Construction, deconstruction, reuse of the structural elements: the circular economy to reach zero carbon

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Abstract. The research work presented aims at setting up an infinite cycle of use of materials by their reuse and answering in particular to the problems of circular economy. Structural work and foundations represent the majority of the embodied energy of a building. The research effort is therefore focused on the structural elements. Reuse is here defined as the reuse of an element without transformation, unlike recycling which induces a new industrial cycle. It is therefore about reducing the consumption of materials and lowering GHG emissions. Today, it is impossible in France to reuse structures because of responsibilities, insurance and lack of traceability. How to make possible the reuse of structural components in order to reach a low carbon building? The challenge of this work is to find the best structural configuration making the components reuse easier at the EOL. The methodology we are implementing aims to design the structural elements by increasing the BIM parameters (6D, LCA), to attach the mechanical information, material durability, ageing to each object of the digital mock-up. A digital and physical traceability makes it possible to follow the evolution of the element over the years and to feed a database. At the end of its life the database is accessible and searchable for the design of a future building. A development of tools and gateways will then allow from a model of calculation to go to query the database to find an element resulting from the deconstruction that can be reused in the future structure.

1. The need for solutions to environmental issues

The environmental findings require rethinking our construction methods to fight against the depletion of natural resources and greenhouse gases (GHGs) emissions.

1.1. The environmental impacts of construction

The construction and building industry is the principal emitter of GHGs [1] with 116 million tonnes of CO₂ equivalent (according to the Global Warming Potential, EN 15804) i.e. 33% of total GHGs, and the biggest consumer of material with, for example, in the USA in 2017, the total value of industrial minerals production which was $48.9 billion, a 3% increase from that of 2016. Of this total, $23 billion was
aggregates production (construction sand and gravel and crushed stone), that is to say around half dedicated to concrete. [2].

These emissions have two distinct causes: energy consumption or functional energy (electricity, heating, ventilation, etc.) and energy used during its construction, known as embodied energy (production of materials, transport, site, etc.). Buildings are now capable of producing their own functional energy and providing the required level of user comfort. Environmental impact assessments show that for recent buildings, the majority of total GHG is due to this embodied energy [3]. In his study [4], Peuportier shows that for a RT 2005-compliant building (RT 2005 for the French thermal regulation for buildings), approximately 12% of total contribution is due to embodied energy but this figure rises to 29% for a passive building, as confirmed by [5]. Research work must now focus on reducing embodied energy due to construction activities.

In terms of where a building’s embodied energy is used, structural works is found to be the main culprit. To this effect, Hoxha, in his doctoral thesis defended in 2015, analysed 16 collective buildings and concluded that concrete was preponderant for impact indicators: waste, renewable energy, and climate change [6]. Accordingly, elements of superstructure linked to elements of infrastructure and foundations make up more than half of a building’s embodied energy with 58% of the LCA Global Warming Potential impact of a building’s component products and systems [7]. This makes civil engineering a key focus to reduce environmental impacts over the coming years according to Figure 1.

1.2. The circular economy (CE) applied to structural works

The research presented suggests solutions to the issues of the CE. The ultimate objective of the CE is to break the pattern of economic growth depleting natural resources. The idea is to extend the useful life of material (reuse, recycling) and products (eco-design) over the product’s entire lifespan. This model is based on creating positive feedback loops for each use or reuse of the material or product before its final destruction. The material is passed on indefinitely from stakeholder to stakeholder until a new use process is found. The research is focused on structural elements, which have a greater impact in terms of GHG as the Global Warming Potential according to EN 15804 reveals, and establishing the conditions for their reuse, which is more sustainable before recycling and then energy recovery. In France, legal definition for reuse is: particular preventive action designating any operation by which substances, materials or products that are not waste are reused for a use identical to that for which they had been
designed. To this effect, in April 2018 the French government presented its roadmap to develop a 100% CE. It wants to “turn existing buildings into a bank of future construction materials”.

1.3. Reuse of structural elements
Reuse induces additional operations for its establishment as dismantling, transport, storage, reprocessing and reconstruct. Brière, in his doctoral thesis defended in 2016, has established five parameters to evaluate the environmental impact of re-use: \( I_c \) (collection impact); \( I_s \) (storage impact); \( I_t \) (transport impact); \( I_r \) (reprocessing impact) and \( I_a \) (avoided impacts) [8]. Brière proposed re-employment specific impacts that were not included in the current standardization. With these parameters he studied three scenarios for a reinforced concrete beam in an existing housing building: its reuse, recycling and landfilling. He showed that the reuse scenario was for many indicators the most relevant solution in the case where 10 beams from the recovery would replace 7 new beams. Now if we consider a structure designed to be disassembled, impacts \( I_c \) and \( I_t \) will be substantially reduced. Better traceability will allow keeping the same number of reused beams as the number of new beams. The present study of ten tall buildings structural configurations for easy reuse leads to the best 86% of reusable hinged posts (for the posts parameter), so that is 18% of the climate change impact of the structure. The database presented here may also decrease \( I_c \).

