Sustainability in lightweight modular construction for housing

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ABSTRACT: The central issue of the research synthesized in this paper is how the building industry sector could develop some resource management strategies which can close the materials cycle. In order to do this, the possibilities of industrialized lightweight architecture were analyzed under the physical demands of the "strong" sustainability. Light volumetric modular building type was studied because it possesses some important characteristics: a) Industrialized construction permits to work whit a limited number of materials and to control related amounts of resources and waste, b) This system has developed an innovative commercialization form. Renting modules come back from building to factory after use allowing reuse, refurbishment and recycling without waste generation. c) Modular units are available globally without technologies inconveniences, d) They are adaptable to different climates and regional conditions and, finally, e) Similar building systems can take advantage from the strategies developed.

1 TOWARDS CLOSING THE MATERIALS CYCLE

1.1 *From a physical point of view*

The Earth is an open system in terms of energy yet a closed system in terms of materials, and it is a lot easier to convert material into energy than it is to convert energy into material. Therefore, material must be effectively controlled in order to ensure proper management of resources and waste matter.

Living organisms need to break down energy and material to keep them alive, and the only way to avoid this process causing entropic damage to the Earth is by using renewable energy from solar sources. This would permit a complete recycling of materials, in a way similar to photosynthesis, the process that allowed the biosphere and the human species to develop (Naredo, Valero).

Can we continue to use non-renewable resources? Human life depends on the 'stock' of material found in the Earth's crust. The question is how natural energy sources can be used to close the cycle of material, allowing waste to convert back into resources, avoiding damage to the Earth's crust due to waste contamination and diffusion of raw material.

Economically speaking, the value of goods (in this case, non-renewable energy) is determined by the cost of extracting the material, not by the cost of replacing it. This explains why extraction is the preferred method to the cost of recycling (an oversight that we will end up paying for), making the civilized world's industrialized system of production less and less like that of the biosphere, which in contrast is sustainable (Cuchi).

There are two clearly different ideas of sustainability. Weak sustainability was developed as a result of the standards of today's economic climate, and strong sustainability was developed on the principles of thermodynamics (physic's version of economics) and ecology (nature's version of economics). The former type of sustainability relies on the Earth's natural stock of capital, supposing the replacement of the stocks by man-made products, and the latter type of sustainability recognizes that the Earth's natural stock of capital can not be replaced by a manufactured material and thus, efforts must be made to avoid the deterioration of these sources (Naredo, Valero).

For this, it is necessary to establish an institutionalized framework and a social conscience that will promote renewable production and recycling as opposed to extracting material and transporting it long distance. These are key issues that must be considered in order to promote the management of closing the materials cycle.

1.2 *From an industrial point of view*

The industrial metabolism is an integrated system of processes that converts raw material and energy into waste. Production is not regulated in itself; it is directly influenced by human factors such as the workforce, and indirectly influenced by the rate of consumption, which in turn determines demand. In a decentralized economy, the industrial system is regulated by the balance between supply and demand of products and work, by means of the price of the product. The economic framework is, in essence, the regulatory mechanism of the industrial metabolism.

One major difference between biological and industrial metabolisms is illustrated when comparing the life cycles of material or nutrients. The water cycle and nitrogen cycle are examples well known to scientists, yet while they are closed cycles, the industrial equivalent is an open cycle. Generally speaking, the industrial metabolism fails to recycle its nutrients. The process begins with high quality raw material that is extracted from the Earth's crust (such as minerals or fossil fuels), which is returned back to the earth in a state of deterioration, thus increasing entropy (Ayres, Ayres).

The cycle of materials is generally seen as a system of compartments containing stocks of one or more nutrients bound by certain flows. The system is closed when it does not need any external supply, like the planet as a whole, for example (except for the phenomenon of meteorites). The system starts to become a closed cycle when stocks of each component are constant or do not significantly vary. This implies that there must be a balance between what goes into and comes out of each compartment.

The closed cycle of materials can sustain itself indefinitely thanks to a continuous flow of exergy. In brief, exergy means the minimum amount of useful energy which is necessary to make a system from its primary elements when they are in a dead ambient. Exergy becomes usual as a cost measure in a sustainable analysis. This is directly determined by the second law of thermodynamics, which states that global entropy is an increasing, yet irreversible process. The exergy would be used simultaneously if it was not conserved, and consequently the closed cycle would be able to sustain itself for as long as the flow of external exergy lasted.

