Reuse of Ceramic Roof Tiles: Enhancing New Functional Design Possibilities Through the Integration of Digital Tools for Simulation, Manufacture and Assembly

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Abstract. The material qualities of ceramic roof tiles have provided new formal interpretations that induced a new functional use—a wall. By disassembling ceramic roof tiles from roofs and assembling them into walls, its circularity potential was enlarged. This paper explores the potential use of ceramic roof tiles, as a single element type, in the definition of wall design systems and patterns of composition that comply with design for manufacture, assembly and disassembly (DfMA-D) requirements, through the development of a shape grammar and implementation through parametric models. The new shape grammar extends the compositional patterns already produced and the redefinition of the connection systems by incorporating DfMA-D requirements into the shape grammar rules sets new combinatorial patterns aligned with European Union goals for building circularity. The parametric models automate the generation of design solutions and extend the design process to the assembly and disassembly stages using robotic fabrication techniques.

Keywords: Circular building, Component reuse, Ceramic roof tiles, Shape grammar, Parametric design

1 Introduction

A wall built with ceramic roof tiles constitutes a recontextualization of construction components, that instead of being applied in a roof—the end for which they were designed—are reconfigured in an element that they were never intended to be. The material qualities of ceramic roof tiles provided new formal interpretations that induced a functional use— as a wall (Franco, 2015). The prevailing techniques of installation of ceramic roof tiles—e.g. laying of tiles interlocked over a lathwork, fixed with screws, nails or clips rather than mortar—comprised technical properties prompting straightforward disassembly of obsolete roofs providing stacks of roof tiles and battens to be put back in use.

Disassembly is a means to reduce waste production and to increase the availability of recovered building components that gather integrity and quality conditions to be reused or remanufactured rather than integrated in recycling waste streams (EU,2016). Thus, when a wall is built with reused ceramic roof tiles it becomes a solution aligned with the goals of the circular economy model in the building construction sector adopted by European Union and other countries around the world.

However, whether for reuse with new functional uses (indirect reuse), or for its original use in roofs (direct reuse), disassembly of roof tiles from buildings without damage becomes an essential condition to maintain its value and functional properties that must be considered at design stages. Design for disassembly (DfD) occurs when disassembly requirements are included in design stages, so *that activities during the stages of use, maintenance, (including repair, replacement, refurbishment), and end-of-life (e.g. disassembly, reuse, recycling, disposal)* increase resource efficiency. DfD includes principles such as ease of access, independence, avoidance of unnecessary treatments and finishes, simplicity, standardization, and safety of disassembly (ISO, 2020). The concept of Design for Manufacturing and Assembly (DfMA), on the other hand, reinforces the idea that designing and optimizing a product together with its production system reduces the development time and cost, and increases performance, quality, and profitability (Thompson et al., 2016). Combining DfMA and DfD principles and guidelines into DfMF-D, connection detailing appears as a major cross consideration. While the use of reversible connections has been considered as making disassembly easier—such as screws and bolts or interlocks—,poured and welded connections—such as mortar—are considered to produce more permanent connections and to contaminate the materials at disassembly operations (ISO, 2020).

This paper presents a new shape grammar (SG) for wall design systems with ceramic roof tiles, starting from the analysis of a set of existing solutions of ceramic roof tiles walls. The new SG extends the ones previously produced by incorporating reversible connection detailing into new and transformed rules and by setting new combinatorial patterns. This SG is implemented through parametric models that comply with design for manufacture, assembly, and disassembly (DfMA-D) main requirements, that automate the generation of design solutions and that extend the design process to the assembly and disassembly stages using robotic fabrication techniques.

1.1 Reuse of ceramic roof tiles

Walls composed of ceramic roof tiles exist in the built environment either as stacked tiles, as shading elements in façades, or as exterior walls cladding, whether built with traditional construction methods or by using computational design tools that challenge new design and assembly possibilities.

In traditional vernacular construction (Case study A), the use of ceramic roof tiles in walls is closely associated with scarcity of resources inducing a reclamation of locally available materials and components from demolitions, subsequently applied by craftsmanship. The architecture of Wang Shu includes several examples where discarded tiles (and bricks) salvaged from demolition sites are stacked as exterior walls cladding—such as Ningbo Tengtou Pavilion (2010), Ningbo History Museum (2008) or Five Scattered Houses (2006)—, recovering Chinese regional vernacular construction traditions (Chau, 2015).

