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Adaptation of portal frames topology for a broader reuse potential

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Abstract

In the context of climate change and material scarcity, potentials of reusing structural elements through 'design from stock' computational methods have been demonstrated. Yet, such workflows still struggle to be put into practice, because they do not match the current market demand. Since the 1980's, structural steel added to the building stock has mostly gone to portal-frame buildings. Most of the frames are built with material-intensive I-shape bars. This paper investigates a design strategy that could foster the reuse of this specific kind of stock. We propose to extend design from stock workflows with a pratical design concept based on fixed-length members and braced connectors that change the portal frame topology, thus enabling a lateral extension of the frames. The work is based on a realistic case study. Warehouses representative of current designs provide I-sections to be rearranged as new sets of frames. Solutions are compared based on environmental criteria. The influence of parameters such as supply distances, manufacturing and refurbisment energy consumptions is assessed. The study confirms the relevance of reuse in structural design compared to business as usual strategies. It opens the way for a new kind of *hybrid* design from stock.

Keywords: Reuse, Portal frames, Bending-dominated components, Environmental impact, Life Cycle Assessment, Design for Reuse, Design from stock

1. Introduction

1.1. Reuse of superstructure components

Due to his high durability, steel appears as one of the best materials to be reused in structural design. In the past few decades, the rise of labor costs compared to material costs has driven steel contractors to highly resort to material-intensive I-section bars [1]. Such steel products have been designed to display good flexural behavior, which makes them suitable for standard frame structures. Building frames with these products requires a reduced number of operations in the steel workshop. In areas with high demolition rates, steel frame and portal-frame buildings can thus be seen as secondary material mines providing reclaimed steel sections. Since the 1980's, industrial buildings represent up to 60% of steel building construction in France [2].

However, several issues still restrain the reuse process, both at the design and construction stages. First, reusing structural elements reverses the design logic: components are not prescribed as per the design, but the design itself shall derive from the available reclaimed components [3]. Computational methods have been developed to carry out stock-constrained design. Such workflows enable to integrate available elements of predetermined length and section into an initial layout which topology is adapted accordingly. Available algorithms minimize global mass, cut-off length or environmental impact while ensuring structural constraints are respected. The methods have mostly been implemented for reticular structures [4] [5] [6]. A similar framework was tested for frame structures [7] [8].

1.2. Technologies to foster the reuse of load bearing components

Intensifying the reuse of structural elements also implies to reduce the complexity and cost of selective deconstruction and refurbishment. Regarding connectors, research mainly focuses on the development of beam-to-slab and beam-to-columns connections [9]. Mechanical bolted connectors are preferred to chemical welded assemblies as, in the case of bolted connections, the components integrity is preserved during the deconstruction sequence [10] [11]. To maximize the elements' reuse potential, connection organs chemically bounded to the elements shall be limited. In the context of steel structures, this supposes to limit plates, haunches and gussets welded to the main element. In the case of portal frames, 20 to 25% of the rafter sections is lost if extremities are cut to remove the haunches. For this reason, connections with independent third component are preferred [10].

1.3. Problem statement

This paper focuses on the reuse of portal frame rafters. A typical configuration is shown in Figure 2 (a), where the rafter corresponds to the BC beam. Rafters of warehouses' portal-frames represent from one third up to half of the total structural mass (see Figure 7). Preserving the structural performance of rafters over the (re)use cycles is key to ensure a high-quality, relevant reuse process. Because bending-dominated I-section bars are optimized for a specific *load versus length* couple, we do not consider cutting reclaimed beams, not even to remove the end connectors. Following the principles of design for *open-ended* reuse exposed by Brand [12], Baverel et al. [13] and Fivet [14], we rather develop a beam-to-column flexible system capable of marginally increasing the rafter length. The system is presented in Figure 1 and will be described in Section 2.1.

