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RESEARCH ARTICLE

Symbiotic architecture: Redefinition of recycling design principles

Milan Šijaković[a,*], Ana Perić[b,c]

[a]*School of Architecture of Barcelona (ETSAB), Polytechnic University of Catalonia, Calle Jordi Girona, 31, 08034 Barcelona, Spain*
[b]*ETH Zürich, Institute for Spatial and Landscape Development, Stefano-Franscini-Platz 5, 8093 Zürich, Switzerland*
[c]*Faculty of Architecture, University of Belgrade, Bulevar kralja Aleksandra 73/II, 11000 Belgrade, Serbia*

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Abstract
The study seeks to examine the possibility of implementing the biological concept of symbiosis into the field of architecture for redefining the design principles of architectural recycling. Through an in-depth analysis of the biological concept of symbiosis (i.e., a close and often long-term interaction between two or more different biological species and the criteria that govern the differentiation between symbiotic associations), three redefined design principles of recycling—commensalism, mutualism, and parasitism—have been described, which form the base for defining the "recycling model." Its value is in its multidisciplinary character and its systematic approach to the topic of recycling architecture. The principles embedded in this model relate to the aspects of structure, material, form, and spatial organization. The research methodology includes three case studies, which correspond to three redefined design principles and illustrate their basic characteristics. The research draws upon the biological concept of symbiosis, and its purpose is to elaborate possible structural, material, formal, and spatial relationships between the existing building and the new intervention in architectural recycling.

*Correspondence to: Vidikovacki venac 23, 11 000 Belgrade, Serbia.
E-mail address: milansijakovic@gmail.com (M. Šijaković).
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1. Introduction

Architectural recycling is the process of altering the existing building using all of its available, useable material to make it suitable for new functions. The concept of recycling implies the notion of change, unlike many other terms that correspond to the intervention on the existing building. Thus, the original building is altered to accommodate a new function. However, most of the original buildings' materials are used, which offer a number of advantages, such as the increase of the working service life of existing buildings; profitability of the resources already applied (Cepinha et al., 2007); the absence of extraction, processing, and transport costs; and reduction of the need for manufacturing new components and products, which directly address the local economy and environment (Couto and Couto, 2007).

Sustainable architectural design includes the principles for the design of sustainable buildings but is inadequate in developing sustainable design principles only for new projects. The existing buildings must also be considered given that structural issues are usually not the reason buildings come to their end-of-life, but rather the shift of the building's original purpose, which makes the existing building unsuitable for new roles and functions (Lee et al., 2011; Baum and Christiaanse, 2012; Sijakovic, 2015).

The current literature on interventions upon existing buildings usually deals with the categorization and classification of projects according to subjective and vague criteria. The results of such studies are mainly catalogs forming a very useful database. Although consecutive, consistent studies have been made in the field of building construction and physics aimed at improving building performance, the lack of research on the recycling approach to existing buildings (beyond cataloging) is evident.

The research subject belongs to the domain of architectural recycling and is focused on elaborating environmentally sustainable design principles suitable for recycling existing building stock. Research in the field of architectural recycling lacks the precise identification of recycling design principles. Thus, the present research aims at the redefinition and creation of the "recycling model." The design principles of recycling elucidate possible relationships between the original building and new intervention. The research draws upon the implementation of biological concepts into the architectural field to redefine the design principles of recycling. This means that the extent of the analogy between the fields of biology and architecture is identified, which makes the firm multidisciplinary research background. Biological principles are also used to form the "recycling model." The concept of symbiosis serves for the definition of possible relationships between the existing building and new intervention in the process of architectural recycling. The terminology used in the field of biology, explaining different types of symbiotic associations between two organisms, has been transferred to the field of architecture. In the process of architectural recycling, original building and new intervention are compared with "symbionts," which are organisms closely associated with one another that take part in symbiotic associations. Three redefined recycling design principles are derived from the concept of symbiosis: commensalism, mutualism, and parasitism. Thus, the interconnections between different symbiotic associations and recycling design principles are elaborated, and new definitions are presented. Three case studies help illustrate the characteristics of redefined design principles.

After the introductory remarks, the correlations between the fields of biology and architecture are extensively explained by drawing on the contributions by architectural theorists and practitioners, such as Georges-Eugène Haussmann, Ildefons Cerdà, Frank Lloyd Wright, John Frazer, and Manuel de Solà-Morales. Such an informed review forms the basis for the redefinition of the recycling design principles. However, the biological concept of symbiosis is first elaborated by making the sound background for defining the recycling model of architectural design principles based on the inputs from the biological domain. The model is then tested in practice and illustrated through three cases of recycling industrial buildings. The conclusion proves the benefits of recycling as a method for environmentally sustainable architectural design.