Arturo Franco, in ‘Nave 8b’ in ‘Matadero Madrid’ (Case study B), changed the direction of the ongoing works when confronted with the opportunity of an abundant stockpile of clay roof tiles removed from other warehouses of the ‘Matadero’. The available material was integrated to build the interior walls and the cladding of the exterior walls comprising, a bioclimatic solution that explored both the thermal inertia of the ceramic material as well as the wall permeability achieved by the configuration of roof tiles (Franco, 2015).

With the purpose of creating a brise-soleil for the main façade of ‘The Beehive’ (Case Study C), electing recycled materials from the beginning of the design process rather than an afterthought, Raffaello Rosselli and Luigi Rosselli selected clay roof tiles as *an overlooked material without adequate reuse market* (Rosselli, 2017) ending up in landfills. In an exploratory design process, full-scale tests and prototypes were developed in a hands-on applied manner.

In a more complex waved reconfiguration, in ‘Reclaimed tiles installation’, Ant Studio applied parametric design tools to a wall of salvaged clay roof tiles, intentionally challenging the stereotypical mindset (Ant Studio, 2019).

The variety of solutions present in this case studies constitutes *a corpus* of design solutions that show that the reuse of ceramic roof tiles in buildings can produce architectural design solutions that both comply with environmental goals and comprise a rich set of patterns of composition that can be extended.

1.2 Shape grammar for the reuse of architectural components

A SG is defined by a set of shape rules that when applied in a step-by-step way allow the derivation of a set of designs or a language of design. Shape grammars are both descriptive and generative. The rules of a SG compute design solutions, but also are descriptions of those design solutions (Knight, 2000). Shape grammars have been categorized into analytical and original. Original SGs create new styles of designs, by combining original formal rules and geometric descriptions. Analytical grammars have emerged with the aim of describing architectural styles or languages historiographically relevant. In the context of this work are relevant previous SGs that aimed to describe the generation of patterns, such as Triangle and T-square windows of Frank Lloyd Wright (Rollo, 1995), or Paraguayan perforated masonry walls for shading and ventilation (Vazquez, 2017). These studies show the potential of inferring SGs from the analysis of a corpus of pre-existing pattern design languages. Thus, these analytical grammars allow the derivation of the initial corpus, as well as new designs in the language. The adequacy of SGs to define an analytical framework, in comparison to others less deterministic generative algorithms, justify its use as computational research methodology.

Additionally, in accordance with Terry Knight (1983), a SG transformation occurs when at least one rule addition, deletion or change is performed. A rule change can take place in the initial form, on the transformation rule itself, or in the final state of the rule, through changes in spatial and state labels. Thus, after rules are inferred from the analysis of pre-existing cases, they can lead to new rules as they can be subsequently used as a starting point accounting for additional features.

The adequacy of Shape Grammars for this work relies on the potential of setting new combinatorial patterns, but also on the redefinition of connection system that consider DfMA-D processes through the addition of rules that integrate reversible connection systems, as opposed to non-reversible ones present in some of the surveyed examples.

2 Methodology

In accordance with the context described previously, the approach followed in this research consisted in: (1) identification and selection of case studies with walls built with ceramic roof tiles; (2) compilation and information grouping into parametric schemas of the formal principles of the *corpus* in analysis; (3) inference of SG rules through analytic process of *a corpus* of ceramic roof tiles wall designs, including the identification of connection types; (4) assessment of compliance of SG rules with guidelines for DfMA-D, namely the reversibility of connection types; (5) definition and description of the transformation rules along the various stages from the grammar and illustration of the rule application to generate a solution *corpus*; (6) finally, translation of the grammar principles into a parametric computational model allowing to evaluate the generative outcome of the grammar principles under a different paradigm.

3 Shape grammar

Three case studies were selected to extract the generative rules of design and the types of connection types used: case study A—a vernacular construction wall—, case study B—Arturo Franco's 'Nave 8b' in 'Matadero Madrid'—, and case study C—brise-soleil wall for the main façade of 'The Beehive'.

Two criteria were used to select the case studies to analyze: functioning as a wall (cladding excluded) and diversity of compositions between case studies.

The analysis of the rules observed in these three case studies revealed diversity in form and function of structures assembled with roof tiles as well as in connection solutions.

Along with the shape analytical process, a broader classification of connections was applied to identify the type of connections used. The classification of connections used is organized according to: (i) the use of joining elements (e.g. direct connections—when no joining accessory is used—or indirect connection—when an accessory element is used); (ii) the type of joining element (no joining element, joining material—such as mortar—, joining section—such as adhesive stripe—, or joining component —such as battens or screws) (Martin, 1977; Meijs & Knaack, 2009); and (iii) the type of strength used (e.g. physical, chemical or mechanical forces) (Messler, 2004;).

