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Connections and joints in buildings: Revisiting the main concepts on building materials life cycle's circularity

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Abstract. Joining methods were set as a field of study and the state of the art on connections in buildings within building materials circularity was reviewed. The cross reference of fields of connections in buildings and resources and waste management has highlighted a set of constraints for implementing circularity strategies such as reversibility of connections: the gap between existing systematisation of knowledge on connections in buildings and the strategies and guidance to support their design, the divergent conclusions reached resulting from partial approaches on circularity and its strategies and, lastly, the questions raised by the consequences of adopting reversible solutions that are still open for discussion.

Keywords: reversible building's connections, irreversible building's joints, building's material life cycle, building's material recovery, building's deconstruction barriers.

1. Introduction

The identification of connections as barriers for the recovery of building materials and components — by means of irreversible assembling methods and contamination of materials—, both for reuse and recycling, and thus to reduce the needs of non-renewable resources and the amount of construction waste produced, has pointed the characteristics of assembling connections as one of the main aspects that should be considered during the architectural design stage [1,2].

To forecast the most-feasible end-of-life scenarios for building materials, the adoption of strategies such as reversibility or flexibility of connections became part of the conceptual guidelines intended to mitigate resources consumption and construction and demolition waste (CDW), which have been considered as evaluation parameters in buildings sustainability assessment tools. Several strategies for implementing circularity in building have been put forward that could increase the potential for materials recovery for reuse and recycling both at building's life-cycle and construction operations [1,3]. Despite literature and well succeeded case studies that justify the relevance of using reversible connections, these solutions keep finding barriers from the construction practitioners' side.



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By enhancing the significance of connections in buildings and the challenges that they represent, this paper reports on the state of the art of connections in buildings within the approach of building materials circularity. Firstly, the background of the research is presented by setting joining methods as a field of study. Secondly, existing building strategies for material circularity are described, progressively focusing on connections in buildings framework. Then, generic considerations on material flows, specific aspects of the implementation of reversible solutions identified on case studies reports, and constraints to implement materials circularity in buildings are here reviewed. Finally, the main questions that have been identified are presented and discussed.

2. Connections and joints in buildings

On the most common sense, connections and joints³ in buildings, are the interfaces on which building elements are assembled, the ways of putting such elements together, the methods or processes of doing so [4] in order to make them continuous or to form a unit [5] and to fulfil particular functions [6]. From a secondary and pragmatic process of design and construction, connections are becoming more and more an enabling technology [5] that reinforces architectural design as an anticipatory act [4].

The need for a theory of connections in buildings did not exist for centuries nor the need for universal terms. On traditional construction systems, the short range of connections taxonomy were result of the available materials and construction techniques grounded on traditional craftsmanship. With technological developments, new materials, new construction systems and new joining techniques have emerged, and the connections taxonomy gradually evolved from crafts related terms to more technological and descriptive specifications [4].

The definition of what is a ‘connection’ or a ‘joint’ also varies. Therefore, and in order to clarify the scope of the study the following definition of connection or joint was considered: “construction formed by the adjacent parts of two or more products, components or building elements, when these are put together or fixed with or without the use of a jointing product” [7].

Aiming to make existing knowledge operational to architectural design and construction, several organized structures of connections in buildings have been developed [4,5,6,8]. Despite the variety of methodologies to classify and describe types of connections and joints, these in-depth approaches have been able to highlight terms, definitions, typologies, functions, design aspects and joining processes and to become fundamental contributions to a broader understanding of connections within building design and construction evolution. The analysis of classification systems applied to connections has shown differences mainly at the characteristics that have been focused: (i) the location of connections (between components as external connections or between components parts as internal connections) [4,6,9]; (ii) the use of joining products (e.g. without joining products as a direct connection; with joining products as an indirect connection; and with joining products as a direct mixed connection) [6,7]; (iii) the joining products type or element (i.e. by material, section or component); (iv) the shape of the components (i.e. section, surface and face); (v) the spacing of connections (i.e. height, depth and margin); (vi) the material of components; and (vii) the type of strength used [5] (i.e. physical, chemical or mechanical). Partial articulations between different typologies were also established (e.g. the relation between position of element, accessibility through application or reversibility character) although only considering a few joining processes (e.g. frequent exclusion of welding or soldering processes) or excluding some design aspects (e.g. strength or aesthetic) [8]. And a set of principles for design of connections has also been sketched by properties of connections (i.e. geometric, structural and environmental). Therefore, lists of functions of connections were extensively described by design aspects: (i) environmental control (related with local environmental conditions), (ii) resistance, (iii) safety, (iv) accommodation of dimensional deviations, (v) fixing of components, (vi) appearance, (vii) economics, (viii) durability, (ix) maintenance (which includes tolerance considerations) (x) ambient conditions, [6] (xi) material, (xii),

