + (1-c_c)C_{demo} \\ &= (C_{prim} + C_{fab} + C_{con} + C_{demo} + C_{disp}) - c(C_{prim} - C_{sec} + C_{disp}) - c_c(r_c C_{sec} + C_{demo} - C_{deco}) \\ E_{LTF} &= (E_{prim} + E_{fab} + E_{con} + E_{demo} + E_{disp}) - c(E_{prim} - E_{sec} + E_{disp}) - c_c(r_c E_{sec} + E_{demo} - E_{deco}) \end{aligned}$$

Total economic cost and energy consumption for the LMD case are:

$$\begin{aligned} C_{LMD} &= (1-c)(C_{prim} + C_{disp}) + (c - r_c c_c)C_{sec} + C_{fab} + (1 - r_c c_c + c_c)C_{con} + c_c C_{deco} + (1-c_c)C_{demo} \\ &= (C_{prim} + C_{fab} + C_{con} + C_{demo} + C_{disp}) \\ &\quad - c(C_{prim} - C_{sec} + C_{disp}) - c_c(r_c C_{sec} - (1-r_c)C_{fab} + C_{demo} - C_{deco}) \\ E_{LMD} &= (E_{prim} + E_{fab} + E_{con} + E_{demo} + E_{disp}) \\ &\quad - c(E_{prim} - E_{sec} + E_{disp}) - c_c(r_c E_{sec} - (1-r_c)E_{fab} + E_{demo} - E_{deco}) \end{aligned}$$

As benchmark for the system performance we take the hypothetical 'worst case' scenario of no recycling and no reuse ($c = 0$), which has the total cost of $C_{prim} + C_{fab} + C_{con} + C_{demo} + C_{disp} = £1050$ and an energy consumption of $E_{prim} + E_{fab} + E_{con} + E_{demo} + E_{disp} = 37$ GJ per ton of fabricated steel section put to use (including demolition and landfill).

3 RESULTS

3.1 Unconstrained reuse yield

We first analyse the unconstrained system, where the reuse yield equals one, $r_c = 1$. Here all end-of-life sections recovered via deconstruction are re-fabricated and reused. There are three different directions in which the system flows can change: Recycling from waste (c_m varies, c_c is constant), reuse from waste (c_c varies, c_m is constant) and a shift between recycling and reuse (c_m varies, $c = c_m + c_c$ is constant). Figure 2 shows that if all end-of-life sections are recycled from waste, the energy consumption is reduced by a factor 2, while the cost only decreases by less than 5% of the benchmark value. These savings of £50 per ton are the saved landfill costs, which provide the financial incentive for demolition contractors to recover the sections. Selling them as scrap creates additional income for the contractors but this is not reflected in the current analysis since it considers system cost and not the economics of the individual supply loop agents. If the system changes from no recycling and no reuse to reusing all arising end-of-life sections as perfect substitutes to BF sections the energy consumption decreases by a factor 5, whereas the system cost is reduced to two thirds of the benchmark value (Figure 3). Since it is estimated that only 1% of the end-of-life sections arising in the UK are lost and landfilled, these two cases are of academic interest; it is the shift from recycling to reuse that is the most relevant system change.

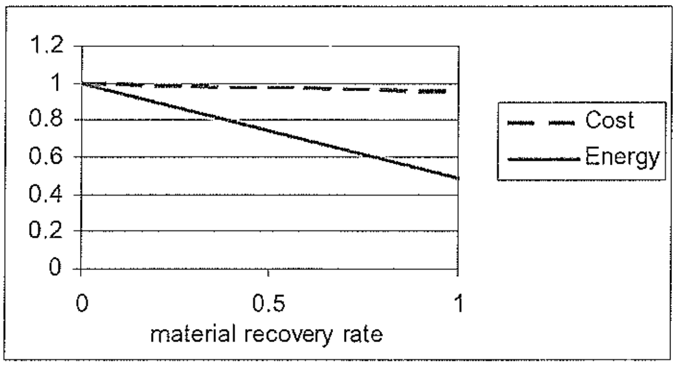

Figure 2 Left: Recycling from waste – Normalised cost and energy as a function of c_m ($c_c = 0$)

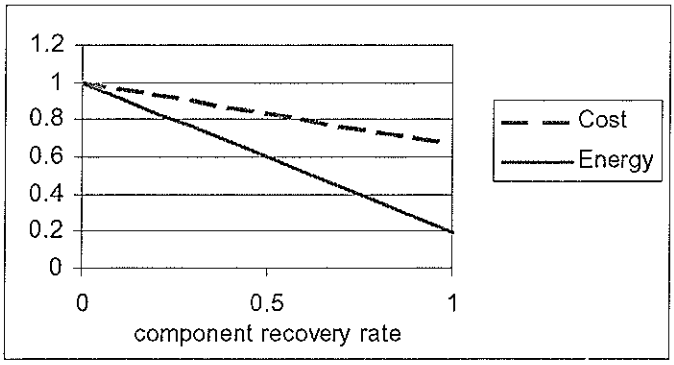

Figure 3 Reuse from waste – Normalised cost and energy as a function of c_c $(c_m = 0)$

