Design for Reuse (DfReu) applied to buildings; anticipate disassembly for the End-of-Life (EoL), in order to preserve resources

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Abstract

The construction and building industry is the principal emitter of GHG in France with 116 million tons of CO_2 equivalent, i.e. 33% of total GHG, according to CITEPA, 2015; and the biggest consumer of material. 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.). 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 of transformation of matter. It is therefore about reducing the consumption of materials and lowering GHG emissions. Reuse is not sufficiently taken into account in environmental assessments and requires new indicators in LCA methodologies. Several considerations are needed to evaluate reuse including: (1) calling the lifespan of buildings fixed at 50 years for the life cycle into question, in order to take into account the different cycles; (2) distinguish the LCA of the building from that of the products; (3) adapt D module from EN 15804 to the very new and not yet professional sector of reuse; (4) new allocation system for both initial deconstructed building and reconstructed second building to benefit from the positive impacts of reuse; (5) integrate the several possible scenarios of second lives for an initial product (same function / downgrading / redirecting, need to be evaluated differently). The missing data identified have to be generated by the relevant stakeholders.

In order to reuse these elements to the fullest of their initial capacity, it is important to transfer the necessary characteristics to the future "reuse designer". The design for rebuild methodology we are implementing aims to design the structural elements by increasing the BIM parameters (6D, LCA), to attach the environmental impact, the mechanical information, material durability, ageing to each object of the digital mock-up. We envisioned to install digital and physical traceability (like RFID chips in the material) that makes it possible to follow the evolution of the element over the years and to feed a database in parallel. 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. The objective is to find an element resulting from the deconstruction that can be reused in the future construction. The challenge of this work is to ensure that the element of the database has all the characteristics to meet its new structural function. Next step is to implement the presented methodology on experimentations.

Keywords:

Reuse of materials, LCA, Building Circular economy, environmental BIM, Design for Reuse

1 THE NEED FOR SOLUTIONS TO ENVIRONMENTAL ISSUES

Regularly, environmental policies indicate that the construction sector must contribute to achieving the Sustainable Development Goals. Construction has a significant environmental impact. 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 tons of CO_2 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, analyzed 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.
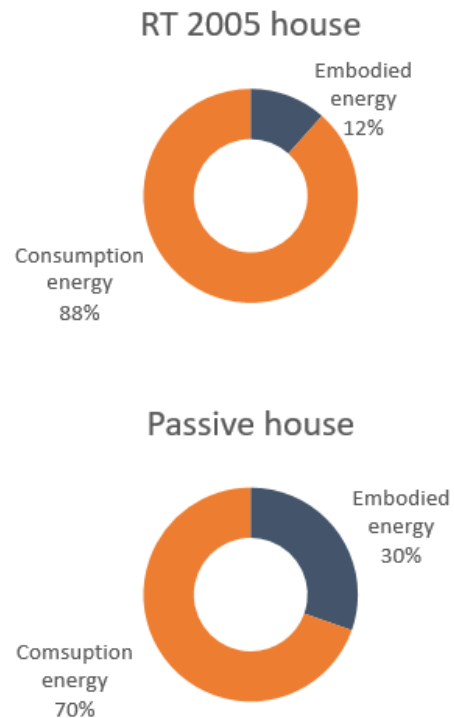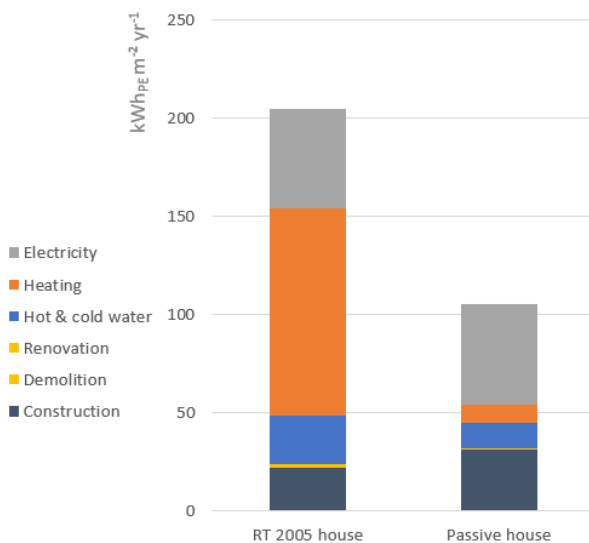

Fig. 1 (a) (b) : Embodied energy contribution to the global balance. Peuportier B, EIVP Summer University of September 6, 2018. [4].