2. Biological analogies in architecture

Cities have long been compared to living organisms. Plato, in his *Politeia*, written approximately 380 BCE, referred to the city as a "macro-anthropos" (in ancient Greek: *μακρο* - large; *ανθρωπος* - man), which highlights the analogy between the human body and the city. Plato also makes that correlation between the man and the city in terms of justice by stating that a just man is not different from a just city. Cerdà (1867) refers to a city as a body and a living organism and points to urban planners as both the diagnosticians and surgeons. Cerdá states that an urban planner should "first be able to distinguish sick areas of the city from those that are healthy, only then can he proceed with a true anatomical dissection of all of them and of all of their constituent parts" (Fraser, 2011:89). Choay (1969) explains that Georges-Eugène Haussmann transformed modern Paris and revolutionized its streets as arteries in the model of a "general circulation system." Fraser (2011) states that the application of the biological metaphors to city life was a practice that predated the work of 19th-century city planners and was even present in the 17th-century with the discovery of the blood circulation. Referring to the discoveries of the seventeenth-century, Sennett (2008: 204) writes,

> The scalpel had permitted anatomists to study the circulation of the blood; that knowledge, applied to circulation of movement in streets, suggested that streets worked like arteries and veins; this was thus the era in which planners began to incorporate one-way streets in their designs. Wren's circulatory city was commercial in intent, aiming to deal efficiently in particular to create streets that moved goods to and from the necklace of warehouses draped along the Thames. But this design lacked the equivalent of a human heart, one central, coordinating square.

Collins (1965) reviews the theories and influences that shaped the modern architecture, which explain the failed attempts of historians to evolve a new architecture with the analogy of the earlier architecture. Thus, theorists are forced to study other types of analogy: biological, mechanical, gastronomic, and linguistic types. The origins of the biological analogy Collins (1965: 149) traces back to 1750, when two scientific books were published.

> Linnaeus' *Species Plantarum* (1975), in which the entire vegetable kingdom was classified binominally according to the disposition of the female reproductive organs, or 'styles', and Buffon's *Histoire Naturelle* (1749), a vast compendium which attempted to incorporate all biological phenomena into a general interpretation of the laws governing the universe.

Moreover, Buffon's evolutionary vision (i.e., that all species must be derived from a single type) is used later by architectural theorists and has two important features (Collins, 1965:149).

> The first is that, in hitting upon the idea of evolution, he saw it as essentially a process of degeneration, not of improvement, since his religious beliefs (or his respect for those held by his contemporaries) prevented him from assigning the evolutionary process to any but to lower animals. On the other hand, he was the first scientist to distinguish correctly between the "vegetative" and specifically "animal" parts of animals, whereby an animal may be regarded simply as a vegetable organism endowed with the power of moving from place to place.

Therefore, "organic life" for architectural theorists is the sum of the functions of the "vegetative" class. Collins (1965) explains that the asymmetry of plants and viscera, rather than the symmetry of animal skeletons, became accepted as a characteristic of an organic structure at the beginning of the 19th century.

The most important proclamation of the evolutionary theory was published by Jean-Baptiste Lamarck, who concluded that living forms have not evolved retrogressively but progressively, and that evolution was due to the environment (Collins, 1965). Lamarck wrote that the organs, which include the form and characteristics of body parts of animals, do not influence their habits and peculiar properties; their habits, manner of life, and the conditions in which their ancestors lived designed their body form, organs, and qualities. Moreover, in the 1800s, *biology* was invented by Lamarck, and *morphology*, which included non-living forms, such as rocks, was created by Goethe (Collins, 1965).

Jacob Schleiden's views that life was a form-building force and that the growth of crystals and organisms are the same phenomena was accepted by Herbert Spencer whose biological works influenced Frank Lloyd Wright (Collins, 1965). Frazer (1995) highlighted that Sullivan, Wright, and Le Corbusier employed biological analogies and that the concept of the "organic" is central to the 20th century. In his essay *In the Cause of Architecture* (Gutheim, 1975:207), Frank Lloyd Wright writes,

> (...) all things in nature have a shape, that is to say, a form, an outward semblance, that tells us what they are, that distinguishes them from ourselves and from each other. Unfailingly in nature these shapes express the inner life, the native quality, of the animal, tree, bird, fish, that they present to us; they are so characteristic, so recognizable, that we say it is natural it should be so.

Wright (1953:296) supports the idea of Louis Sullivan, his employer and mentor, whom he called his *Lieber Meister*, and says, "Already it has been said – *lieber meister* declared it – and biology knows and shows us that form follows function." Costa Guix (1988:53) explains that George Couvier established the organic and functional model of natural science in his study of anatomy, which considered all parts of the biological system that are interrelated through precise laws of function: "The anatomist, for instance, could reconstruct an entire digestive system from a single tooth —and from this digestive system (and by studying the natural environment to which it is adapted) even the animal itself."

Viollet-le-Duc introduces the principle of "organicity," according to which each part implies the whole, links it to architecture, and explains that the whole plant or animal can be understood from one of its parts, and thus one profile or an architectural element explains the whole structure. Viollet-le-Duc believes that the monument is an organic body and "the comprehension of its organic entity permits the architect to undertake its restoration" (Costa Guix, 1988:55).

Biologists and classical architects of the early 18th century believed in evolution; they believed that the modern has improved on the Romans, just as the Romans improved on the Greeks (Collins, 1965). Four features are in common between biology and architecture: 1) the relationship of organisms to their environment, 2) the correlation between organs, 3) the relation of form to function, and 4) the principle of vitality itself. Moreover, Collins (1965) analyzes discoveries by Claude Benard that concern the way the body adapts itself to changing conditions and argues that a clear parallel can be drawn to architecture.