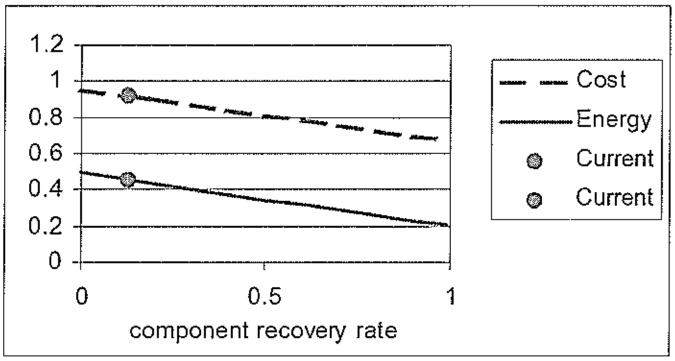

Figure 4 Shift from recycling to reuse – Normalised cost and energy as function of c_c $(c = 0.99)$

Figure 4 shows how the system cost and energy consumption change as more and more of the recovered end-of-life sections are reused rather than recycled, assuming that c remains at the present value of 0.99. The current situation of an estimated section recycling rate of 0.86 and a reuse rate of 0.13 is marked on the graphs. We now calculate the normalised marginal cost per unit reduction of energy consumption for the three different system changes, dC/dE. This index indicates if the energy savings of a system change result in cost savings, and the extent to which the cost savings are of the same size as the energy savings. The index is zero if increased energy savings produce no cost savings at all and one if improved energy savings result in cost savings of equal size. We see that the economics of section recycling are very weakly aligned with its energy savings (but apparently high enough to achieve a recycling rate of 86%). However, the system costs strongly encourage a shift from recycling to reuse, which suggests that there are important constraints preventing this from happening.

Recycling from waste: $$\frac{dC}{dE}(\text{increasing } c_m, \text{constant } c_c) = \frac{(\partial C/\partial c_m)_{c_c}}{(\partial E/\partial c_m)_{c_c}} \cdot \frac{37GJ}{£1050} = 0.09$$

Reuse from waste: $$\frac{dC}{dE}(\text{increasing } c_c, \text{constant } c_m) = \frac{(\partial C/\partial c_c)_{c_m}}{(\partial E/\partial c_c)_{c_m}} \cdot \frac{37GJ}{£1050} = 0.41$$

Shift between recycling and reuse: $$\frac{dC}{dE}(\text{increasing } c_c, \text{constant } c) = \frac{(\partial C/\partial c_c)_{c}}{(\partial E/\partial c_c)_{c}} \cdot \frac{37GJ}{£1050} = 0.98$$

3.2 Constrained reuse yield

These conclusions raise the question of why there is relatively little reuse, in spite of the economic incentive. Our hypothesis is that there exist supply loop constraints which effectively prevent an increase in the reuse rate of steel sections. Other research based on surveys confirms that there are substantial barriers to reuse [7,11]. Deconstruction is still the exception due to its labour and time intensity and the additional cost of having to comply with ever-tighter health and safety regulations. The production of technically acceptable re-fabricated sections can be limited due to damage suffered during use or deconstruction or simply because of the lack of documentation on section origin, specifications and use history. The reclamation and re-fabrication industry also suffers from lack of infrastructure and missing economies of scale. If re-fabrication of sections from deconstruction is feasible then it can still be impossible to find markets for the re-fabricated sections. Current building legislation and lack of standardisation for re-used construction components seem to discourage their use. Contractors and customers can mistrust the integrity of the 'used' product, dislike its dated design or simply be biased against non-new construction components. Re-fabricators will also find it difficult to match the time-dependent flows of their input supplies with their output demands and face the difficult choice between re-fabricating sections to order or to stock.