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: Ic (collection impact); Is (storage impact); It (transport impact); Ir (reprocessing impact) and Ie (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 Ic and Ir 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 Is.

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 characterization 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: 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.

2.4 Types of traceability

Digital traceability: BIM model

Each stakeholder tends to take ownership of a model by modifying part of the initial data for their own use. 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.

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. 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).

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 (mechanical).

3 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.

3.1 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.

3.2 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.

1ST STEP : database of existing real estate

REVIT
existing structures

Data extraction :
.IFC, Excel?

DATABASE
Visual Studio and SQL server

responses

*requests
(via clustering)*

2ND STEP : new project design

REVIT
*design iterations,
modeling*

*Spaceclaim?
Dynamo?
Grasshopper?*

PYTHAGORE
KARAMBA
ETABS
*calculation models,
iterations*

.TXT, Excel, Decoda

3RD STEP : shared new project data

REVIT
*execution, update of the
digital model for owner
delivery*

*Extracting data
for supplying the database
.IFC, Excel?*

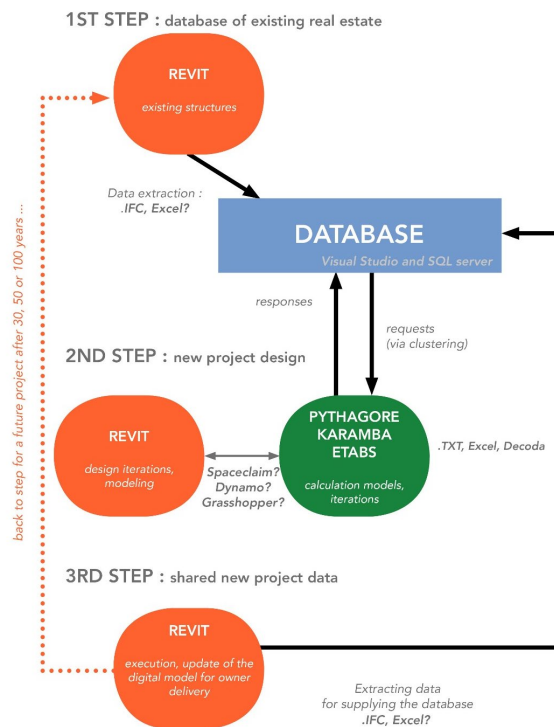*back to step for a future project after 30, 50 or 100 years ...*

Fig. 2: Methodology for a database from the BIM

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.

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 [11]. Use of reversible connections [12], 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 [13] 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) of a high-rise office 41-storey building, attempting to hinge as many elements as possible and comparing their carbon impact. Several number of hinged elements variants (none / façade / interior / façade + interior) are developed.

Sensitivity studies of these variants on LCA (EN 15804) parameters are underway in this PhD research.

4.3 New life cycle scenario

Reuse is not sufficiently taken into account in environmental assessments and requires new indicators in LCA methodologies. Several considerations are needed to evaluate reuse including: (1) calling the lifespan of buildings fixed at 50 years for the life cycle into question, in order to take into account the different cycles; (2) distinguish the LCA of the building from that of the products; (3) adapt D module from EN 15804 to the very new and not yet professional sector of reuse; (4) new allocation system for both initial deconstructed building and reconstructed second building to benefit from the positive impacts of reuse; (5) integrate the several possible scenarios of second lives for an initial product (same function / downgrading / redirecting, need to be evaluated differently).

5 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.

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