61. Industrial heritage of the rural environment: recovery by means of modular and prefabricated materials

Rivero-Lamela, Gloria (1, *), Ramos-Carranza, Amadeo (2)

(*) Contact author: grivero@us.es (+34) 635182970 (G. Rivero-Lamela)

(1) Department of Architectural Projects, Higher Technical School of Architecture, University of Seville

(2) Department of Architectural Projects, Higher Technical School of Architecture, University of Seville

Abstract Productive rural architecture represents one of the more significant building ensembles of the rural heritage. In the region of the Sierra de Cádiz there is a network of more than 70 water mills whose state of abandonment and disuse means that they need an intervention as a preservation mechanism, as they are heritage assets which attest to the historical connections of a community. The challenge is to intervene in these rural architectures, constructed with traditional systems, with the insertion of new small modular systems that allow their spaces to be re-inhabited. This article presents lines of action with new products and their associated construction technologies, typified by light- or self-assembly, and suggests intervention strategies related to the ideas of recycling, lightness, flexibility, modular design and environmental economy. Therefore, it is of interest to explore the capacity of these constructions as a *laboratory*, where two current themes are combined but which have been unconnected until now: rural heritage and small and industrialised modular systems. This presentation begins with some basic premises on prefabrication and industrialisation. It continues with the choice of systems, in accordance with the new environmental objectives, and the detection of products compatible with the principles and needs of the project, and finally test them in a specific place: the water mill of El Rodezno, proposing some outlines of intervention by means of a small modular system.

Keywords Heritage intervention, Water mills, Prefabrication, Industrialisation, Modular design.

1 Introduction

Productive rural architecture, shaped by mills, community granaries, tithe barns, tithe houses, farm houses, estates, presses, etc., represents one of the more significant building ensembles of civil construction in the south of the Iberian Peninsula. In accordance with this importance, the passage of time has defined a scope of buildings of rare wealth and diversity, whose values and mere survival have nevertheless been seen to be seriously threatened in recent decades as a result of the transformations that have affected the rural environment (Olmedo, 2007). These architectures are constituent parts of a landscape with heritage value, explanatory of the territory in which they are located. Even in their present state of disuse, they explain the social, cultural and economic structure of a region.

Architecture, as an empirical science, requires something concrete to recognise, review and critically opine a methodology. For that reason, this research needs to choose a scenario with well-defined actors, in our case the water mills of the Sierra de Cádiz. This region, located in the north-eastern end of the Province of Cádiz, has some differentiating physiographic, landscape and human aspects. The orographic and hydrographic conditions of this area, as well as its mountainous character, with its population and economic operation defined by dispersion and organisation into small properties, have favoured the survival of its water mills, which continue to constitute a network that contributes an interesting historical and logistic reading of the territory.

This article presents lines of action in these traditional architectures of this rural sphere, with new products and their associated construction technologies, typified by light- or auto-assembly, which enable their recovery allowing their reuse. It is not about defining new uses, but about suggesting intervention strategies related to the ideas of recycling, lightness, flexibility, modular design or environmental economy, exploring the capacity of these constructions as a *laboratory*, where two current themes are combined but which have been unconnected until now: the rural heritage and prefabricated and industrialised materials and systems.

Methodologically, this on-going research is structured into three parts from which will later be derived an important and extensive systematisation of information. The first part is dedicated to the study of prefabricated systems used in paradigmatic architecture to understand their functioning and possibilities. It is thus attempted to systematise the technical characteristics of their construction systems and structural behaviour. After a selection of these first models, the second part investigates how to update these construction solutions by means of products, materials and techniques that the construction industry offers today, to give rise to new solutions that respond to the aforementioned criteria. Finally, considering the experimental character of this research, possible intervention strategies are proposed for the semi-ruined water mill of El Rodezno, located in Ubrique, using small structural systems constructed with prefabricated products and materials that fulfil the requirements of the *Triple Zero Concept*, verifying their possibilities and capacity of adaptation, as a result of the studies undertaken in the two preceding parts.