³ The use of ‘connection’ or ‘joint’ terms in this paper is made interchangeably, referring to the global definition that is further presented, as both were found within main document consulted.

execution (which includes demountability and sequence of assembly and), (xiii) formal or dimensional complexity, (xiv) types of material to connect or (xv) portability (e.g. transportation of structural elements to construction site) [5,10].

The analysis of these classification systems also revealed how different aspects of connections design are related with the changes that occurred in the construction and architectural practices in the few past decades: (i) how the placement of connections in the building had its evolution directly related with the place of its execution (i.e. in site or off site) which shows the increase of pre-fabrication and standardization; and (ii) how design aspects account for the performance requirements of connections which underline the importance of construction detailing as an anticipatory act, deeper than that existing in traditional architectural design.

3. Building's material life cycle circularity

3.1. Global strategies

Material selection presents one of the most difficult decision within sustainable construction [3] because unlike other elements as water or energy, materials have unique properties that give them value, define their use and result in distinct environmental impacts that cannot be easily assessed or compared [11].

In order to link theoretical requirements for sustainability and practical measures for its application to the built environment, the main procedures for its implementation are inherited from Industrial Ecology principles. These procedures analyse the two kind of materials' flows that occur between the built environment (anthroposphere) and the natural environment: the input flow (dematerialization) and the output flow (rematerialization). One third analytical procedure establishes the relationship between the first two: the dynamic balance of the flows (i.e. the steady-state).

On the input side, dematerialization focus on quantitative aspects of material flows (absolute and relative) and primarily on reducing the need for resources inputs. The flows of resources should be kept within regenerative capacities of the natural environment. By shifting to a more efficient use of materials and energy, by reducing the flow of materials within anthroposphere, and by reusing nonrenewable resources, demand for natural resources might be reduced, as well as the "rucksack flows" which lead to several environmental impacts [12, 13, 14, 15]. On the output side, rematerialization focus on qualitative aspects of materials flows and primarily on outputted waste flows aiming to close materials cycles by reuse, remanufacturing and recycling [13]. The flows from built environment to nature should be kept within the assimilation capacity of the natural environment. By keeping emissions bellow the local, regional and global capacities of assimilation of wastes and emissions by nature and by keeping resources within the anthroposphere system through reuse and recycling processes, final disposal needs should be reduced [13, 14, 15]. And the third approach stemmed from the notion that future coexistence of man and nature would only be possible for future generations if, besides reducing the flows between anthroposphere and nature, conditions for keeping a steady-state situation between flows would be reached. In order to reach the balance, rematerialization is already taking place and the waste output from buildings stock is being reduced through recycling and remanufacturing activities. A developed socio-industrial metabolism would be one where the inputs and output flows would occur within materials stocked in buildings and infrastructures, where new buildings would use materials and components from the deconstruction of existing ones. Thus, reused and recycled materials would replace nature as the main source of material resources input. In this perspective, a shift from new building construction to maintenance, refurbishment and upgrade of existing buildings must need to occur [13].

The factors that have been considered to be mostly influent in the dematerialization of construction went beyond reducing materials weight or volume [13, 15] and include: (i) type of construction that determines the volume and the mass consumed by the building, (ii) material selection which determines the direct and indirect impacts associated with raw materials as well as material quantity and mass, (iii) reparability which contributes to the increase of the life time of the building or element and (iv) demountability which determines de possibility of repair, reuse and recycling. These factors have

supported the development of specific strategies such as: (i) efficiency (e.g. efficient use of materials for a certain function using less resources); (ii) replacement (e.g. provision of similar activities with less resources through alternative materials or technologies) (iii) service (e.g. replacing products by services in order to focus on supplying functions instead of objects) and (iv) durability (e.g. prolonging the life of buildings or elements in order to avoid intensive use of new materials) [16].