Frazer, in his *An Evolutionary Architecture* (1995), claims that architecture is a living and evolving entity; thus, fundamental form-generating processes in architecture are explored by studying the process of morphogenesis in the natural world. Architecture is considered "a form of artificial life, subject, like the natural world, to principles of morphogenesis, genetic coding, replication and selection" (Frazer, 1995:9); thus, genetic algorithms, cellular automata, emergent behavior, complexity, and loops are needed to create truly dynamic architecture. Frazer describes the emerging field of architectural genetics and makes an analogy with multi-celled relationships found in nature and their ongoing metamorphosis as a response to the changing conditions. Therefore, "the aim of an evolutionary architecture is to achieve in the built environment the symbiotic behavior and metabolic balance that are characteristic of the natural environment" (Frazer, 1995:9).

Solà-Morales (2008) uses terms, such as skin, epidermis, nerves, arteries, acupuncture, and prosthesis, to explain architectural and urban processes in the city, which is seen as a living, breathing organism. Working on the "skin of cities," he states that the city epidermis enables the city to discern its deepest structures. He explains that the skin of cities is composed of construction, textures, and contrasts; streets and empty spaces; gardens and walls; and contours and voids. He further elaborates the concept of city skin by drawing an analogy with the skin of the human body. According to the ancient oriental practice of acupuncture, the human skin can be explained as a "(...) principal energy transport system, with 361 sensitive points scattered over the surface of the body transmitting their sensory impressions to the rest of the organism, exterior and interior, by means of twelve meridians or pathways" (Solà-Morales, 2008:24). The author further stresses that the human skin, just as the urban skin, transmits and channels qualitative energy. Therefore, urban acupuncture to Solà-Morales (2008) is a method of treating the urban skin, which occupies in the first place similar to therapeutic acupuncture with the identification and localization of sensitive points, which need adequate energy to function properly.

The previous review provides a sound argument on the importance of using biological concepts in the architectural domain. However, a profound analogy between the mentioned domains is needed because this research aims at redefining the principles of architectural recycling. Therefore, the next section sheds light to the terminology issue related to the biological concept of symbiosis (i.e., the view of two structures, original building, and new intervention as symbionts (organisms that are closely associated with one another)).

3. Concept of symbiosis

Heinrich Anton de Bary first uses the term symbiosis (in ancient Greek: *σύν* - together; *βίωσις* - living) to explain an internal partnership between two organisms. He addresses the term in *The Phenomena of Symbiosis* (delivered at a general meeting of the Association of German Naturalists and Physicians in Kassel, 1878) and defines it as "the living together of unlike named organisms" (Sapp, 1994:7).

Symbiosis defines a relationship in which one symbiont lives within the tissues of another (endosymbiont), either within the cells or extracellularly; it also refers to any relationship in which the symbiont lives on the body surface of the host (ectosymbiont), which includes the inner surface (Ahmadjian and Paracer, 2000). Symbiosis includes mutualism, where both species benefit, and the two organisms help each other; parasitism, where one species benefits, and the other species is harmed; and commensalism, where one species benefits, and the other species is unaffected (Bary cited in Ahmadjian and Paracer, 2000).

Organisms that live in a symbiotic relationship can have completely different physiognomies. Kurokawa (1994) states that the philosophy of symbiosis defines the relationship of elements that need each other, while constrictions and opposition exist between them. Douglas (2010) understands symbiosis as any kind of persistent biological interactions, whereas Ahmadjian and Paracer (2000:3) indicate that organisms function only in relation to other organisms; thus, symbiosis is defined as follows.

> Symbiosis is an association between two or more different species of organisms. The association may be permanent, the organisms never being separated, or it may be long lasting. This definition excludes populations, which are associations between individuals of the same species. Organisms that are involved in a symbiosis may benefit from, be harmed by, or not be affected by the association. Symbiotic associations are common in nature, from bacteria and fungi that form close alliances with the roofs of terrestrial plants to those between giant tube worms and sulphur-oxidizing bacteria that live together in the deepest depths of the ocean. No organism is an island – each one has a relationship to other organism, directly or indirectly. Even humans bear a reminder of an ancient symbiosis – their cells contain mitochondria, organelles which once were symbiotic bacteria (...) It is difficult to imagine life and its evolutionary history without symbioses.

Ahmadjian and Paracer (2000) state that all forms of life contain symbiotic associations, which play an important role in the evolution of plants and animals and in shaping the physical features of the earth. Moreover, symbiosis has been seen as a major source of evolutionary novelty. Some symbiotic associations can lead to novelty in the host organisms given that "the incorporation of an entire functioning organism, with all its metabolic pathways, may at once confer a suite of novel traits to the host organism" (Feldhaar, 2011); therefore, the view that the form and function of host organisms is conditioned solely by their own genotype (the genetic makeup of an organism) and phenotype (the composite of an organism's observable characteristics or traits) is changing. "Hosts are increasingly studied as holobionts, i.e., as an organism whose phenotype is determined by the combined genotype of the host's genome and genome(s) of all symbionts carried by the host" (Feldhaar, 2011:534).

Ferrari and Vavre (2011) stress that symbionts have a variety of effects on the host's characteristics, such as the costs imposed on the host for maintaining the symbiont population, the fitness advantages provided to the host, or the manipulation of the reproduction of the host. Thus, the form and function of the host in some symbiotic associations is conditioned by other symbionts. Peacock (2011:231) explains that "symbiosis plays an obvious role in the generation of functional novelty, and it may be an essential part of the explanation both of rapid bursts in evolution, and the very existence of certain types of organisms." Thus, symbiosis plays a major role in the genesis of functional and genetic novelty.