So the idea is to reduce consumption of materials and cut GHG emissions. Eventually, anticipated design in terms of end-of-life (EOL) reuse will prevent any waste being produced. The primary energy will also necessarily be reduced if we avoid the manufacture of new elements thanks to the reuse of the elements manufactured in the past. However, materials already used in the structures of the buildings surrounding us, known as “stockpiles”, will be difficult or even impossible to reuse. Technically, there are no major obstacles but as far as liability and consequences in terms of insurance and above all due to the cost involved, reuse of current structures is not worth a client considering. However, methods and processes are progressively being consolidated, as explained in the “Repar 2” paper [9], which looks at the loadbearing wall deconstruction and reuse methodology. However, today re-use implies the downgrading of the structural elements. To achieve the minimum environmental impact, the structural function should be maintained at the same level.

The lack of traceability of material characteristics and the loss or inexistence of documents such as as-built records faced by prime contractors working on existing real-estate, often prevents them from making any attempt to reuse materials. The residual performance characterisation and assessment process can become an obstacle to decision-making.

To enable this reuse of structural elements, it is essential that it be anticipated in current designs of structures that will be built tomorrow.

2. The need for data traceability from the design
In the same way that information on the existing structure is to be found in the case of rehabilitation, reuse induces an anticipation of the necessary information in 30, 50 years or more for future engineers.

2.1. Liability data
By being properly insured in France, the engineer can cover their mandatory ten-year liability. From an insurance point of view, evidence of use of a standard technique must be provided to be insured without having to pay any additional premiums. However, reuse is neither covered by standardised technical documents. So for the moment reuse cannot be recognised as a standard technique.

To this end, all structural data essential for the engineer recovering the element in 30 or 100 years’ time will need to be linked during the design phase. On a structural level, knowledge of at least the physical and mechanical properties of the materials is expected. The list must be drawn up based on the structural function: column, beam, loadbearing wall, crosswall, slab, but also the type of material:

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[1] https://www.lemoniteur.fr/article/economie-circulaire-les-5-mesures-qui-imacteront-le-btp.1966709
concrete, steel, wood, etc. Additional studies by structural engineers may be required based on the
degree of complexity of the dismantled structure and the project featuring the reused elements.
Traceability must be made reliable using digital tools to guarantee the data linked to the structural
elements.

2.2. 6D BIM: sustainable development data
A study shows that existing DfD practices and tools are not BIM compliant [10]. Tools are developing
to optimize deconstruction and EOL but have not been thought for reuse and DfReu (Design for Reuse)
practices. The described methodology here aims to design structural elements by increasing the BIM
6D² and life cycle assessment (LCA) parameters. 6D is the “dimension” covering environmental data³
relating to sustainable development. The BIM tool then helps the designer and client to assess the
environmental impact of decisions taken throughout the project until its EOL. Engineers can react to
this carbon footprint and propose the most environmentally-friendly construction systems.

2.3. Structural calculation data: BIM to reuse structure
For essential reasons of liability, a structural engineer who decides to reuse an element previously used
in another building must make sure he is fully aware of the characteristics of this element and possibly
the conditions of life of the entire structure of which it was a component. The principal structural data
for high-rise buildings can be divided into four categories:

- the properties of the element (static): geometry, composition, resistance class, relevant standard,
etc.;
- the behaviour of the element (mechanical): position, type of loads, stress applied, connection
conditions, creep, ageing characteristics, etc.;
- the overall behaviour of the structure (mechanical): exposure class, differential shortening, soil
compaction, top displacement, top acceleration, differential displacements between floors,
scaling criterion, useful life of structure, etc.;
- information for the reuse process: checks required, residual performance tests, deconstruction
phasing, etc.

3. Types of traceability
As previously seen, many pieces of information needed for the reuse of structural components have to
be obtained through specific traceability.