Regarding the perspective of rematerialization, the aspects that have been considered as determinants for suitable end-of-life scenarios, which are grounded on the analogy between natural metabolic systems and the industrial (or technical) systems, include: (i) the scale of element (from building to material) [17], (ii) differentiation within each scenario (according to resulting quality of element) [17]; the waste treatment method (natural or technical) [17]; (iv) the flexibility degree of hierarchical structure [17]; and (v) and the nature of materials (replacement of materials for new materials with higher recycling capacities) [14]. Through time, thermodynamic principles have been emphasized regarding the importance of quality aspects from recovered materials as constraints to close materials loop (e.g. loss of shape, degradation, and purity) [18] as available recovery technologies are still not able to completely eliminate loss of economic value from recovered materials and components due to decrease in quality and demand, and also because not all recovered materials and components are suitable to be reused or recycled (e.g. as metals extraction and production is so expensive and they are easily recovered, metals have a high recycling rate). Consequently, by exhaustive detailing of waste management options, the initial hierarchical organization of possible scenarios has been gradually replaced by a dynamic understanding of suitability which is based on a clearer distinction between the processes that are included in a closed loop material cycle and those that are excluded, as well as their consequences [19].

Finally, the steady-state balance of material flows, has been considered to be determined by the ratio between the construction of new buildings and the deconstruction of old ones [13]. The notion of existing building stock as the main material and component storage (buildings as material banks) gained value for its inherent ecological attributes. By direct actions over pre-existing building material stock such as (i) permanence (e.g. some materials can be maintained), (ii) subtraction (e.g. some materials can be removed); and (iii) addition (e.g. some materials might be added) [20], existing buildings would feed future construction activities. The immobilization/permanence of materials and components in existing buildings would extend, as far as technically possible, its useful life, as means to avoid any type of intervention that would result in the production of waste, most likely not recyclable or reusable. As new materials, those existing in buildings, were extracted from natural environment and therefore, the perspective that they should not be wasted has been put forwarded [18, 20, 21]. The subtraction of materials from buildings has been described as directly dependent of demolition or deconstruction with its known impacts because existing buildings present high barriers to deconstruction or material recovery as they were not built to be dismantled [3, 21]. The possible benefits resulting from deconstruction have been described as dependent on the quantity and quality of recovered materials as well as the environmental benefits inherent to raw materials that are saved and kept as natural resources and to the hidden value within the global system to supply those resources [18], which are the core of dematerialization and rematerialization strategies. Addition has been associated with impacts of new construction, being the interfaces between existing and new building the exceptional aspect, where connections between existing and traditional materials and newer ones have been subject of several studies. The connection between the risk of obsolescence and deterioration of buildings, the impacts of waste flows and the need to use new materials to adapt an existing building to new conditions or requirements has been established [22] and would justify suitability of options.

3.2. Specific connections and joints in buildings

Within the global strategies for circularity of materials, some specific building design strategies have been developed such as Design for Deconstruction, Design for Change, Design for Assembly Disassembly, among others. Conceptual guidelines for these strategies have put forward several lists of

criteria and principles for design [1, 23] and have been object of exhaustive and expanded literature reviews [15, 24] which covered mainly technical and economic aspects.

Concerning technical aspects, while some approaches include assessment parameters in order to justify different suitability levels (e.g. use of benchmarks and indicators), others focus on compliance with specific attributes considered necessary in order to accomplish established goals [15] (e.g. material nature and properties). Also, differentiation of criteria for deconstruction, reuse, recycling [2, 15, 24] and natural recovery have become present [15, 23]. Within existing literature embracing higher number of principles and criteria, economic considerations have been gradually limited by its specific geographic or time dependency nature [15].