Douglas (1994):v) points out that symbiosis "is a route by which organisms gain access to novel metabolic capabilities, such as photosynthesis, nitrogen fixation, and cellulose degradation." Peacock (2011:232) broadens this viewpoint by adding that the metabolic capabilities are gained through symbiosis, but "novel symbiotic associations could also allow organisms' ways of responding to rapid changes in habitat and climate." Moreover, symbiosis is as responsible for the novelty as mutation and other mechanisms of direct genetic change.

The present research draws a direct analogy with terms which explain the types of symbiotic relationships between two organisms. Thus, symbiosis refers to all types of close relationships between two symbionts, a new intervention

Table 1 Tectonic criteria.

Structure	• The old structure is retained; no new structure is added. • The new structure is added, which is independent of the old structure. • The new structure is added, which is dependent on the old structure. • The old structure is completely replaced.
Material (*Exterior*)	• Old and new materials are completely interwoven. • A clear division is seen between the old and new materials.
Material (*Interior*)	• Old and new materials are completely interwoven. • A clear division is seen between the old and new materials.

and the original building. These relations can be commensal, mutualistic, or parasitic, depending on the influence symbionts have on each other's structure, material, form, and spatial organization. In biology, some symbiotic relationships imply a certain degree of change to symbionts genome and phenotype (i.e., its form and function). In architecture, symbiotic relationships can alter the host's (original building) genome (its form), which depends on the type of the symbiotic association. These associations are formed in nature in that at least one of the symbionts can draw benefit (i.e., nutrition or protection). These benefits can be directly translated to architecture as structural, material, formal, or spatial upgrading.

The following sections present the recycling model that comprises three redefined recycling design principles. The redefined design principles of *commensalism*, *mutualism*, and *parasitism* are explained, and a correlation with the original meaning of the term used is drawn. Each of the redefined recycling design principles is relabeled according to a proper biological term, which depends on the type of the relationship between the two symbionts (i.e., original building and new intervention).

4. Recycling model

The translation of the biological principle of symbiosis into the field of architecture is possible due to the clear set of criteria for the redefinition of design principles: structure, material, form, and spatial organization (i.e., the structural, material, formal, and spatial relationship between the existing building and the new intervention). Therefore, each of the three redefined design principles of recycling was determined by the structural, material, formal, and spatial relationship between the original building and the new intervention.

The first set of criteria relates to the building tectonics and determines the relationship between the new and the old structure and materials. This set of criteria focuses on the interaction between the structural elements (i.e., foundations, vertical and horizontal load-bearing structures, and roof structures) and materials (i.e., façade, internal surfaces, floor coverings, and wall and ceiling coverings) of the old building and the new intervention. The possible relationships are presented in Table 1.

The second set of criteria relates to the spatial-formal relationships and determine the degree of change induced to the formal and spatial characteristics of the original building. This set of criteria focuses on the building's volumetric composition, symmetry, fenestration rhythm, and spatial organization. The possible spatial-formal relationships between the existing building and the new intervention are presented in Table 2.

The multiple case study is selected as a particularly appropriate method for empirical analysis. The cases occur in different places and at different times but with the same research subject. The use of the same apparatus is of special importance; it allows the comparison of the information from different cases chosen according to the same or similar parameters (Swanborn, 2010). The cases in the present research are the three projects of recycling industrial architecture. This building type was chosen as the most appropriate for the research on architectural recycling due to its physical characteristics, that is, large flexible spaces with great adaptability potential. The projects selected for the analysis are chosen according to the following parameters.

1. **Spatial scope.** The examples from three Western European countries (i.e., Spain, Portugal, and Great Britain) are selected given that they have remarkable industrial legacy and are countries with an internationally recognized practice of reconverting industrial architecture.
2. **Location.** Only the cases placed in urban areas are analyzed. Industrial buildings were traditionally built on the outskirts, but they are situated nowadays in the central zones due to the expansion of the city area. Such buildings were considered especially interesting given that they occupy the potentially most attractive city sites.
3. **Scale.** The selected cases are the examples of transforming individual buildings. The in-depth analysis of design principles is appropriately conducted by focusing on one single building rather than a complex of buildings or industrial landscape.

The method of the case study is considered an appropriate methodological choice for this research for two reasons: 1) the elaboration of the design principles of architectural recycling is conducted by analyzing “good practice” examples (i.e., internationally recognized and awarded projects of recycling industrial architecture), and 2) research by a multiple-case study offers the possibility for the systematization and validation of data in a broad context, which develops a research approach that can be used for other examples (Yin, 2009).

The case study method includes a variety of other methods. This research used 1) content analysis 2) field research, and 3) interviews. The data were collected from

Table 2 Spatial-formal criteria.

Form	• The formal logic of the old building is respected and unchanged. No new elements are added. • New elements are added. The old building's formal logic is respected. • The formal logic of the old building is disrupted.
Spatial organization	• The spatial logic of the interior spaces is preserved and unaltered. • The spatial logic of the interior spaces is altered but depends on the host building. • The spatial logic of the host building's interior spaces is completely changed.