3.1. Digital traceability: BIM model
Each stakeholder tends to take ownership of a model by modifying part of the initial data for their own
use. At the end of the chain, some data is definitively lost as a result. For reuse, digital building models
and as-built records are particularly crucial. A system of filters to manage access to certain data based
on stakeholders concerned must be set up to prevent deletion of data not used at this stage of the project
but also guarantee a level of confidentiality.

3.2. Passive physical traceability: RFID chips
Passive physical traceability refers to systems that can be integrated into materials for a very long time
(life of the element) and that will be self-sufficient over this time. So most will not have a built-in power
supply but rather the reader, e.g. “Near Field Communication” (NFC) system, will supply the power
needed to read the data built into the material. The most fully-developed technology is currently the
“radio frequency identification” (RFID) chip. Start-ups plan to incorporate RFID chips into concrete
before or during its implementation. RFID chip are self-sufficient and could potentially last forever.

² 6D: Covers all issues concerning a building’s sustainable development, e.g. energy assessments and estimated carbon footprint
for each phase.
³ http://www.mediaconstruct.fr/ha-ba-bim/fondamentaux-bim
Today the RFID chips used are designed to withstand attacks (especially in concrete). Once trapped in the material, nothing can come to damage the chip as the structural element is not damaged either. However, this contemporary technology has a very short experience feedback (2013 for the first chips in concrete in France). But current designers point to a potentially infinite lifespan inside the elements. The information is hosted digitally and remotely. Potentially, this information could be corrupted (malicious modifications, deletions). RFID chips can also internally store an unmodifiable text file but it must be extremely limited in size. Today, there are three types of RFID chips [11]: passive, semi-passive, and active. Active chips have a power source. This means they have a significant read-write range (5 to 30m), further than passive chips (approx. 2m or under). But this makes these active chips more expensive than passive labels. Passive chips, however, are very cheap and very resistant to harsh environments, which means they can be submerged in concrete when its pouring.

The problem with these contemporary technologies is their immaturity. There’s still only very limited user feedback, well the reuse process covers periods of 20, 50, 100 years, or even more. Passive traceability is better suited to recording the properties of the element (static).

3.3. Active physical traceability: sensors, IoT

Though active RFID chips are available, it’s preferable to use sensors to benefit from full-building instrumentation. Using sensors linked to the Internet of Things (IoT), changes to the element can be monitored over time and data progressively added to the database. The IoT’s potential was initially identified for the operation and maintenance of smart buildings. It is also very useful for reuse, offering comprehensive monitoring of a structure’s functional behaviour.

To reuse structural elements, their full history, particularly in terms of specific stresses and strains to which they have been subjected, needs to be known. Today, it can help to improve knowledge of the structure, for example including: monitoring of the structure’s overall behaviour, direct marking of materials for geolocation purposes, real-time strain alerts. So instrumentation monitoring can be easily adapted for reuse purposes. Structural health monitoring (SHM) methodologies provide information on the ageing of elements and data for updating and checking calculation models.

Finally, it should be noted that active traceability is better suited to the needs of monitoring the structure’s overall behaviour (mechanical).

4. Design to reach total reuse

As previously discussed, reuse of existing building is not optimal. However today it is necessary to build differently to systematize the reuse of the elements implemented in new buildings.

4.1. Bank of available materials

The reuse process is anticipated in the very long term. The objective is of course to integrate the principles of this methodology into contemporary design. The actual lifespan of buildings varies according to criteria that cannot always be predicted when they are built (real-estate market trends, changing development project needs, etc.). Current trends show a sometimes very short lifespan of around twenty years (mainly for offices) and the history of architecture is littered with buildings that practically last forever. The reuse process is based on a certain level of renewal of existing real-estate, which is estimated to have a lifespan of between 20 and 100 years.

So a materials bank created today, from the structures we are currently building, must be designed to remain effective over the next 100 years or at least to enable its upgrading to ensure compatibility with future technologies. The materials bank can be designed for a multi-owner client who wants to become self-sufficient in raw materials and who would use his material resources to supply materials for the entire renewal of his existing real-estate, just-in-time. It can also be designed at a national level on a very large scale based on the trend set by the French government with the objective of achieving a
100% CE. If data on all new-builds is added to this database, there will be sufficient choice to integrate a large number of reuse elements into new structures.

4.2. New paradigm of design

High-rise buildings have potential for reuse due to the repetitiveness of its structural elements. For this exercise, structural elements subjected to simple stresses (compression) are preferable and overly complex elements are to be avoided (combined bending and axial load). In fact, the more an element is subjected to a simple stress, the less specific it will be, which will increase its chances and fields of subsequent reuse. For a complex element, it will be even more difficult to find a use configuration similar to its initial use.