The open cycle however is unstable and unsustainable. It either stabilizes or collapses against the thermal equilibrium of each of the flows until all physical and biological activity comes to a halt.

The industrial metabolism is normally an open cycle. Hence it can synthesize in a systematic sequence the extraction of raw material and the production of waste. Yet this system possesses a hypothetical number of intermediary cycles that would allow the system to be closed.

What was until recently considered as waste can nowadays be considered as raw material. In the last few years, various companies such as carpet manufacturers have developed new technology that allows their factories to be powered by recycled raw material. This technology replaces the linear production process that has been in use since the industrial revolution (extracting unlimited quantities of raw material and converting it into contaminated waste). Instead it is a cyclical process similar to that of the biosphere, which does not create waste, but raw material that can be used over and over again to manufacture brand new products. Nylon coating can be recycled into new nylon thread, and polyester casing into new polyester fiber. An example of this development is Interface, the world leader carpet producer; it has created a biopolymer derived from natural resources such as plants. It is 100% recyclable, but also compostable and can be used to make a single material carpet. Some of the Interface factories are changing our energy sources to renewable energy ones (Anderson).

Another method of closing the materials cycle is by using eco-industrial systems. These are areas, for example an industrial park or a region, where all material used is collected then recycled back into the system. In this way the system only consumes renewable energy from outside, and produces a service, not a product, to be sold on the market (this is made possible by renting instead of selling the service). Perhaps the most famous case of this type is the Kalundborg industrial park in Denmark where, in brief, residual heat from an energy plant and a petrol refinery was used to heat greenhouses. The industrial waste was converted into products such as fertilizer or building material.

In an eco-industrial system, four basic conditions permit the material cycle to be a closed cycle. Firstly, the operation must be large scale to allow for the interchange of diverse material, and include a company that will ensure large scale activity, such as an exportation company. Secondly, there must be a large company in the local area that would be able to absorb the waste produced by the first company, after having converted the waste into usable material. Thirdly, there must be other specialized 'satellite' companies to use the rest of the first company's waste, either as raw material or as marketable goods. Fourthly, and most importantly, a mechanism needs to be put in place that will ensure long-term technical co-operation between participating companies. The organization with the responsibility of ensuring such conditions would be the exportation company, or an organized group of companies, or even a public agency.

2 HOW CAN THE MATERIALS CYCLE BE CLOSED IN ARCHITECTURE?

When it comes to closing the material cycle, there are many advantages associated with industrialized construction systems as opposed to the traditional ones (which normally have an on-site factory, intensive labor and non reversible joints).

Modular co-ordination, standardization, mass production and control of the manufacturing process all facilitate the streamlining and optimization of the use of resources. Such characteristics also permit the reduction, revaluation and reuse of waste matter. Industry is technically capable of converting left over and faulty material into new raw material or components, and this is important to the strategy of revaluing waste, and converting it into usable raw material.

Industrialized construction normally uses both heavy systems (500-2000 kg/m^2, usually concrete) and light systems (approximately 150-500 kg/m^2, wood, plastic or metal). Each type uses different amounts of material and energy resources. Heavy systems need larger quantities of on-site materials and fixed weights for larger structures, and also require the means of transport and assembly suitable for heavy loads. Light systems can use smaller amounts of material, and therefore require transport and assembly suitable for light loads.

The use of light systems can therefore give rise to dematerialization (or increase in the productivity of material resources), which is the second important strategy.

An interesting type of light industrial system is the modular 3D which is usually made of metal, and measures 2.44m (interior width), 2.6m (exterior height), and 6.01-12.02m (length), conforming to the standard ISO norm for transport containers. Modular units and reversible joints allow the buildings to be assembled and dismantled time and again, and also allow for changing the layout or function of the building. Therefore, the building's modular units can be reused at other times, in other buildings, and can also be used for partial restoration. This is the third strategy, deconstruction and reconstruction, (instead of demolition, the building can be rebuilt and taken down numerous times, until its modular parts are no longer fit for use.)

The modular 3D structure is generally made of two frames (floor and roof), and four columns made of tubes or cross sections of steel. Modular paneling, such as floor, covering, roof, insulation, woodwork and interior finish, is assembled onto the structure. The paneling is easy to assemble and dismantle, and component parts can be changed with ease. In addition, when the parts can no longer be used, they can be separated into their component materials. This is the fourth strategy; the substitution of materials (for example substituting polyurethane, PVC, and organic solvent-based paints for other non-contaminating materials that can be recycled.)