2 On prefabrication

The construction industry makes construction products by means of industrial techniques in specialised factories, which process the materials into construction elements, independently of the atmospheric conditions and under optimal production conditions (Staib et al. 2008). *Prefabrication*[1] is a form of the industrialisation of construction (Salas 2008). One of its main advantages is the reduction of on-site time and, thereby, costs. The productive model that characterises the construction of architecture can be summarised in the linear sequence: extraction - manufacture - use - waste. This model entails an environmental load and pressure on the planet. Against this panorama, it is necessary to replace the linear productive model by a closed cyclical system: recycling - manufacture - use - new recycling (Wadel et al. 2010).

There are individual elements in prefabricated construction that determine if the process *is closed* or *open*. In the *closed* system, one single manufacturer makes all the construction elements which are coordinated with each other, and cannot be interchanged. This system, with large panels as the dominant element, had its period of splendour in Europe from 1950 to 1970. However, the crisis of the following decade[2] exacerbated the debate on its limitations. This method originated homogenous and standardised products, however, the architecture did not constitute a closed or uniform product. An effective industrialised system is the *open* system that can adapt to any architecture. The challenge of architecture does not consist of camouflaging it in a finished industrial product, but of constructing it using industrial processes of assembly of the components from a catalogue, always open to innovating solutions (Ruiz-Larrea et al. 2008). As J. Stirling (1968) indicates, each project has distinctive features (Fig. 1):

> I would argue that our buildings have always evolved from a broad but usually complex understanding of logic. Logic is many faceted and its properties are not normally the same for every buildings; each project has its own hierarchy of importance, sometimes revealed by Client´s Brief and always determined by the sensibility of the Architect.

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[1]The word *prefabrication* is not in the RAE Dictionary; however, the adjective *prefabricated* does appear: said of a construction: formed by parts made previously for their later assembly.

[2]The 1970-1973 economic crisis and Oil Crisis entailed the considerable reduction of the average size of works.

For that reason, from 1985, the open systems were developed, which offer the possibility of constructing by combining prefabricated products from different sources and generated with different industrial production methods, thereby introducing flexibility and extending the construction possibilities. Although the evolution of *industrialisation* in construction is not linear nor homogenous and does not have a start date, the studies that have shaped its theoretical framework are important. One of the most important contributions in the housing field has been the method of *supports*, produced in Holland in the 1960s by N.J. Habraken, which is based on the idea of separating everything that cannot be removed from a building, the supports, from that which can be transformed by the user (Habraken, 1962). As a result of his ideas, Stichting Architecten Research (SAR) was created in 1964, under which Habraken proposed pilot programmes and prototypes, and which has resulted in the *Open Building*[3]. A current application based on this theory of Habraken was proposed by E. Corres in the System C (Fig. 2):

Fig. 1 Leicester Engineering Building (Stirling, 1968)

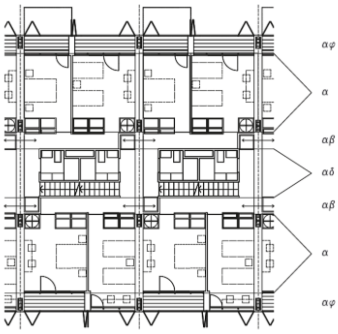

Fig. 2 System C, based on the method of Supports (Corres, 2012)

Component based industrialisation defines the functional elements or units of a project, which are the group of variables that must be the object of joint design decisions (Salas 2008), and must be, primarily, standardised and dimensionally coordinated components, to enable interchange and additions.

These basic notions on prefabrication provide a better understanding of where the latest reflections on the construction industry are headed. Thus, *industrial ecology* (Cervantes 2011) compares industrial systems with natural ecosystems, understanding the flows of materials as a metabolism in which the waste of one

[3]Residential Open Building (Kendall and Teicher, 2000): separation between the support that forms part of the permanent structure and has building and group characteristics, and the filling which can be altered, because it has fulfilled its useful life or through the desire of the user; participation of the end users in the design process; design of the construction as a multidisciplinary process; the constructed environment in constant transformation should be recognised and understood; the constructed environment is the product of a continuous design process.

activity can be the resources of itself, or of another. This idea of natural growth was already pointed out in 1968 by Jorn Utzon when reflecting on the concepts *tradition* and *renovation* during the construction of his assembled building in Kuwait, the National Assembly. He indicated *flexibility* as one of the most important characteristics of progress, when affirming that:

> The building thrives like a tree putting out new shoots, getting new branches that can be cut off if necessary, but following the pattern of nature. In the first instance, the project was slightly pruned. Since then it has found its natural growth.