Equally, specific guidance on criteria and principles for connections design has been provided. Basically, different requirements between those needed to enable reuse of building elements, those needed to enable recycling of materials and those needed to enable deconstruction were progressively proposed. Reuse requirements have been described as more demanding for the need to enable removal of elements without damaging them, and preferably, without damaging the connection or fixing. Damage was not so problematic for recycling, as long as contamination and deterioration were not excessive [15]. Deconstruction requirements related with the ability to remove the element from the building, whether for future reuse or future recycling. Frequently, connections methods were ranked from most demountable to least demountable [1, 15] or from flexible to fixed [2] translating the relations between quality after deconstruction and end of life scenario. Most common types of connections have been grouped on a hierarchical order from fixed to flexible connections: (i) direct chemical connection (e.g. two elements are permanently fixed, not allowing reuse nor recycling); (ii) direct/ direct integral connections between two pre-made components (e.g. two elements are dependent in assembly/ disassembly, not allowing components reuse); (iii) indirect connection with third chemical material (e.g. two elements are connected permanently with third material, not allowing reuse nor recycling); (iv) direct connections with additional fixing devices (e.g. two elements are connected with accessory which can be replaced. If one element has to be removed than whole connection needs to be dismantled.); (v) indirect/dry connection via dependent third component (e.g. two elements/ components are separated with third element/ component, but they have dependence in assembly, restricting reuse); (vi) indirect/dry connection via independent third component (e.g. there is dependence in assembly/ disassembly but all elements could be reused or recycled); and (vii) indirect/ accessory connection with additional fixing device (e.g. with change of one element another stays untouched (all elements could be reused or recycled) [2]. The association of mechanical fixings (e.g. screws) with higher demountability and chemical joints (e.g. adhesives) with higher destructibility has been common to most of classifications.

Although some guidance has been based upon a hierarchic perspective of end-of-life scenarios, where reuse was considered as a preferred option when compared to recycling, other arise from the understanding of a dynamic order of end-of-life options. Guidance related with hierarchic perspective has highlighted the relevance of reversibility of connections as indispensable to the reuse of all elements, while that arising from a dynamic order of waste treatment, which are more dependent on material properties that exhibit different potential for reuse, recycling or even other scenarios, has introduced a variety of options such as removability (i.e. technically less demanding by disregarding damage in the connections) or recycling-compatibility (i.e. joining products or means identical or compatible with material recycling processes) [15] that, although not considered on initial guidelines for Design for Deconstruction, have also been referred within guidance to buildings material circularity.

3.3. *Main consequences*

3.3.1. From global analysis. Studies reporting on the interaction between different factors previously described, have brought to light some possible side effects that might occur associated with implementation of dematerialization, rematerialization and steady-state strategies.

Technical aspects, such as the construction using lighter elements has been put forward as a possible solution to use less resources and generate less waste, but its adoption has sometimes been associated with rebound effects (e.g. overall increase of resources for production and generation of wastes [25]) relating with durability (e.g. lower durability of elements), replacement operations (e.g. increase of need to replace elements and number of units produced) or waste generation (e.g. anticipated end of life). Materials and components replacement have also been directly associated with some negative effects on durability (e.g. lower durability of elements), energy needs (e.g. increase of energy needs) and air pollutants (e.g. increase of transportation needs), faster obsolescence, recyclability (e.g. loss of quality), among others [25]. Also big scale production on larger facilities for pre-fabrication, initially considered as needing less resources for a certain product, has been confronted with new technologies for pre-fabrication based on customization and local production that are further suggested as alternative when energy needs and air pollutants emissions regarding transportation to site are also as part of the equation.

Other studies followed deeply different strategies to the same problems. How to design for durability has been one fundamental aspect of disagreement. Some strategies intended to increase durability of buildings life-cycle have preferred pre-configuration and flexibility, dealing with the speed of transformation and quality of design through standardization and pre-fabrication of components. These approaches have been described as technically determined and explored through delivery and assembling of buildings and product innovation [26]. Other strategies, like reconfiguration, generality or versatility [26] represent the spatial geometry focused on long operation phases or reuse of building based in a set of rules or specification as guide for architect decision process. These approaches allowed the accommodation of a large variety of possible uses through a broader understanding of the requirements of that uses [26]. This dichotomy of approaches has also been made by differentiating technical flexibility, which is related to the replacement capacity of components and systems of building to be easily reconfigured, reused and recycled, and spatial flexibility, which is related to transformations that occur during operation phase of the building [2].