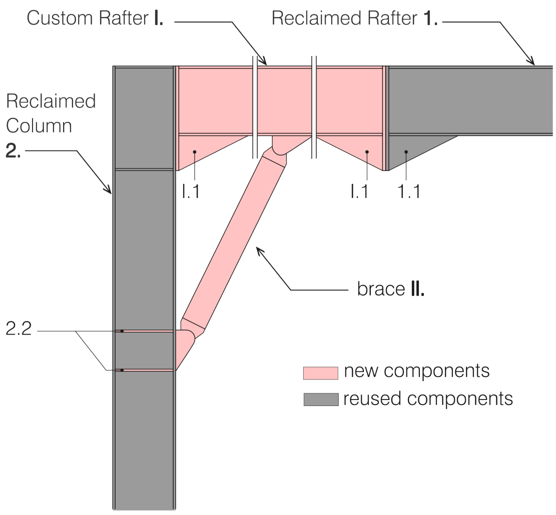

Figure 1: Outline of beam-to-column custom connector used for rafter extension

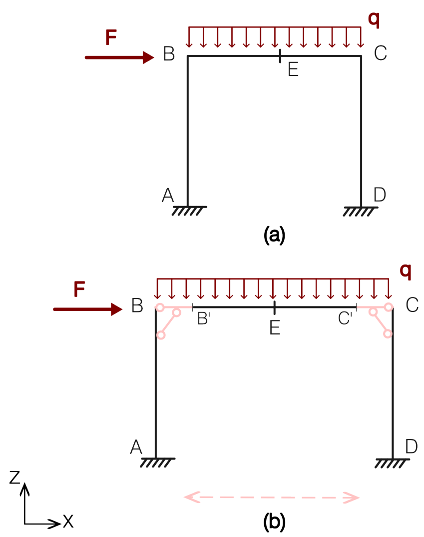

Figure 2: Statics and loads, with and without custom braced connectors

This design strategy is compared to different reused scenarios based on Life Cycle Assessment (LCA) (Sections 2.2 to 2.4). The benefits from preserving the rafter's length over the reuse process are confirmed (Section 3.). Thus, this new system opens the way for a *hybrid* stock-constrain design (Section 4.).

2. Methodology

2.1. Extending rafters with custom connectors

The proposed constructive system is composed of a custom rafter and a brace : in Figure 1, Custom Rafter **I.** is attached to Reclaimed Beam **1.** and to Reclaimed Column **2.** with bolted end-plate standardized connections. The dimensions of Haunches **I.1**, **1.1** derive from the beam cross section. The haunchs' height (resp. length) corresponds to one half (resp. one unit) of the cross section height. Brace **II.** is made out of SHS section in order to optimize out-of-plane buckling resistance. If necessary, stiffeners (**2.2**) are added to the column where Brace **II.** is connected. At the end of Reclaimed Beam **1.**, haunches increase the cross-section static height and create a bending-moment connection to Custom Rafter **I.**. In such a system, the rafter statics is preserved : in Figure 2 (a), the rafter beam from B to C is moved to B' to C' in Figure 2 (b). In both cases, end restraints B and B' (resp. C and C') are rigid.

2.2. Evaluating the reuse strategy: a case study

We evaluate the environmental relevance of the above system thanks to a LCA. A case study is carried out to compare our strategy with other reuse scenarios. The study outline is depicted in Figure 3 : warehouse wh_1 has to be built. To do so, two existing warehouses ($wh_{0,1}$ and $wh_{0,2}$) are available for deconstruction and reuse. We consider these old warehouses as one-off material banks in which we can invest to get secondary materials for our new construction project. Warehouses are defined by a set of specifications, displayed on Figure 3. The specifications include geometric parameters - frame span L, frame height H and long side L_{ls} - and load parameters - dead load G, wind pressure W and snow load S. We study the reuse of primary portal frame structures and of roofs' purlin systems.