A final point to consider is that the marketing strategy for modular systems is based on leasing, rather than selling. In this way, the temporary and permanent modular 3D buildings can be leased from the suppliers, who will take care of assembly, maintenance and dismantling, and once finished with, the modular units are returned to the manufacturer. There are many companies in Europe who offer this service, for example Algeco, Balat, Bauart, Erne, Interlink, Yves Cougnaud. This leads to the fifth strategy, the three R's, repair, reuse and recycling (the modular components are sent back to the manufacturer, this proves to be technically and economically viable).

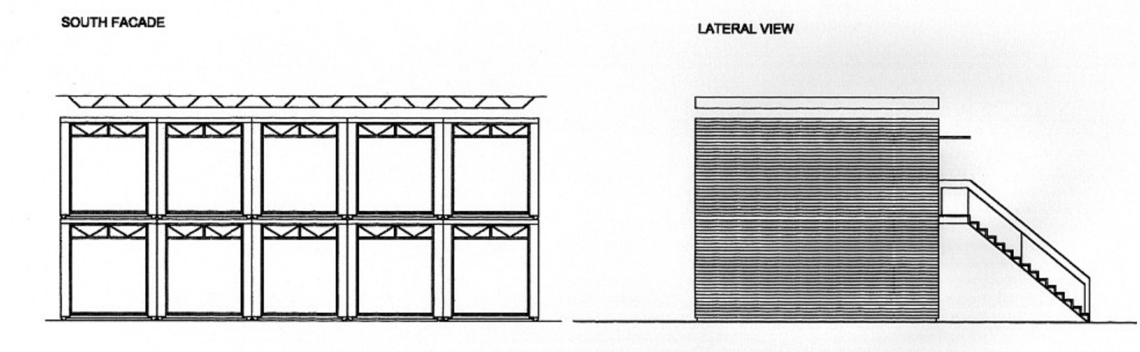

Figure 1. Typical lightweight modular units available in Spain.

3 WY BUILD BY STEEL?

The composition of modular 3D structures that are sold in Spain (eg Algeco, Balat, Yves Cougnaud systems etc.) is as follows; steel 105.4kg/m^2, wood 17kg/m^2, polyurethane 5.6kg/m^2, aluminum 20kg/m^2, paint 1.5kg/m^2, copper 0.3kg/m^2 (Algeco). Steel accounts for two-thirds of the total material weight, and is the principal area of study in this type of building system.

One can consider that there are three types of recyclable material. The first group is made up of materials that are economically and technologically compatible in question in terms of price and regulations. The second group is material that is not recycled for economic reasons, although technically recycling it would be possible. The third group consists of material that cannot be recycled due to economic and technological reasons. The majority of structural metal belongs to the first category of materials, and steel in particular offers many advantages over other types of metal when it comes to recycling (eg. magnetism for an easy separation process).

The technology to manufacture and use steel in construction is widespread, and it is globally available. This means that, in principle, a particular technological innovation constructed in steel could have an impact in many other parts of the world. Its structural capacity allows for the effective use of small quantities of material that can be reinforced using laminating streamlining and folding techniques.

Steel is one of the most recycled materials in the world, 350 million tones are recycled each year, and this recycling process dates back to approximately 100 years ago (IISI). Steel can be recycled many times over, without losing the quality of the material. From the fourth recycling process, embodied energy and emissions of CO_2, SO_X and NO_X gases from the steel produced from minerals reduces by between 25 and 30% (British Steel 1). Electric arc furnaces can use nearly 100% of the scrap metal to produce new steel, a process which in some countries is economically convenient to make several types of building pieces (ISSI). At the moment, about 80% of the scrap metal available is converted into new steel and there is still demand for a lot more because approximately a half of the world's industrial production is still derived from minerals (IISI).

Material that has been painted and galvanized can still be recycled. This will not affect the process, as the gases are either eliminated during melting, or turned into solid waste which can be separated from the recycled material at the end of the process. Galvanization zinc is usually recovered when recycling steel (ATEG). This is different for other metals, as once they have been covered, they cannot be easily recycled (eg some painted aluminum).