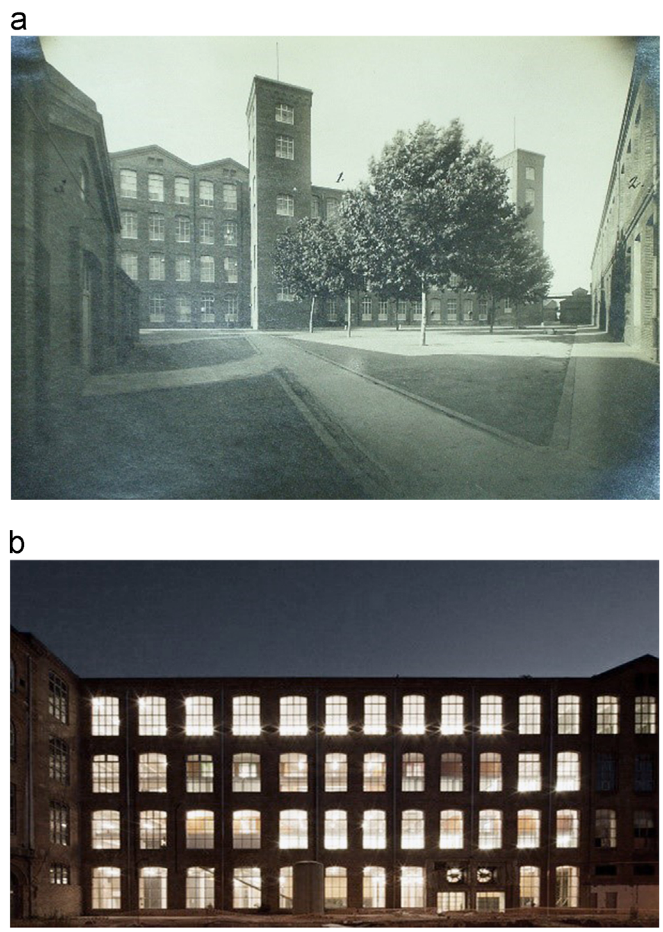

Figure 1 (a) Fabra i Coats before the intervention, (b) Fabra i Coats after the intervention. *Source:* courtesy of Manuel Ruisánchez Arquitectes.

different sources: publications on selected individual projects of recycling industrial architecture and conversations with project leaders of chosen projects (by the technique of direct interview). Methodological triangulation, which is the application of multiple methods and techniques to conduct an objective analysis, was applied.

The first recycling design principle of commensalism was analyzed through the project of “Fabra i Coats” in Barcelona, Spain by Manuel Ruisánchez Capelastegui and Francesc Bacardit Segués. The second recycling design principle of mutualism was examined through the project of “Centro de Monitorização e Interpretação Ambiental – Casa dos Cubos” project, in Tomar, Portugal by the architectural office, Embaixada Arquitectura. The third recycling design principle of parasitism was evaluated through the “192 Shoreham Street” project in Sheffield, England by a London-based architectural office Project Orange.

4.1. Commensalism

The term commensalism (from Latin, “com” and “mensa” mean “sharing a table”) was used first P. J. van Beneden in 1876 “for associations in which one animal shared food caught by another animal” (Ahmadjian and Paracer, 2000:6). According to the same source, the term commensalism refers to a relationship where one of the symbionts benefits in terms of nutritional or protective benefit, and the other is not harmed nor helped. Therefore, commensalism is a relationship in which one species benefits, a

b

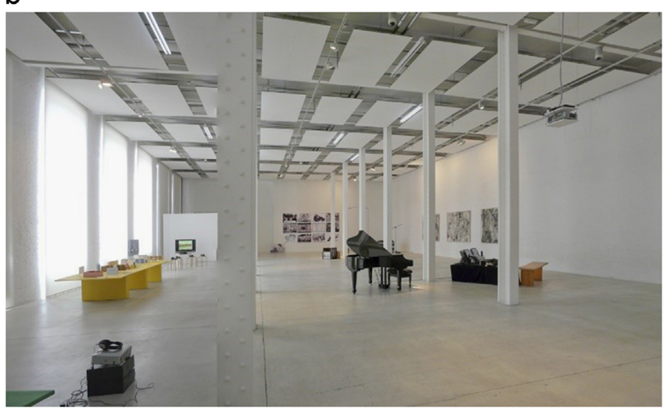

Figure 2 (a) Interior of the Fabra i Coats before the intervention, (b) Interior of the Fabra i Coats after the intervention. *Source:* courtesy of Manuel Ruisánchez Arquitectes.

Table 3 Commensalism – key criteria.Source: Authors.

Structure	The old structure is retained. If a new structure is added, it is dependent on the old structure.
Material - Exterior	Old and new materials are completely interwoven.
Material - Interior	Old and new materials are interwoven. A distinction that is found between the old and new materials form a harmonious union.
Form	The formal logic of the old building is respected-unchanged. No new elements are added.
Spatial organization	The spatial logic of the interior spaces is preserved and unaltered.

whereas neutral impact exists on the other. This relationship is often formed between a large host, which stays unmodified, and a smaller symbiont, which may show great structural adaptation.

A direct analogy with the biological concept of commensalism can be drawn to the field of architecture. This type of symbiotic relationship can occur between an existing, underused building, which obtains "nutrition" (i.e., structural, material, formal, or spatial upgrading), while the newly introduced elements possess no threat to the formal and spatial integrity of the original building. These new elements, such as structural or installation units, provide the normal functioning of the underused building, without altering its form or interfering with its spatial organization. The exterior of the existing building is left unchanged. Any reparation work that has to be done to the building's façade (e.g., material replacement, crack repairs, patching, cleaning, and painting) preserves and reveals original aesthetic, material, and historic value. All new interventions in the building's interior are made using materials that follow the aesthetic logic of the old. New and old are interwoven. New materials added, which are distinguishable from the original, are always integrated harmoniously with the whole.