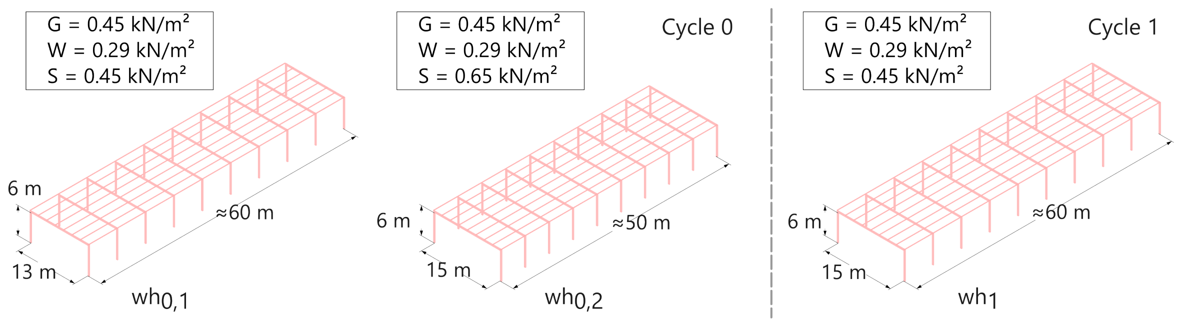

Figure 3: Design specifications: two existing warehouses at Cycle 0, one to be built at Cycle 1

All the scenarii are illustrated in Figure 4. Scenario 1 corresponds to the business as usual default scenario where wh_1 is built new. In Scenario 2, only wh_{0_2} is deconstructed and provides frames for wh_1. The bay length l_{bay} needs to be adjusted, so the whole purlin system is replaced. In Scenario 3, only wh_{0_1} is deconstructed and reused. The purlin system is kept and rafters are extended following Section 2.1. reuse strategy. Finally, in Scenario 4, we consider that both wh_{0_1} and wh_{0_2} are deconstructed and combined in a full-reused stucture.