Approximately 95% of the total amount of steel used in a building can be recycled, thus the building can be leased for an amount of time, still as part of the structure. Like the modular 3D, many structural components and even completed steel structures can be leased for the space of time that they are required for, instead of being sold. In some cases the parts are designed to be assembled and dismantled, allowing for further use. An example of this type of building system is the Hangar Nº2 in Cardington Airport, which was relocated to the Building Research Establishment (British Steel 1).

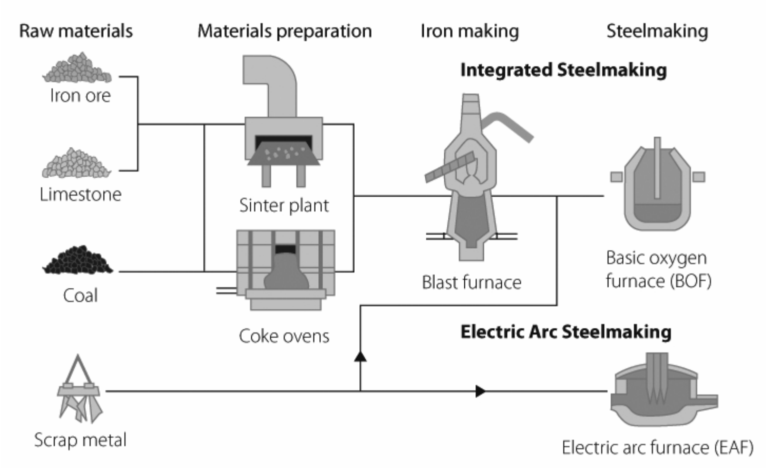

Figure 2. Basic oxygen and electric arc furnace production steel system

4 AN ENVIRONMENTAL ASSESSMENT APPROACH

Three types of houses were analyzed by using TCQ 2000 Environmental Management Module software developed for the Institut de Tecnologia de la Construcció de Catalunya, ITeC. First, predominant concrete structure and brickwork based (Conventional). Second, standard Algeco's modular unit steel based that are usually sold in Spain (Basic modular). Third, improved modular unit based on environmentally friendly materials modifications (Optimized modular).

Direct and indirect materials consumption, embodied energy and green house emissions of the construction phase were calculated for each type of building. First, all materials involved were accounted in order to determinate its weights in a representative square meter composition. Second, these materials amounts were converted to energy consumption and CO_2 gas emissions using the environmental information of the PR/PCT building database of the ITeC. Third, a similar process were followed in order to determinate the material intensity per unit of service (MIPS) for abiotic, biotic and water resources affected into the extraction and production stages, where Wuppertal Institute MIPS indicators were used.

The results chart shows that there are several gaps between Conventional, Basic modular and Optimized modular types. Synthetically speaking the last one reaches the smallest levels at each environmental impact effect considered but in order to evaluate the closing the loop condition a recycling potential and zero waste approach should be developed in deep.

Table 1.Environmental indicators for both conventional and modular construction at the building phase (basic modular is showed as reference).

	Conventional	Basic modular	Optimized modular
Building materials (kg/m^2)*	2.961 (285%)	1.038 (100%)	205 (20%)
Energy (MJ/m^2)*	6.987 (90%)	7.768 (100%)	2.721 (35%)
Greenhouse emissions (kgCO_2/m^2)*	672 (79%)	847 (100%)	143 (17%)
Total material requested TMR1 (kg/m^2)**	7.405 (232%)	3.193 (100%)	1.072 (34%)
Total material requested TMR2 (kg/m^2)**	23.777 (119%)	19.990 (100%)	7.435 (37%)

* ITeC building materials PR/PCT data base was utilised. ** TMR1: abiotic + biotic resources, TMR2: abiotic + biotic + water resources. Wuppertal Institute Material Intensity indicators were used.

In order to see how the optimized module house type can be affected for the different Barcelona climate conditions an indoor temperature simulation was done. Solar protection (textile screens on south exposed windows) and mass inertia (10cm thick concrete floor slab) building components were added to the initial configuration. By using Balanç (De Bobes, Tribó), dairy interior temperatures were calculated for winter and summer without both heating and cooling help. Analyzing them into the comfort temperature band (18-22ºC for winter and 24-26ºC for summer) it can be seen that heat peaks on winter and summer go beyond the maximum level. Conventional construction houses present similar cooling energy consumption areas. This is a frequent situation on several buildings like workplaces ones at Barcelona but in order to reduce them ventilation and mass inertia should be increased on module units.