3.3.2. From practical case studies on reversible design. Reversible connections have been put forward as part of strategies for higher transformation capacity or within high technical flexibility [2]. Within this framework, some practical case studies have been developed, where both strategies adopted, and results obtained were documented, and some of their technical, regulation, economic and social/ cultural consequences were described.

Overcoming technical aspects of reversibility in buildings has been considered an issue that, despite being described as a still existing challenge, could be currently overcome, mainly through the use of alternative materials to those already in use, or of non-conventional construction systems, already being developed but that still rely on design specification. The perspective of design as an anticipatory act has also been highlighted because of the need to design and detail different scenarios in advance. Barriers regarding the certification of reused components within existing regulations have also been reinforced. Also economic aspects have been described as harder to overtake as they would have to rely on changes in supply chain and production, which constitute new business models that would take longer to occur and depend on the interaction of stakeholders with different perspectives and roles [27].

The unlikely possibility or mainstream acceptability of adoption in main construction of technical solutions resulting from reversibility requirements has also been raised for its aesthetics implications in design [15] and has brought to discussion the social and cultural consequences if adopted. While some results considered that such conclusion justified the need to a shift in design culture and mentality to overcome the barrier to circularity in the built environment [27] others, based on a more holistic nature of design approach, raised the question of what design consequences would result from strictly following the strategies like reversibility. Simultaneously, resource optimisation has been described as an implicit quality of vernacular or historical architecture by means that include reversible connections but that have not yet been explicitly forwarded within most of the studies having in mind resources and wastes management [24].

4. Discussion

The background previously described has been put forward from the identification of a set of constraints for implementing solutions for circularity that have been associated with technical aspects (e.g. options to be made on architectural design), regulations (e.g. certified materials for reuse), economic factors (e.g. shift from traditional construction techniques to new ones), and social/cultural values (e.g. value of reusing or using recycled materials).

Firstly, the review made revealed a gap between existing systematisation of knowledge on connections and the strategies and guidance to support design of connections in building for circularity that practical case studies analysed did not fully fulfilled. On one hand, existing classifications of connections have produced little or no considerations regarding material and connections properties related with material quality for waste management strategies. Specific studies on connections exist corroborating a deeper relation between the properties of connections and recycling or reuse, but mainly the framework of execution aspects of reversibility and removability were considered. On the other hand, although guidance to support design of connections in building for circularity has been developed, some aspects were not fully taken into consideration: (i) few of the existing joining methods have been considered; (ii) just part of the complexity and variety of characteristics that can be used to describe connections has been addressed; and (iii) relationships between design goals or functional reasons for connecting or joining, and strategies for material resources and wastes have not been clarified.

Secondly, mainly due to the partial nature of the approaches on circularity and its strategies, some significantly divergent conclusions have been reached depending on the perspective adopted for: (i) the end-of-life scenarios (e.g. hierarchic or dynamic); where the existence of alternative connections characteristics other than reversibility able to contribute to circularity were brought forward (e.g. recycling-compatibility); (ii) the technical characteristics of solutions (e.g. innovative solutions or traditional solutions) where the existence of alternative solutions has not yet been fully explored and documented; and (iii) the rebound effects (e.g. to which extent rebound effects that have been already identified in the analysis of broader contexts of materials waste flows and resources management or newer ones can occur within the construction industry if these solutions are adopted).

Thirdly, consequences arising from the adoption of reversible solutions have raised some fundamental questions that are still open for discussion: (i) will the adoption of solutions such as reversibility conduct to the partial or full replacement of existing local technical construction systems?; (ii) or will it contribute to the recovery of vernacular traditions that have in them some of the principles of deconstructability?; (iii) is a shift on design culture and mentality needed?; (iv) or may it already be present within common approaches to architectural design or traditional construction solutions?; and (iv) as stated before, being materials waste flows and resources management strategies only a partial view on what architectural design for sustainability might be, how does materials circularity will influence the understanding of sustainable architectural design?

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