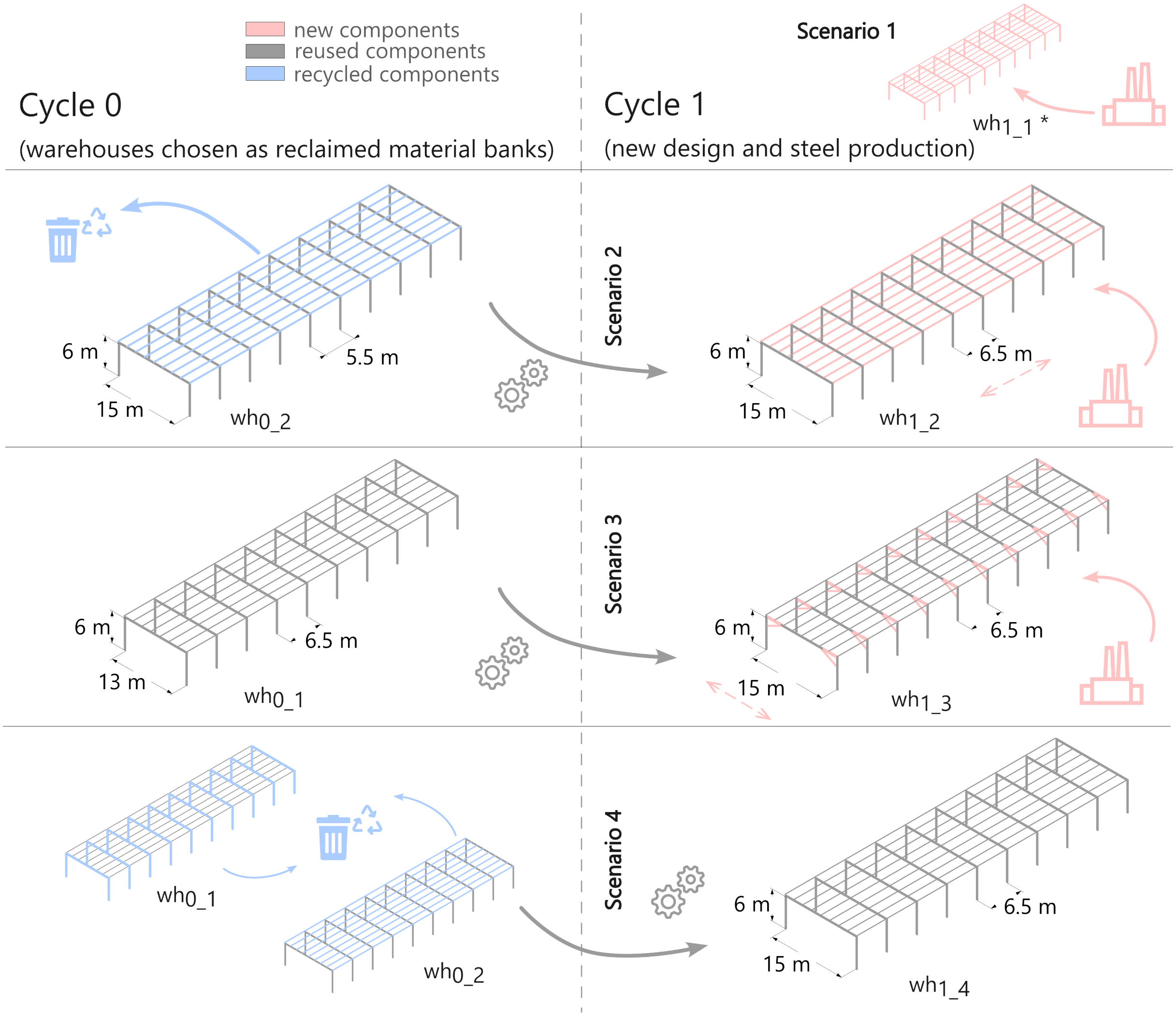

Figure 4: Case study scenarii. * Geometrical parameters for wh_{1_1} are given in Figure 3.

2.3. Computational model for baseline configuration

Baseline configurations correspond to the warehouses designed as minimal weight structures made out of new components. Warehouses wh_{0_1}, wh_{0_2} from Cycle 0 and wh_{1_1} from Cycle 1 (Scenario 1, business-as-usual) are computed this way. Design parameters include the rafter (resp. column, purlin and brace) cross-section (denoted by Sec_rafter, resp. Sec_column, Sec_purlin, Sec_brace) along with the distance from frame to frame, denoted by l_{bay}. The frames have three statically indetermined internal forces so we use the brut force algorithm. For each component, the algorithm iterates over the I-section standard catalog. Thus, the whole combinatorial space is explored. Analytical formulations of normal force N, shear force V and bending-moment M are used to evaluate the internal forces of each combination. The space of admissible solutions is determined by checking each combination against resistance criteria at ULS (Equations (1), at all nodes) and deflection criteria at SLS (Equations (2), at nodes B and E). Finally, the minimum mass solution is retrieved. Results of business-as-usual minimal mass solutions are provided in Table 1. For all reuse scenarios, structural checks of Equations (1) and (2) are carried out to validate the new configurations.

$$M_{Ed} < M_{Rd}\,,\;\; V_{Ed} < V_{Rd}\,,\;\; N_{Ed} < N_{Rd}\,,\;\; N_{Ed} < N_{pl,y,Rd} \tag{1}$$

$$u_x^B \ < \ H \setminus 150 \ , \ \ u_z^E \ < \ L \setminus 250 \tag{2}$$

Table 1: Warehouses designed with *new* I-section bars. See design specifications above in Fig. 3.

wh	l_{bay} (m)	N_{bays}	Sec_rafter	Sec_column	Sec_purlin	M (kg)	m $(kg.m^{-2})$
wh_{0_1}	6.5	9	IPE330	IPE300	IPE140	17484	23.0
wh_{0_2}	5.5	9	IPE400	IPE300	IPE120	19642	26.5
wh_{1_1}	6.5	9	IPE400	IPE300	IPE140	21800	24.8

2.4. Environmental impact assessment

The system's boundaries and the processes considered in our LCA model are shown in Figure 5. We choose the 100:0 allocation approach, also referred as *cut-off*. In the context of this case study, this means that all the impacts of steel production occuring at Cycle 0 are allocated to Cycle 0 only, even if components are reused later on. Similarly, the end-of-life impacts (e.g. impacts of deconstruction) are allocated only to the components employing reused content, in Cycle 1. Although other allocation approaches have been studied in the context of reuse [15], only *cut-off* is evaluated here, for the sake of concision.

For each scenario, the functional unit (FU) is the erected warehouse structure.