The design principle of commensalism is reviewed through the "Fabra i Coats Creation Factory" project (Figure 1(a) and (b)), which is the reconversion of the well-preserved textile factory building in Barcelona, Spain into a multidisciplinary arts center. The project was designed by Manuel Ruisánchez Capelastegui and Francesc Bacardit Segués. The design strategy was highly respectful of the existing building. It is a transformation and recovery

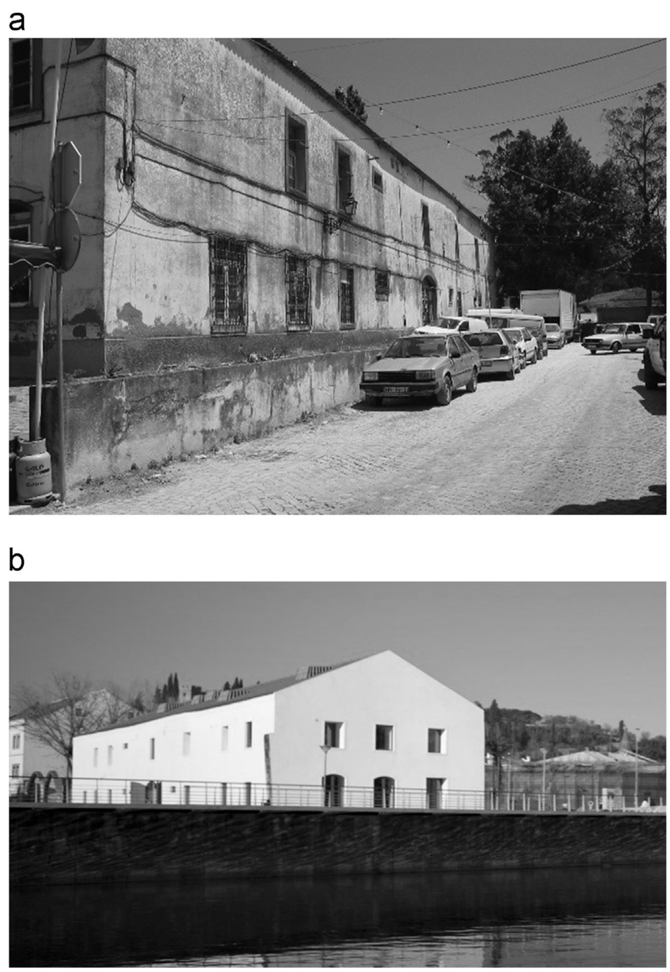

Figure 3 (a) Casa dos Cubos, storehouse before the intervention, (b) Casa dos Cubos, view of the building after the intervention. *Source:* courtesy of Embaixada Arquitectura.

of an industrial space. The old structure is retained. The roof structure and foundations are reinforced and upgraded.

The interior view of the factory before and after the intervention (Figure 2(a) and (b)) shows that the original open floor plan was preserved. The existing column grid and the perimeter walls stay unchanged. New light volumes introduced by the intervention do not alter the space. That is, new elements follow the spatial logic of the original building.

The form of the building stays intact. Its volumetric composition, fenestration rhythm, and proportion is preserved in its totality. No additions are executed to the building envelope. All newly introduced elements follow the spatial logic of the host building. The division of spaces within the building (i.e., its internal organization) is preserved and governs the new intervention. New elements are defined by the host building's physical characteristics: the dimensions, scale, and disposition of spaces. The character of the old building's interior was not changed by the intervention. The original building has predominance and fully governs the new intervention. A summary of the key criteria that describes commensalism as one of the recycling design principles is indicated in Table 3.

4.2. Mutualism

Ahmadjian and Paracer (2000) state that mutualism is a type of a symbiotic association, where both partners benefit from the relationship. A reciprocal exchange of nutrients always exists even though the extent to which each symbiont benefits may vary. The close complementarity between two partners "increases the success and evolution of the mutualistic association" (Ahmadjian and Paracer, 2000:6). Thompson (2005) considers mutualism the driving force that triggered the revolution of the biological diversity and the co-evolution between groups of species. Symbionts can trade resources, services, or protection. This trade between species is a biological barter given that "physical resources are largely concerned with nutritional gain (e.g., carbohydrates, inorganic nutrients, and water)" (Ollerton, 2006:412). In mutualistic symbiosis, the endosymbiont (i.e., symbiont living inside the host) adapts to the host. These adaptations lead to changes, such as the drastic reduction in the endosymbiont's genome size and the changes in its phenotype (Moran, 1996). Thus, this mutually beneficial symbiotic relationship implies the adaptation of one symbiont, its genome, and phenotype to the host and some adaptations of the host to the other symbiont.

Figure 4 Casa dos Cubos, interior view of the building after the intervention. *Source:* courtesy of Embaixada Arquitectura.

In terms of architecture, a mutualistic relationship occurs between two symbionts, the existing building and the new intervention, which have different physiognomy (i.e., different spatial-formal logic and material expression) but are dependent on and conditioned by each other. The physical characteristics of the original building determine the properties of new intervention: its scale, rhythm, and disposition of spaces. In terms of structure, the new intervention retains and upgrades the existing structure if necessary. New structural elements that are introduced can be either dependent or independent on the existing structure based on the scope of the intervention. New structural elements that are self-sufficient are certainly conditioned by the purely physical characteristics of a host building, its size, and the disposition of its structural elements. The positioning, size, and rhythm of the new structure depend entirely on the old building's spatial organization.