From all this, some keys and guidelines can be obtained that should govern new interventions and rehabilitations under the industrialisation of construction: reduce the number of materials, guaranteeing that they are recycled or that they can be recycled and that they entail a low environmental impact; use open construction systems that allow the substitution of the parts, thus making it perfectible … as it is not applicable to speak of closed functional programmes for the rural architectures under study, which through their location and their own features can have a wide variety of uses, both public and private.

2.1 Analysis of prefabricated industrialised systems

There follows an analysis of the compositional and environmental characteristics of three materials in frequent use as prefabricated systems components in rehabilitation: timber, structural steel and light steel.

2.1.1 Laminated and cross-laminated timber

Combinable with other insulation materials and dry wall elements like plasterboard, giving rise to cross-laminated timber panels, appropriate for almost all the elements of a building (wall panels, interior partitions, floors, roofs, etc.). In addition, this system is compatible with any other construction system on the market, enabling a totally dry construction.

The thermal conductivity of a light conifer is $\lambda = 0.13$ W/m·K according to the Catalogue of Construction Elements of the Technical Building Code (CTE), with a thermal transmittance of the order of 1.58 to 0.59 W/m^2·K for thicknesses of 60 to 200 mm respectively. This gives good thermal behaviour, and the insulating capacity can triple, for the same thickness, that of a double brick construction system, allowing a saving in air conditioning costs and a reduction of the energy demand of the building. If compared with prefabricated metal systems (Bestraten and Hormías 2015), the prefabricated timber systems have better behaviour in the following sustainability criteria: 58% less CO_2 emissions, 37% less heating consumption and 55% more global insulation. Regarding environmental characteristics, certificates should be used that guarantee the sustainable management of the forests[4]. There is very little fossil fuel use, minimising CO_2 emissions and reducing energy consumption by 80%, and the generated waste by 60% with respect to the manufacturing processes of materials, such as concrete, brick or metal (Rodríguez 2012). The material used is 100% recyclable and re-usable, and there is the possibility of leaving the material visible, which also reduces the need of finishes with respect to conventional construction.

2.1.2 Industrialised structural steel

Structural profiles, bars and plates, pieces of laminated steel whose assembly is made with metal joints, resulting in a high grade dry system. It is an open system, used mainly for the construction of structures, which can be compatible with other construction materials. The main advantages of the system lay in the rapidity of manufacture, assembly and erection, and excellent mechanical resistance, whilst giving rise to rigid but light and slender structures, and the high level of quality control, etc. In addition, steel can be reused or recycled to obtain new steel: 90% of the product is recycled. It is important to know the limitations of size and weight for transport and on-site handling. Due to the linear and slender nature of this system, the compositional advantages are numerous: it enables the production of diaphanous and flexible spaces, with the capacity for future modifications.

Regarding prefabricated floors, two groups are differentiated: mixed and dry. The mixed type require a prior assembly phase and a later pour of concrete, which is contrary to our objectives. With respect to the dry floors, new types are being marketed that have not yet received a generic name[5].

From the environmental perspective, the constant recycling of the material is fundamental. In addition, the working conditions are safer, controlled and programmed, without emitting polluting substances to the atmosphere.

2.1.3 Light Steel framing

This is a construction system based on a structural skeleton of cold-formed galvanised steel profiles, arranged every 40-60 cm and joined by means of self-drilling screws. These profiles work uniformly, giving rise to structural and non-structural panels. The envelope is made with waterproof and non-flammable panels which can receive different finishes. Other sub-systems such as insulation, facilities, waterproofing and finishes can be added. All of them give rise to an

[4]For example, PEFC (Programme for the Endorsement of Forest Certification) certificates or FSC (Forest Stewardship Council) certificates.

[5] *Supportsol* and *Cofratherm,* floors without concrete, products of ArcelorMittal.

open and light system that can be integrated with other traditional construction systems and finishes.