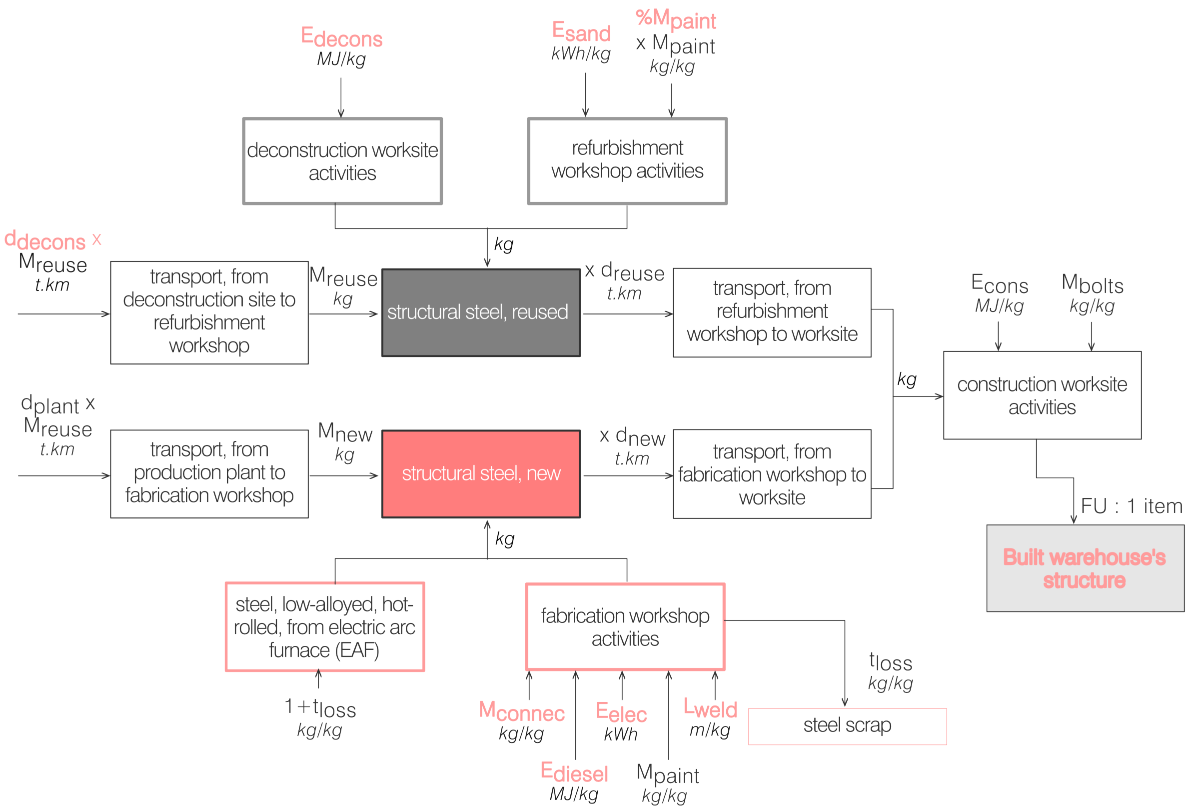

Figure 5: Foreground processes used in computational model. Flows highlighted in light red are parametrized according to Table 2

We use ecoinvent 3.9.1 as background data. Steel contractor VIRY - who founded this research - provided the foreground data, which corresponds to the baseline workshop and worksite activities. For these activities, we consider a loss rate $t_{loss} = 8\%$ within the fabrication workshop. The following quantities of paint and bolted fasteners are required per kilogram of structural steel : $M_{paint} = 0.01\ kg/kg$, $M_{bolts} = 0.02\ kg/kg$. In the construction worksite, cranes and engines consume $E_{cons} = 0.12\ MJ$ per kilogram of erected steel. Other baseline parameters are described in Table 2. We compare Reuse Scenarios 2 & 3 to Baseline Scenario 1, in which steel beams are made out of recycled steel scrap. Thus, we consider an electric arc furnace (EAF) production process for the production of new steel. The EAF production plant is supposed to be located at a distance $d_{plant} = 350\ km$ from the fabrication workshop. From the workshops to the erection site, we consider a distance of $d_{new} = d_{reuse} = 300\ km$.