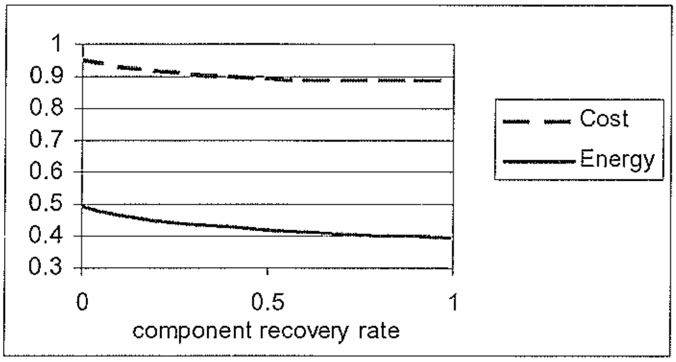

Figure 5 Shift from recycling to reuse with constrained reuse yield - Normalised cost and energy as function of c_c $(c = 0.99)$ for the case of limited technical feasibility (LTF)

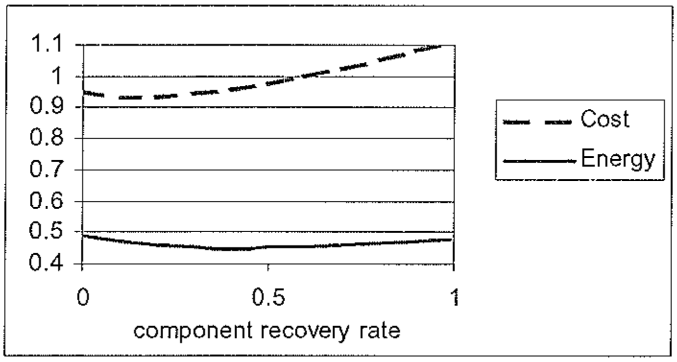

Figure 6 Shift from recycling to reuse with constrained reuse yield - Normalised cost and energy as function of c_c $(c = 0.99)$ for the case of limited market demand (LMD)

It is far beyond the scope of this paper to derive the exact forms and relative importance of the different reuse constraints for sections. So we have to content ourselves with a hypothetical example to illustrate how constrained market demand or constrained technical feasibility can impact the energy and cost savings of reuse. For this first analysis we assume that market demand and technical feasibility is virtually unlimited for very low component recovery rates, decreases with increasing amount of available deconstructed sections and reaches limit values as the component recovery rate approaches 1. One possible analytical form of the resulting reuse yield for both cases is $r_c = 0.5/(0.5 + c_c)$. Here, the reuse yield for complete component recovery $(c_c = 1)$ is 0.5/1.5=0.33, which means that the reuse loop is only able to absorb a maximum of a third of all arising end-of-life sections. If we assume that limited feasibility of re-fabrication constrains the reuse yield in such a way, the cost and energy functions for the LTF case, C_{LTF} and E_{LTF}, show that increasing the deconstruction rate beyond a certain value does not deliver any additional cost or energy savings (see Figure 5). More and more of the deconstructed sections have to bypass the re-fabrication step and serve as scrap input for the EAF route, a poor second choice. In the LMD case we now assume that re-fabrication happens unconstrained but market demand is limited in the way outlined above. Figure 6 shows that C_{LMD} and E_{LMD} decrease slightly, reach a minimum and then increase again, the system cost even rising above the initial value at zero deconstruction. In the LMD case increased deconstruction leads to increased re-fabrication but more and more of the re-fabricated sections lack market demand and have to be diverted to the EAF route instead. So the cost and energy expenditure of re-fabrication increasingly turns into a failed investment. Note that system cost and energy consumption reach their minima at different deconstruction rates, which means that economic and environmental incentives are not aligned any more. Our hypothetical example shows that a constrained reuse yield can completely alter the economic and environmental performance of reuse. Quantitative analysis of such supply loop constraints is new and demanding research territory but will be necessary for the successful design of environmentally desirable but currently constrained supply loops.

4 CONCLUSIONS

Our paper supports the view that there are strong environmental and economic incentives that favour a shift from recycling structural steel sections to reusing them. We find that the general unconstrained economics of the production and consumption system adequately mirror the environmental gains to be made from increased reuse. Our research also shows, though, that bottlenecks in the supply loop of section reuse like limited deconstruction, limited technical feasibility or limited market demand can readily invert the situation. An uncoordinated supply loop can even lead to an increase in system cost or energy consumption. For section reuse to increase it will be necessary to coordinate the three activities of the supply loop, deconstruction, re-fabrication and re-marketing, and address their various issues and constraints simultaneously, since the most restrictive constraint determines the overall viability of the supply loop. The systematic collection and exchange of information throughout the entire production and consumption system will be indispensable for this. Coordination within the supply loop is not enough, though, but has to be expanded to the entire production and consumption system. It is, for example, obvious that within current supply chain and loop structures the producers of BF or EAF sections have a disincentive against reuse since it results in missed revenues for them. The overall economics of the system has to be reflected in the financial incentives of each of the economic agents. New business models will be needed to address this. The systems approach we used for our quantitative analysis is ideal to model these issues and can be readily extended to research not just the economic and environmental performance of the entire system but also of the subsystems in control of the various agents and the conflicts between them.

5 REFERENCES

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