The connections between these elements play a decisive role in determining whether the structure can be deconstructed [12]. Use of reversible connections [13], which do not damage the materials or its characteristics, must be anticipated during the design phase. This means that their impact on the overall model must be assessed. An in-depth structural analysis is then required to determine the points that should be hinged and the ones that need to be fixed. The choice of the structural typology is also essential [14] and must be analyzed for its reuse potential. Accordingly, a study conducted at setec tpi (the French engineering and civil engineering company that finances this PhD research) analysed 10 models (based on four different concrete load-bearing systems rated M1 to M4 in Table 1) of a high-rise office 41-storey building, attempting to hinge as many elements as possible and comparing their carbon impact.

The variants of a single load-bearing system are rated A to D (none / façade / interior / façade + interior) with a varying number of hinged elements illustrated in Figure 2. For M2C (Model with “Outriggers + cross bracing” and 540 hinged posts) to M2D (Model with “Outriggers + cross bracing” and 1452 hinged posts), an increase in the number of articulated poles of 269% causes an increase in the climate change indicator of only 0.56% in 1st cycle. This study promises also an 18% decrease for this impact in 2nd life cycle, if the posts are reused. It is particularly important for there to be a balance between types of connections, deconstructability, quantity of material used and safe disassembly.

![Figure 2. Study of structural variants of an office tower with the aim of hinging as many columns as possible.](image-url)
Table 1. Relationship between increasing articulated posts and increasing the climate change impact of the structure.

| Number of hinged posts (maximal increase) | Total CO₂/sqm (maximal increase) |
|------------------------------------------|----------------------------------|
| M0 “Concrete tube”                       | -                                |
| M1 “Tubed mega frame + outriggers”       | -                                |
| M2 “Outriggers + cross bracing”          | 268,89%                          |
| M3 “Crosswall + cross bracing”           | 242,22%                          |

5. End-Of-Life (EOL) reuse process to design a new building

Therefore, the first effort is to build reusable buildings today. But tomorrow, we must learn to build anew with these components from deconstructions.

5.1. Conceptual margins

Designing a new building using reused elements is different from the “traditional” design process that we use on a daily basis. Depending on what element are available in the database, the geometry of its structure will have to be more or less flexible. One of the challenges is setting acceptable margins for the choice of elements. For the span of a beam, for example, a range will have to be determined such as plus or minus 50cm for the span of a batch of beams, according to the materials available in the database. The new geometry of the building must then be adapted according to the batch of available beams. These margins inevitably have an impact on the overall design. However, it is expected that most reused elements will be available in batches and it will be easy to find several identical elements, which will mean only one criterion will have to be adjusted. If the span of the beam is adapted by increasing it by +50cm, this will be the case for all the beams. The more beams on the database, the easier it will be to find the right span, without margins.

The same applies for ceiling height, which is today calculated for maximum gain with a view to building the maximum number of floors for operational profitability. With reuse, increased structural height can be expected, but also a considerable economic gain on the cost of the reused materials. For safety reasons, an additional margin in the safety coefficients is to be expected. Even if in the very long term, design needs to be adapted to reuse as many reused elements as possible, the transition will be progressive, with first, integration of vertical elements, which are more structurally suited to recovery.

5.2. Compiling this information: the database

This database is a bank of materials for future buildings. When the existing building, of which the elements feature in this database, is set to be deconstructed, the elements become available for a new structural project. When the structural engineer designs their new project, they create a calculation model. Based on this calculation model, queries are sent to the database to identify a structural element that could fulfil a new function over its second life cycle. This process is illustrated in Figure 3.
This database system, to which data is added whenever a new building is constructed, makes it possible to work on a just-in-time basis with these structural elements and avoid storage issues, particularly in areas with little space available such as metropolises. However, the amount of data must be limited and optimised. Reducing the amount of data will, inter alia, make it possible to save both calculation and database search time, plus energy on the servers that are used.

For this research, the parameters were listed by materials and by phase according to the different stages of the project and entered in the BIM model. The information is attached to the objects in the BIM model. The methodology proposes to export, at each end of phase, these parameters on the database (ultimate normal effort, etc.). A gateway between the BIM model and the database and then the software for calculating reused structures has been developed.

5.3. Database queries
Depending on the stage of the project, queries will be more or less complex. For a column, for example, the initial issue may be to find a column in the database with an allowable stress enabling it to bear the load determined in the calculation model following analysis of the distribution of loads in the building. Next, the compatibility of the existing reinforcement drawing with the new use must be thoroughly checked.