Since deconstruction and refurbishment processes are still not known in details, the quantities of material and energy required by these processes are parametrized following different hypothesis : *low*, corresponding to baseline and/or optimistic values, *medium* and *high* pessimistic values. The parameters include the energy consumed during deconstruction E_{decons}, the energy required for sanding reclaimed steel components E_{sand}, the ratio of paint to be replaced $\%M_{paint}$. Furthermore, the system introduced in Section 2.1. potentially presents higher fabrication rates than a basic steel structure. For Scenario 3, the fabrication energies E_{diesel} and E_{elec}, the welding rate L_{weld} and the connection rate $M_{connect}$ are parametrized according to Table 2. Beware that, in Scenario 2, only the purlin system is replaced and produced as new. Purlins correspond to traditionnal structural components for which we only consider baseline fabrication parameters. Additionnaly, we set different supply distances d_{decons} from the deconstruction worksite to the refurbishment workshop. The influence of each parameter should be assessed independently. For the sake of concision, they vary all together in the context of this paper.

The environnmental impact is then computed with ReCiPe 2016 assessment method [16]. This method proposes Endpoints indicators which aggregate intermediate environmental indicators into damages categories : *Ecosystems Quality*, *Human Health* and *Resources Scarcity*. Well-known environmental indicators such as global warming, water scarcity or particulate matter formation contribute to each of these three Endpoint categories.

Table 2: Fabrication and refurbishment parameters used in the LCA model

Parameter	Unit	Values low	med.	high	low	med.	high
		Scenarii 2 & 4			*Scenario 3*		
E_{diesel}	MJ	0.2 (*baseline*)			0.2	0.6	0.9
E_{elec}	kWh	0.1 (*baseline*)			0.1	0.3	0.5
L_{weld}	m	0.1 (*baseline*)			0.1	0.2	0.3
M_{connec}	kg	0.05 (*baseline*)			0.04	0.07	0.1
d_{decons}	km	100	300	1000	100	300	1000
E_{sand}	kWh	0	0.1	0.5	0	0.1	0.5
$\%M_{paint}$	%	0%	50%	100%	0%	50%	100%

3. Results

3.1. Contribution analysis for new and reused steel

Figure 6 (a) illustrates the processes' contributions to the impacts of $1kg$ of structural steel, either from the recycling or the reuse industry. While reading this figure, one should be careful that, from