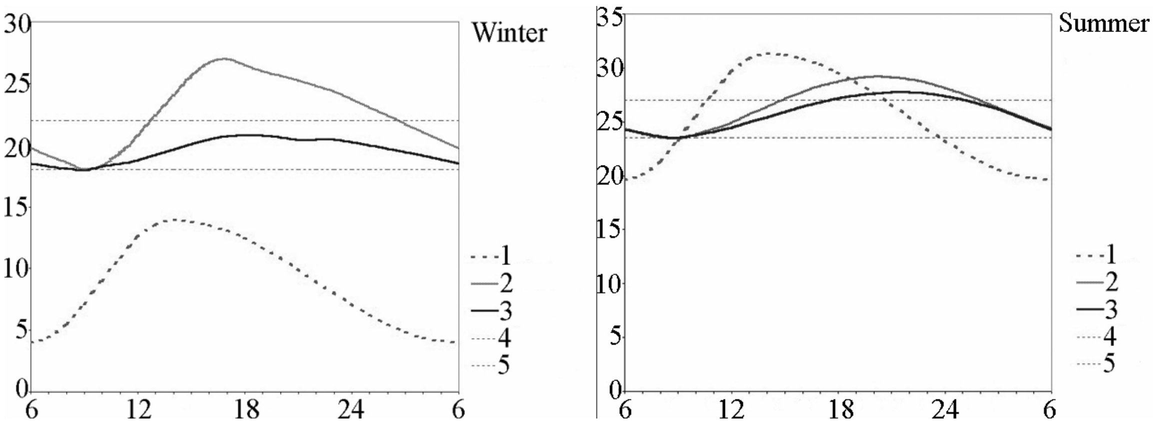

Figure 3. Typical one-day cycle of interior temperatures into the optimised modular house.
References: 1 exterior temperature, 2 sunny day interior temperature, 3 cloudy day interior temperature, 4 minimum level of comfort, 5 maximum level of comfort.

5 THE CASE OF THE VALLES SCHOOL OF ARCHITECTURE COMPETITION

In October 2001, the Technical University of Catalonia ran an open competition to extend the existing Valles School of Architecture.

One proposal was based on the same idea explained in this paper using light steel 3D modular components, in order to extend the school without any new impact on the environment. The design team was composed for Albert Cuchí, Albert Sagrera, Gerardo Wadel (architects), Anna Pagés, Isaac López (students in collaboration).

This proposal suggested the use of modular systems that are presently available on the market, and also proposed leasing the structure for 5 year periods. In order to do that an agreement would be reached with the supplier (Ormo, S.A., which is called today Algeco Spain) to gradually improve the structure, facades, roof, windows, which would create a new generation of more sustainable modular units.

From the point of view of materials, the proposal suggested the dematerialization of modular units, the revaluation of manufacturing waste and the substitution of contaminated or non-recyclable materials for other materials. Also, the deconstruction and separation of materials into their component elements, and the three R’s, repair, reuse and recycling were proposed.

From the point of view of use, the project suggested the reduction of consumption by using more efficient equipment, the collection of natural energy, the installation of thermal energy storage into the horizontal frame (British Steel 2), the refrigeration of naturally cooled air to protect from excessive heat gains in the summer. In this way the modular construction system presently in use would evolve, the cycle of resource material would be closed, and auto-sufficiency of energy resources would be maximized.

The project was praised by judges for its ‘didactic spirit, and the sheer effort that was made to establish the basis of an architectural system which respects the environment’ (Act).

In spite of this, the proposal could not awarded first, second or third price as the university management chief objected to the system of leasing. Unfortunately, the competition guidelines did not mention this expressly, yet it was interpreted that the new building had to be purchased and the leasing system could be objected from other competitors.

A few years ago, on 2004, a similar modular lightweight building system called Spacebox began to be used at some Netherlands's universities like Utrech, Delft, Eindhoven, and Hilversum, for student housing accommodation (www.spacebox.info).

Figure 3. A view of the Vallès School of Architecture proposal.