The building's exterior is often preserved or restored to the original state if necessary to maintain its appearance and integrity. However, additions can be made to the host's building volume, and they are always executed using materials that are clearly distinguishable from the old yet carefully chosen to create a harmonious relationship with existing materials. New and old are not interwoven but form a union. What is new and what was already there can be clearly distinguished. If new additions are made, the elements added to the building envelope follow the formal logic of the old building, its symmetry, and the relationship between its elements.

Mutualism as a design principle is reviewed through the "*Centro de Monitorização e Interpretação Ambiental – Casa dos Cubos*" project (Figure 3(a), (b)), which is a reconversion of a former rundown storehouse in Tomar, Portugal. The project was designed by the Portuguese architectural office, Embaixada Arquitectura.

The external perimeter construction of the original building was kept. However, its rundown interior was totally scooped out. The external walls were preserved and upgraded, while the new structure, which is independent of the old one, was introduced. A clear-cut is observed in terms of the structural behavior of old and new elements. New and old structures have completely divided roles. The authors of the project point out that the new structure is independent of the anatomy of the existing building. A new architectural body runs throughout the available space and tectonically divides the finite interior into a new series of places and programmed situations (Figure 4).

The new intervention has its own spatial logic but is nonetheless influenced by the physical characteristics of the industrial building. This influence is limited to the new intervention's dimension and not to character. Therefore, the spatial organization of the industrial building is changed, but newly introduced elements are conditioned by the scale and the physical dimensions of the original building. Mutualism creates a much more dynamic relationship with the original building compared with the design principle of commensalism. Both symbionts (existing building and new intervention) are dependent on each other. The original building could not be operational without the structural and service support of the new intervention, which is provided with the suitable environment and "protection" (i.e., physical space to be installed in or attached to). The characteristics of the design principle of mutualism are indicated in Table 4.

4.3. Parasitism

The term parasite is defined as the "one who lives at another's expense," according to Etymology dictionary, or "feeding beside" (in ancient Greek: *παρά* – beside; *σιτς* – food). Combes (2001) defines parasitism as a type of relationship between species, where one species, the parasite, benefits at the expense of the other, the host. Webster's Third New International Dictionary invokes directly the concept of harm, which defines the term as "(...) an organism living in or on another living organism obtaining from it part or all of its organic nutrient, and commonly exhibiting some degree of adaptive structural modification – such an organism that causes some degree of real damage to its host."

Table 4 Mutualism – key criteria.Source: Authors.

Structure	The new structure is added, which can be dependent on or independent from the old structure.
Material - Exterior	The division between the old and new materials is clear.
Material - Interior	The division between the old and new materials is clear.
Form	New elements are added. The formal logic of the old building is respected.
Spatial organization	The spatial logic of the host building's interior spaces is altered but depends on the host's physical properties.

a

b

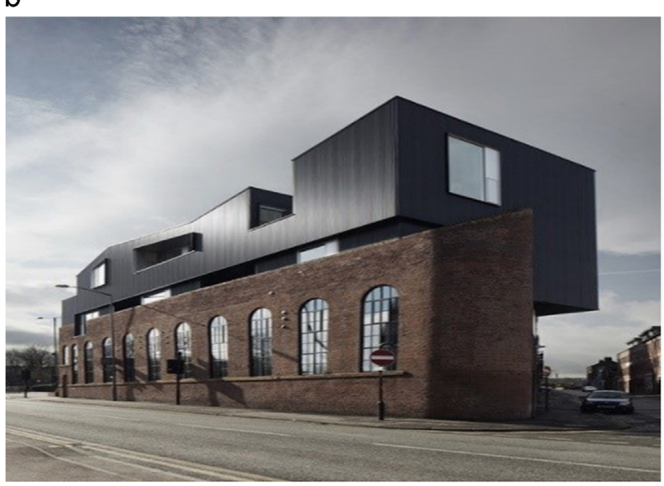

Figure 5 (a) 192 Shoreham Street, industrial warehouse before the intervention and (b) 192 Shoreham Street after the intervention. *Source:* Hobhouse (2012).

Ahmadjian and Paracer (2000:7) state that, "as in mutualism, the primary factor in parasitism is nutrition: the parasite obtains its food from the host"; yet, symbionts that draw the benefit from this relationship can be pathogenic in that they produce a disease in host shortly after parasitism begins. Barnard and Behnke (2005:1) point out that "parasites are exploitative, taking from their host nutrients and energy made available through the latter's foraging efforts, as well as perhaps benefitting from transport, protection and a thermally-regulated environment provided by the host."

The parasite manipulates the physiology, behavior, and defense mechanisms of the host. Combes (2001:6) explains the parasitic association and writes, "In a parasite-host association, the signals produced by the genome of one of the partners may act on the phenotype of the other, thus crossing the species barrier and inducing morphological, anatomical, physiological, or behavioral changes in the recipient."

Poulin (2010) underlines the idea that a parasite can modify the phenotype of its host by either taking control of the host behavior or changing the host's appearance; this

Figure 6 192 Shoreham Street, exterior of the building after the intervention. *Source:* Hobhouse (2012).

Table 5 Parasitism – key criteria.Source: Authors.