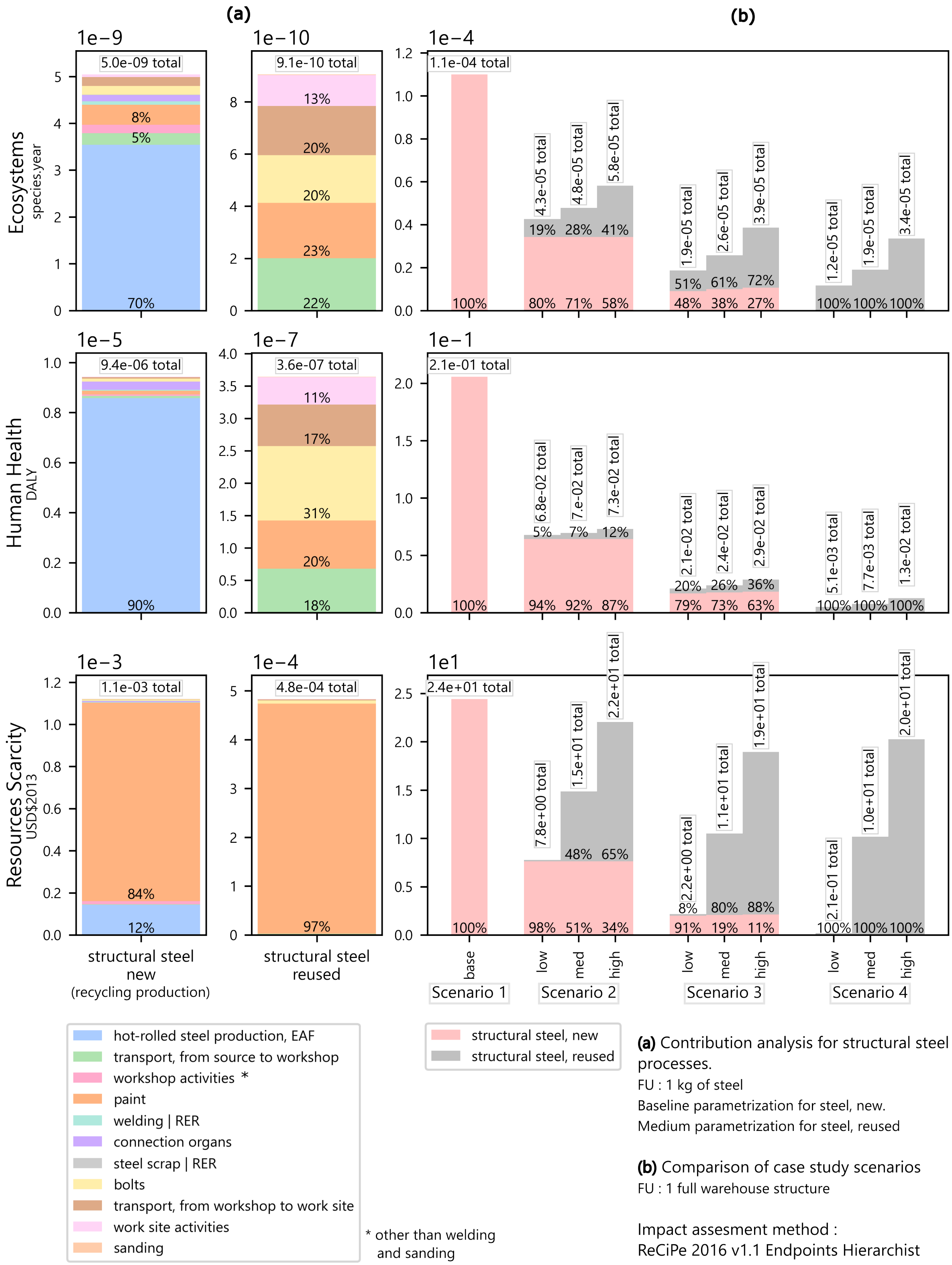

Figure 6: LCA results : Contribution analysis for 1kg of steel. Endpoint-based scenarii comparison.

recycling to reuse, the vertical scales vary by an order of magnitude. In the case of new recycled steel, EAF production is still responsible for 70% of the impact on ecosystems and for 90% of the impact on human health. The three main contributors are : production of hot-rolled steel, paint surface protection and transport. This suggests that, for new recycled steel, high manufacturing rates (such as welding or workshop energy consumption) will not affect global environmental results. As for reclaimed and refurbished steel, the top contributor is transport (from deconstruction site to workshop and from workshop to erection site) for the impacts on ecosystems and human health. Contributions of bolted organs, paint and worksite energy consumption are then shared almost evenly, from 10 to 20% of total impacts. Concerning resources scarcity, in both cases, the impact is mostly driven by the paint protection. Anti-corrosion paints usually display high concentrations of metals and minerals. The paint from ecoinvent that we chose shows a high content of titane dioxide. The relevance of using such paint to model a structural anti-corrosion protection should be further investigated. Overall, total impacts are around ten times (resp. one hundred times) higher for new recycled steel than for reclaimed and reused steel.