This database query process will be an iterative process as a series of hypothetical uncertainties will have to be examined. Clearly, if the modelling of the new structure requires the use of a 50x50cm section beam and, in the database, the beam best meeting the stresses of the model has a section of 60x60cm, the structure’s overall weight will be modified. As a result, a certain number of iterations are to be expected.

6. Concluding remarks and work to be continued
The contribution of the article concerns the reflection on the properties that must be known for reuse and the best tall building structural typology to achieve this. The environmental assessment of this unusual design questions impact allocations, especially for future reuse benefits. This research work has so far focused on the design of high-rise buildings to make their structure removable. Decommissioning scenarios must now be clarified and optimized to reach zero carbon. Data from traditional demolition sector must be refined for deconstruction. Then the data from deconstruction, transport, storage and
reconstruction will make it possible to specify life cycle assessments with all the environmental impact indicators.

References

[1] CITEPA Réaliser une analyse environnementale, Guide sectoriel 2015 [Online] Available: http://bilans-ges.ademe.fr/docutheque/docs/guide%20finalis%C3%A9%20FNTP%20avril%202015.pdf. [Accessed November 29, 2017]

[2] U.S. Department of the Interior and U.S. Geological Survey Mineral Commodity summaries 2018 [Online]. Available: https://minerals.usgs.gov/minerals/pubs/mcs/2018/mcs2018.pdf. [Accessed September 13, 2018]

[3] Cabeza L F, Rincón L, Vilarriño V, Pérez G and Castell A 2014 Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review Renewable and Sustainable Energy Reviews 129 pp 394–416

[4] Thierry S and Peuportier B 2008 Thermal and environmental assessment of a passive building equipped with an earth-to-air heat exchanger in France Solar Energy 182 pp 820–831

[5] Zabalza Bribian I, Aranda Uson A and Scarpellini S 2009 Life cycle assessment in buildings: State-of-the-art and simplified LCA methodology as a complement for building certification Building and Environment 144 pp 2510–2520

[6] Hoxha E 2015 Amélioration de la fiabilité des évaluations environnementales des bâtiments, Université Paris-Est, Ecole Doctorale Sciences, Ingénierie et Environnement, Thèse de Doctorat

[7] CTB, n° 349, Mars 2016, «Béton vert, la prescription décisive,» Mars 2016 [Online] Available: https://www.cahiers-techniques-batiment.fr/article/beton-vert-la-prescription-décisive.16789. [Accessed April 30, 2018]

[8] Brière R 2016 Etude ACV des chantiers de démolition en vue de la préservation des ressources, Matériaux composites et construction, Université Paris-Est, Thèse de Doctorat

[9] Benoit J, Saurel G, Billet M, Bourgain F and Laurenceau S April, 2018 REPAR 2 : Le réemploi passerelle entre architecture et industrie (Paris: ADEME, BELLASTOCK, CSTB) pp 23-360

[10] Akinade O, Oyedele L, Omotoso K, Ajayi S, Bilal M, Owolabi H, Alaka H, Ayris L and Looney J H 2017 BIM-based deconstruction tool: Towards essential functionalities International Journal of Sustainable Built Environment 16 pp 260-271

[11] Lacovidou E, Purnell P and Lim M K 2018 The use of smart technologies in enabling construction components reuse: A viable method or a problem creating solution? Journal of Environmental Management 216 pp 214-223

[12] Akanbi L, Oyedele L, Akinade O, Ajayi A, Delgado M, Bilal M and Bello S 2018 Salvaging building materials in a circular economy: A BIM-based whole-life Resources, Conservation & Recycling 129 pp 175-186

[13] Escaleira C, Amoêda R and Cruz P J S 2013 Buildings’ connections and material recovery: from deductive to inductive approach Portugal SB13 - Contribution of Sustainable Building to Meet EU 20-20-20 Targets

[14] Banks C, Burridge J, Cammelli S, Chiorino M, Ha T, Jaeger J-M, Keleris G, Marsh S, Romo J, McKechnie S, Truby A and Wells J 2014 Tall Buildings: Structural design of concrete buildings up to 300 m tall (London: fib and The Concrete Centre) pp 3-24

[15] Université Numérique Ingénierie et Technologie, «Le BIM normalisé IFC dynamiquement partageable,» UNIT, Janvier 2012. [Online] Available: http://www.unit.eu/cours/bim/u11/co/u11_110_11-4-1.html. [Accessed November 18, 2017]