With respect to its thermal behaviour, the system is described as very efficient thanks to the multilayer insulation system and its possibilities for optimisation without increasing the thickness of the walls. Due to its lightness, it does not overload the existing elements. It is a recycled and recyclable material, which can be disassembled, allowing its reusability. On site, the reduction of waste is high, and the consumption of water and energy with respect to other systems is low.

2.2 Horizon 2020 and the Triple Zero Concept

In other words it includes one of the objectives for the Cultural Heritage of *Horizon 2020*, the Framework Programme for the period 2014□2020, within the *Europe 2020* strategy:

> The objective consists of providing knowledge and innovating solutions, by means of strategies, methodologies, technologies, products and services of adaptation and mitigation, with a view to the conservation and management of the tangible cultural heritage of Europe exposed to risks due to climate change.

The continuous transformation of our social surroundings is a consubstantial fact of the cultural dynamic. If it is considered that water mills play an important role within the concept and uses of the Cultural Heritage, it is not only to form part of our memory or to constitute our collective identities, but also for their contribution to economic support (architectural resources for rural development and sustainable tourism) and for being potential factors of progress and innovation. A new approach is envisaged to the most evident aspects of the building tradition to incorporate them into the new construction models, aimed at fulfilling the intentions of bioclimatic architecture, of the new parameters of materials, structures and energy saving … trends that review, learn and incorporate solutions, systems and traditional techniques that have been used in rural architecture for ages.

New lines of work that have the same objectives, such as the *Triple Zero Concept*[6], which take into account the three life stages of the materials: *the before* - zero emission, using materials that do not emit harmful substances into the environment during their manufacture; *during* - zero energy, which demands the reduction of energy consumption in the operating systems of a building, using only renewable energies; and *the after* – zero waste, using construction materials or systems that can be flexible, recyclable and dismountable, and which can be reintroduced into the cycle of the materials.

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[6] Concept developed by the German architect and engineer, Werner Sobek.

3 Choice of a test site: The El Rodezno water mill

Fig. 3 The current state in El Rodezno (the winter of 2016). On the right the remains of the water mill and left the remains of the old tanneries

An architectural examination of its original state is essential (Fig. 3), recognising the area of the tanneries and the area of the flour mill (Fig. 4).

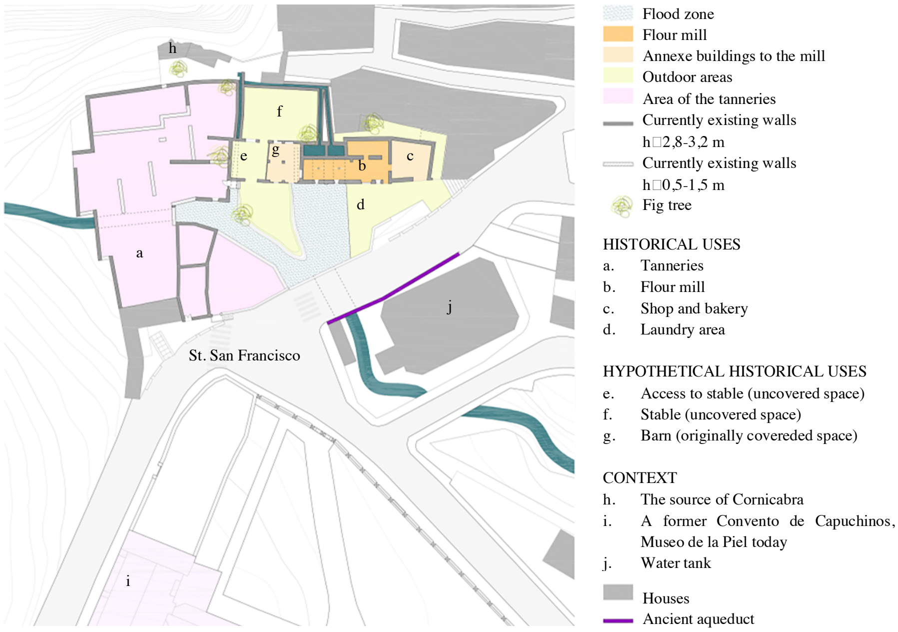

Fig. 4 Architectural examination of El Rodezno today. Plan of the historical uses

At first, St. San Francisco was at the same level as the areas that were not subject to flooding (Fig. 5). These images show an aqueduct, created in 1723, connected to the old Convent of the Capuchinos. It was active until 1937, the year in which works were made to bring water to the locality of Ubrique, which raised St. San Francisco to accommodate the underground pipework, producing the present unevenness with El Rodezno, and making access difficult (Fig. 6). The elevation of the street meant that part of the aqueduct was hidden (Fig. 7).