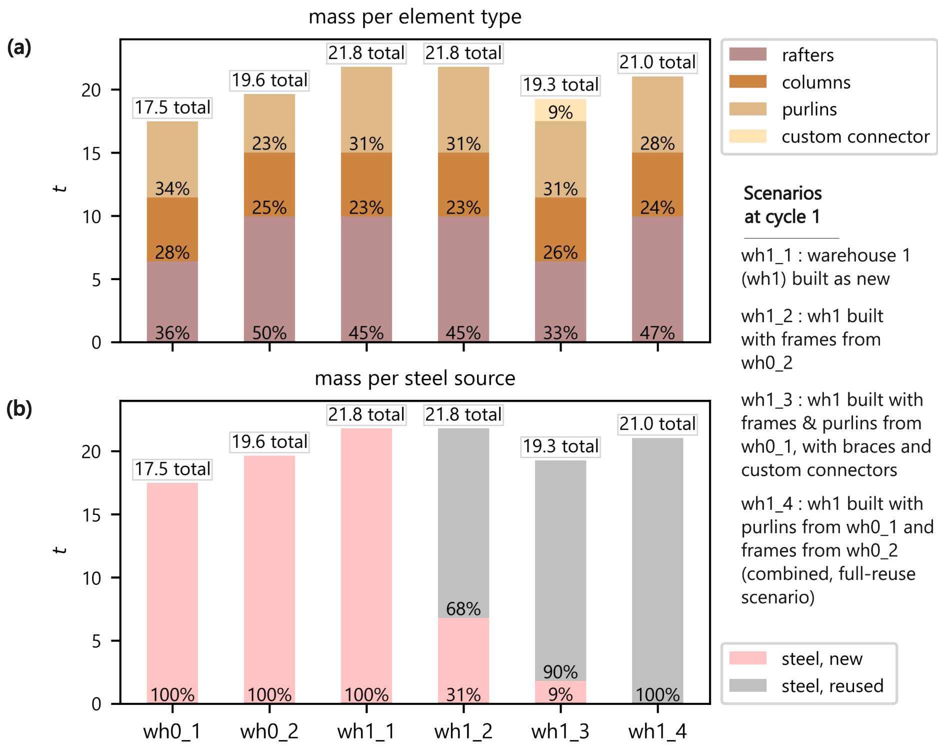

Figure 7: Mass repartition for all warehouses' structures

3.2. Scenario comparison

For the adopted allocation approach, Figure 6 (b) confirms that, regardless of the scenario, reusing steel enable to reduce from two third to half of the impacts on ecosystems and from two third to 90% of the impacts on human health (medium parametrization for Scenarii 2, 3 & 4 compared to Scenario 1). Even under unfavourable fabrication and refurbishment hypothesis (*high* parametrizarion), our design strategy evaluated through Scenario 3 still leads to substantial impact reductions. The custom connector displays higher manufacturing rates than a traditional structural component, but it represents less than 10% of the overall structural mass (Figure 7 (a)). The contribution analysis described above is confirmed: high manufacturing rates do not affect the global environmental results. Yet, impacts on Human Health are still mostly driven by steel production, even in Scenario 3. Further improvements may then be achieved by a full-reuse approach, as evaluated in Scenario 4, or by looking at the drivers of EAF production impacts and improving the supply chain accordingly. Yet, such levers would only lead to minor reductions compared to what has already been obtained through Scenario 3. From business-as-usual Scenario 1 to custom component strategy in Scenario 3, we reduced the impacts by an order of magnitude. From Scenario 3 to Scenario 4 (or with supply chain improvement), we only gain a fraction of the impacts. Moreover, economical challenges may appear when trying to achieve a design with reused components only. As a larger stock is required, one may need to invest in the deconstruction of multiple buildings, as Scenario 4 depicts it.

4. Discussion & conclusion

Results commented in Section 3. confirm the relevance of the system presented in Section 2.1. in terms of environmental performances. Efforts in structural design have always been focused on reducing the structures' mass. This study highlights that this concern can be combined with reuse in order to pursue resource sobriety and reduction of environmental impacts. Figure 7 illustrates that our design strategy evaluated through Scenario 3 features the lowest overall mass among wh_1 designs. This study on portal frames shows that well-known design parameters such as statics and topology are key even for the most basic structure of all, and are compatible with standardization. They shall be reinvestigated in the light of future reuse. The concepts developed in this paper open the way for a new kind of stock-based design, in which beam components are combined with custom components. Thanks to bar lengths adaptation, one single dismantled warehouse can be considered an adequate stock, saving the costs of looking for more beam references in other *urban mines*.

A two-level standardization process could then be considered, with a first catalog of standard beams, and a second one made of more versatile braced connectors. As their contribution to the total steel mass is minor, connectors could arguably be remelted for recycling, if a reuse possibility is not easily found for them. Combining two kinds of components might first increase stock-based design complexity. Yet, we saw that introducing bracings within portal frames enables to extend the rafters' length while keeping the same cross section. Future studies should investigate the conditions under which this system could actually reduce the number of items required in the catalog composed of standard beams. Eventually, further research should also focus on anti-corrosion surface treatment and its durability over the (re)use cycles, as the results suggested that paint is mainly responsible for resource scarcity impacts. The LCA results should also display the contribution analysis of the EAF production process as, even in a context of reuse, it still represents an important share of the impacts.

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