6 THE CASE OF THE INCASOL COMPETITION FOR YOUNG PUBLIC HOUSING

Few years ago the Incasol (Institut Català del Sòl), an institution of the Catalonia Government which promotes public housing, organised an open competition calling both architects and builders to show together their last technology innovations developed in the previous years as a part of their regular works.

A management idea based on the 3D lightweight modules was presented by Albert Cuchí, Albert Sagrera, and the author of this paper in collaboration to Algeco Construcciones Modulares, S.A. (modules manufacturer), obtaining a special recognition from the jury for its environmental characteristics.

From the sustainability point of view this was a closing the loop strategy for renting housing, making possible to leave behind the traditional building concept that only can consider them as a real state goods.

The project presented to the Incasol competition was based on a lightweight modular building system witch can be assembled and dismantled entirely without any important waste generation nor materials decreasing, in order to be transported and assembled in another place (reuse), to be returned to the modules factory (refurbishing), or to be given to recovering materials industries (recycling).

The central concept was focused on the change that the traditional public promoter's role should experiment in order to reduce the environmental impact of the renting housing they habitually build and manage.

To assure the described conditions it is necessary that all resources involved can be maintained into the industrial management avoiding the usual waste generation. Some traditional promoter's tasks like construction, maintenance and finally demolition, have to pass to the modular industry so new roles can be determined into the public housing promotion. The most important one probably could be to consider housing like a service in place of a building.

Modular buildings that can be assembled, dismantled and reassembled offer some other important advantages. Lightweight (150-200kg/m^2) make possible to build on low resistance grounds that usually can not resist a conventional building on (2000-2500 kg/m^2) or, in addition, make possible vertical extensions on existing buildings.

Construction-deconstruction condition permits to use ground temporararily because it does not modify the original soil characteristics (there are several locations like that in any Spanish middle or big size cities). Short construction process time (45 days approximately for the whole building) helps to accurately respond to the dynamic location of housing need.

Finally, building evolution (either parts or module units are replaced for newest ones along the building lifespan) can improve the global system performance.

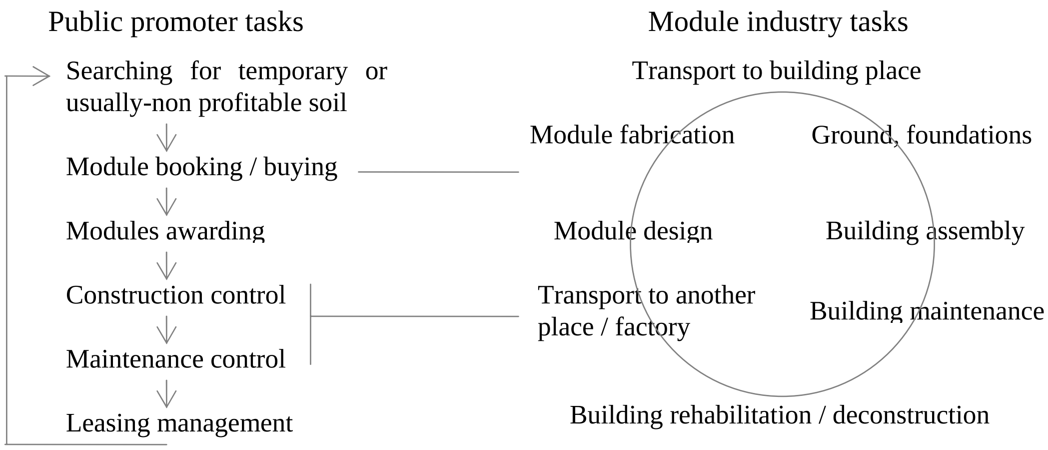

Figure 4. Promoters / industry tasks and the building closed life cycle proposed.

7 CONCLUSIONS

Only 'strong' sustainability will lead to global environmental improvement, as it can revert the process of environmental damage, while 'weak' sustainability merely focuses on parts of the overall problem.

There are two key areas to consider in the search for alternative ways of constructing sustainable architecture: closing the cycle of materials, and using renewable energy sources.

The industrial and commercial characteristics of the light 3D modular systems available in Europe provide an ideal opportunity to formulate an experimental proposal to close the cycle of materials.

The most important material to be used in this area of investigation and development would be steel, due to the mass nature of its use and the fact that it is easy to dematerialise, transport, reuse and recycle.

The technological development that allows for higher levels of sustainability in these construction systems could be used in other systems, using steel and reversible joints.

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