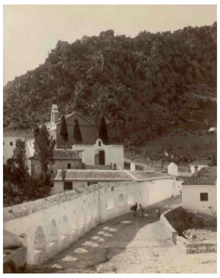

Fig. 5 St. San Francisco 1908 (Romero, 1934)

Fig. 6 St. San Francisco, 2016

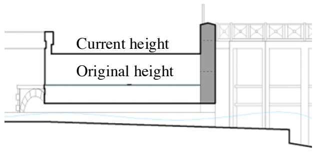

Fig. 7 Section St. San Francisco

Fig. 8 Elevation of El Rodezno, current state

The structure of the building, which had two floors, is of mixed type, with load-bearing walls of irregular stone masonry with sand and lime mortar, of 60-65 cm thickness and with wooden beams. The roof was gabled with a wooden structure covered with Arab roofing tile. Currently, its supporting walls remain, but the first story floor and the roof have disappeared (Fig. 8).

3.1 Intervention strategies

At this moment of the research[7], we cannot propose specific intervention solutions, but we can suggest outlines and formulate a series of strategies that the chosen prefabrication systems must satisfy when implemented in El Rodezno.

[7]This article is framed within the line of research by the authors, in which they attempted, under the same principles (*small prefabricated systems)*, the recovery of the free spaces in the Siedlugen of Ernst May, concluding in the definition of a modular prototype; with the same project philosophy but changing the support, from garden to mill (Ramos-Carranza et al. 2015).

These requirements could be extrapolated to actions in other water mills given their spatial and constructional similarities.

- Open systems, compatible with the existing traditional construction.
- Systems available in the current construction industry.
- Reduce the number of materials.
- Dry work, to reduce assembly times, emissions and waste.
- Small modular systems (dimensions of bays: 4.30 and 3.30 m).
- Dismountable and perfectible, re-usable or recyclable systems.
- Light systems, low weight, avoiding overloads, facilitating self-assembly.

According to Article 20 of the Law of the Historical Heritage of Andalusia of 2007, additional parts must be recognisable to avoid the mimetic confusions. For that reason, it is sought that the spatiality of the container, the mill, is recognisable in its totality, which is why new prefabricated modules introduced into it must avoid, to the maximum possible, direct contact with the supporting walls, except when they contribute to bracing the pre-existing walls.

The materials analysed in section 2.1 (wood, laminated steel and cold-formed steel, which can fulfil the previously stated premises) give rise, under the industrial discipline, to:

- Linear products: beams and pillars
- 2D, surface products: sheets, boards and panels, self-supporting or not.
- 3D, spatial modules.

The possible combinations with this triple product range are very extensive. Factory produced spatial modules have not been analysed in this article, and a construction system of beams, pillars and panels is chosen. The dimensions of the panels from the consulted[8] sector companies will determine the structural modular design and the lengths of the linear elements. If the reduction of the number of materials used is fixed as a starting objective, two construction possibilities open: wood and steel. To give shape to the analyses and compositional proposals made in this article, wood was selected as the main material. Attention is given to two types of panels, available in the market, to fix the structural grid:

- Laminated timber: *Thermochip* panel. Dimensions: 550 x 2,400 mm.
- Cross-laminated timber: *EGO_CLT* panel and *EGO_CLT MIX* (with insulation). Usual dimensions (transport limits): 2,400 x 10,000 mm.

A grid of wooden beams and pillars of 2.40 x 1.65 m (Fig. 9) is dimensionally coordinated with the two previous formats, combining both panels (*Thermochip* for the roof and *EGO_CLT* for the first story floor). An independent structure of the mill: 16 modules inserted between the pre-existing masonry walls. The connected modules would avoid the duplication of pillars. In order to fill the horizontal surfaces of the grid in El Rodezno (Fig. 10), 48 *Thermochip* panels and 7 *EGO_CLT* panels would be needed of 2,400 x 10,000 mm (each panel would be

[8] *CupaGroup* for laminated timber and *Egoin* for cross-laminated timber.

divided into 3 panels of 2,400 x 3,300 mm, filling two modules, which is why they would be triply supported).