Structure	New structure is added, which is independent from the old structure. The old structure can be completely replaced.
Material - Exterior	Clear division is between the old and new materials.
Material - Interior	Clear division is between the old and new materials.
Form	Formal logic of the old building is disrupted.
Spatial organization	Spatial logic of the host building's interior spaces is completely changed.

idea is a well-known concept in the study of animal behavior. The changes in the host behavior and appearance induced by the parasite can be far from being subtitled. Thus, this type of symbiotic relationship implies a drastic change in the host's physiology and behavior.

The design principle of parasitism implies the dynamic relationships between different architectural entities. In structural terms, parasitism implies the introduction of new structural elements independent from the old structure and, in some cases, complete the replacement of the old structure. The positioning and size of the new structural elements depend entirely on the new intervention and do not follow the structural logic of the existing building. Additions and alterations to the host building's fabric are executed in materials that are distinguishable from the old and even confrontational. A clear division is observed in the host building's interior between the old and new material.

The design principle of parasitism is reviewed through the "192 Shoreham Street" project (Figure 5(a) and (b)), which is a reconversion of a Victorian industrial brick warehouse in Sheffield, England, into a mix use building designed by Project Orange. The brief task was to transform a rundown warehouse into a mixed-use building by combining desirable double height restaurant/bar within the original shell with a duplex studio and office units above.

The form of the existing building was substantially changed. The balance of its composition, symmetry, and fenestration was broken and altered by the new intervention. New volumes were added following its own formal logic. New elements belong to a different style. This intense relationship extends to the building's interior, where the new intervention changed the spatial composition of the old building. The logic of interior spaces was altered, and the character of the host building completely changed. Thus, the new intervention was fully governed by its own formal and spatial logic, independent from the existing one. Newly introduced volumes push themselves through the dip line of the host building's façade to conquer the space of their own within the existing structure (Figure 6).

This design principle implies the highest level of change to the original building and the complete inferiority of the old building to the new intervention. The recycling design principle of parasitism and its main characteristics are shown in Table 5.

5. Concluding remarks

The analysis revealed a wide variety of concepts that bridge the gap between the fields of biology and architecture, such as evolution, adaptation, organic, circulation, genetics, skin, epidermis, nerves, arteries, acupuncture, and prosthesis. Moreover, the research shows that the concepts have been extensively used in architecture to explain urban and architectural phenomena and processes. However, the concept of symbiosis is chosen as appropriate because it places an emphasis on various forms of symbiotic associations. These are understood as close and often long-term interactions between two or more different biological species. In the field of architecture, the symbiotic association is translated to the relationship between an existing building and new intervention. The sole purpose of the symbiotic associations is to allow at least one symbiont to draw benefits, nutrition or protection from this relationship. In architectural terms, these benefits refer to structural, material, formal, or spatial upgrading. Thus, the following lines highlight the basic characteristics of three recycling design principles, commensalism, mutualism, and parasitism, illustrated in the comparison of three analyzed cases through the lens of environmental sustainability.

In the case of "Fabra i Coats," the industrial building was preserved in an excellent state, structurally and materially. By applying the recycling design principle of commensalism, all the available original building material was saved, the embodied energy of these materials preserved, and unnecessary demolition avoided to cut down the associated environmental impact.

The case of the "Centro de Monitorização e Interpretação Ambiental – Casa dos Cubos" project showed that the building's perimeter walls, façade, and foundation needed upgrading, but its interior elements needed remodeling. The design principle of mutualism for the "Casa dos Cubos" project is the most environmentally sustainable given that all the available elements of the original building were used, and unnecessary demolition was avoided. Authors of this intervention have saved the embodied energy of the original building's material and cut down the associated environmental impact of production and transportation of new materials by preserving and upgrading all the structure and materials that could be used again. The interior of the host building was in a state beyond repair, and authors had the liberty to use new contemporary elements with their own formal, spatial and material logic. These elements are conditioned by the host building. They enhance it and provide a new 'reading' of existing space.

The industrial building in the "192 Shoreham Street" project was in a poor state structurally and materially. Many of its elements were in a state beyond repair and had to be demolished for the building to be operational again. The recycling design principle of parasitism indicates that all the elements of the original building that could be reused are put to use, thus saving the embodied energy of its material, and cutting down the associated environmental impact of production and transportation of new materials. However, much of the original building was heavily deteriorated and practically beyond repair. Thus, the authors of the project introduced a significant change by designing new contemporary elements with their own formal, spatial, and material logic. These elements are not conditioned by the host building. On the contrary, they are dominant and overpower the old structure.

Contribution of the case study analysis is twofold. First, the case studies show that the selection of the recycling design principle greatly depends on the structure and material conditions of the original industrial building. Moreover, architects create their strategies and choose design principles according to the physical characteristics of the given industrial building. Second, the analysis confirms the validity of the recycling model and provides an understanding of how a range of physical characteristics of an existent building can be considered systematically. The conducted analogy between biology and architecture implies a highly precise apparatus for the operationalization of the redefined recycling design principles in the practice of architectural recycling. Therefore, the model is seen as universal and can be applied to different building types and spatial and social contexts.

Environmental sustainability, as one of the components of the sustainable development, was recognized as important for this research, considering the impact of the building sector on the environment. This component is where the devastating effects of the construction industry are the most obvious. Therefore, the research focused on elucidating the concept of architectural recycling as an environmentally sustainable solution for dealing with the existing building stock. Nevertheless, recycling architecture has several benefits, which relate to other components of sustainable development (social and economic). The relationship between architectural recycling and these components can be addressed in detail in future research.

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