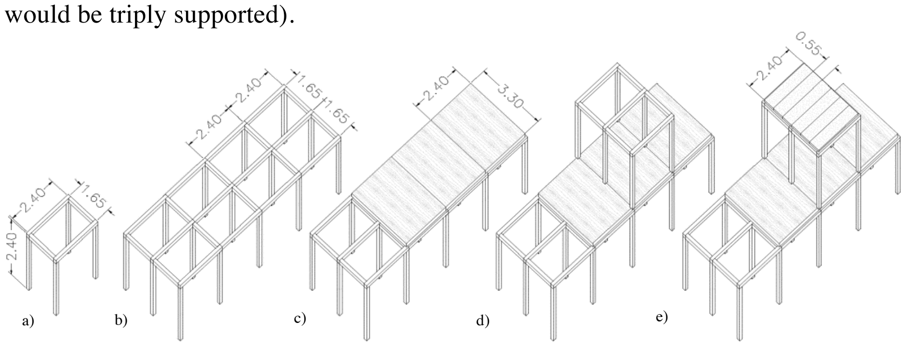

Fig. 9 a) Modular structure. b) Addition of modules. c) Positioning of *EGO_CLT* cross-laminated timber panels. d) Addition of modules at height. e) Positioning of *Thermochip* panels

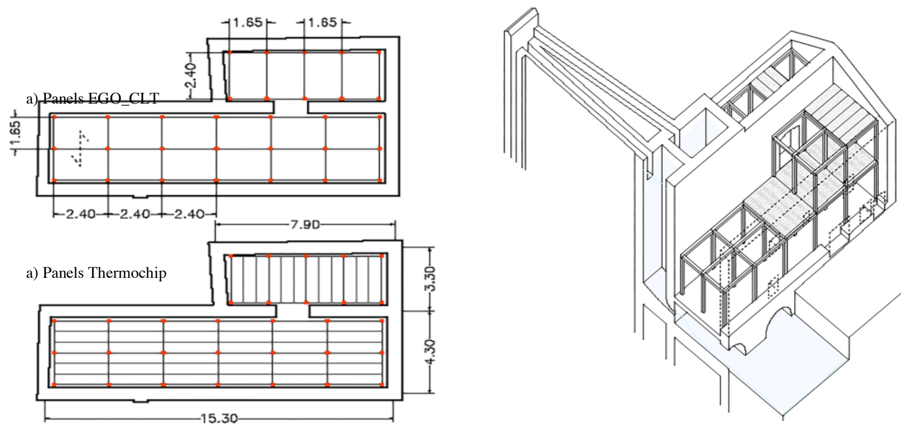

Fig. 10 Insertion of the modular system in El Rodezno. Floors and axonometry

4 Conclusions

This article presents some of the initial keys of the on-going research by its authors. It starts by detecting architecture with heritage value which, through abandonment and disuse, needs a recovery intervention as a preservation mechanism. The challenge considered, is to intervene from the concept of these pre-existing architectures as *containers* in which to insert small modular systems from the construction industry, and allow the spaces to be re-inhabited when necessary, without a predefined use. These small systems are assembled, extended, stacked, dismounted, recycled, etc. They become a living system capable of adaptation to what already exists and to the energy demands. The reasons that justify this approach are several, and they are based on criteria of rationality, sustainability, innovation and optimisation of time, resources and materials.

Based on previous premises of the project, three materials were selected from products available in the market, according to the research interests, and a modular design solution has been attempted with the timber option. The other materials, as well as possible combinations, will be studied as the research advances. Obtaining the optimal modular system will entail the corresponding structural and economic calculations. This is an open, on-going research, the objective of which, as announced in the present Conference, is to conclude with a sustainable and echo-efficient solution; a small modular system applicable to a large scale sustainable project; to recover and to reactivate productive rural architecture.

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