From case study A, the possibility of a regular, simple aggregation with bearing capacity represented in rule A1 should be highlighted, where the mortar—an indirect connection established by an accessory joining material that applies a chemical force— ensures the vertical stability of the elements.

From the analysis of case study B, rule B emerges. In this rule, the author uses the knowledge and the practice acquired in traditional brick construction where the brick is laid also with mortar and applies this process to the placement of tiles that are laid in the traditional way in row in a horizontal and then vertical interspersed distribution. The B1 variation allows the creation of another one, B2, which allows openings in mostly massive walls, giving to this light permeability and ventilation represented in B2. In case study C, we identified several compositional rules that integrate the building's façade, each one of them with different formal purposes.

Rule C consists of three variants that aim to allow different levels of permeability of the façade. The C1 variant is the one that allows for greater permeability with a span of one tile in length that allows for great visual permeability and greater ventilation. C2 is a variant of C1 which divides the span in two, doubling the number of tiles and consequently decreasing the span and the permeability. Also, B2, C1 and C2 use mortar as connection solution between roof tiles. Despite being a variation of the previous ones, C3 is achieved by using the tile laid along its length, directly without any accessory to establish the connections between roof tiles— direct connection with no joining element depending exclusively on mechanical forces— which makes it possible for its angle to be variable during placement, allowing the gap between tiles to be different along the wall. C4 is a variation used for interior walls but has structural dependence from third elements, also with direct connection between tiles. Due to space restrictions Figure 1 only illustrates some of the rules.

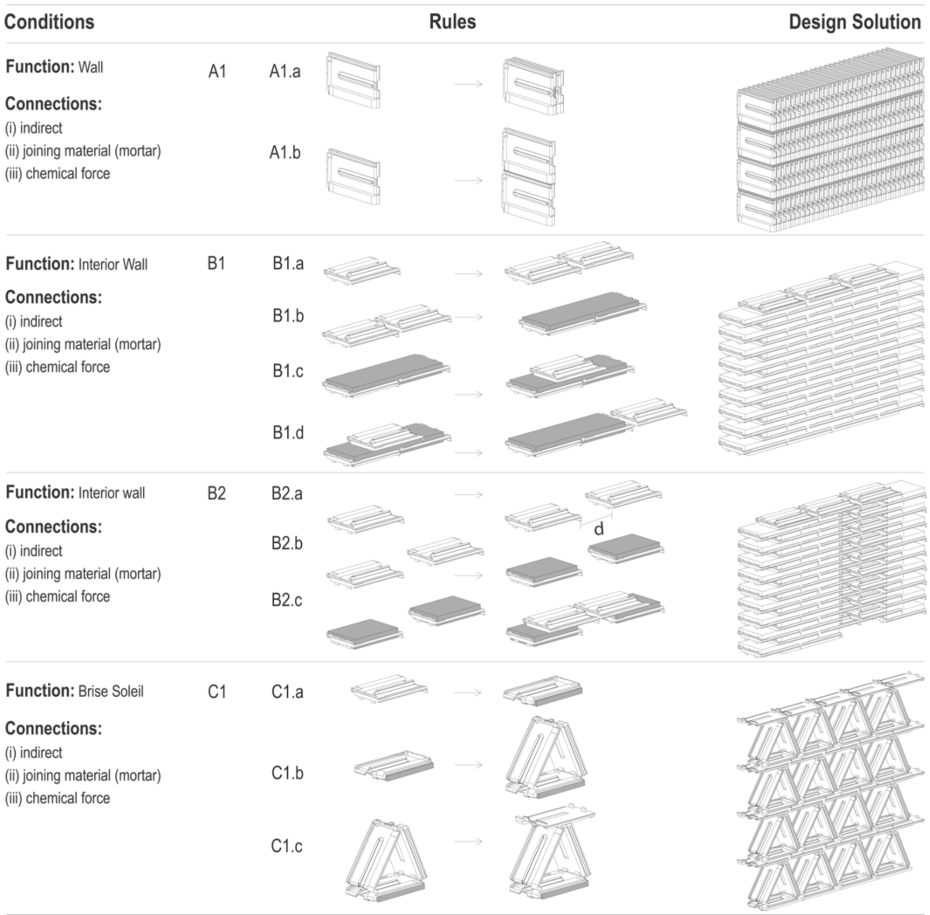

Figure 1. Analytic grammar of *a corpus* of ceramic roof tile walls

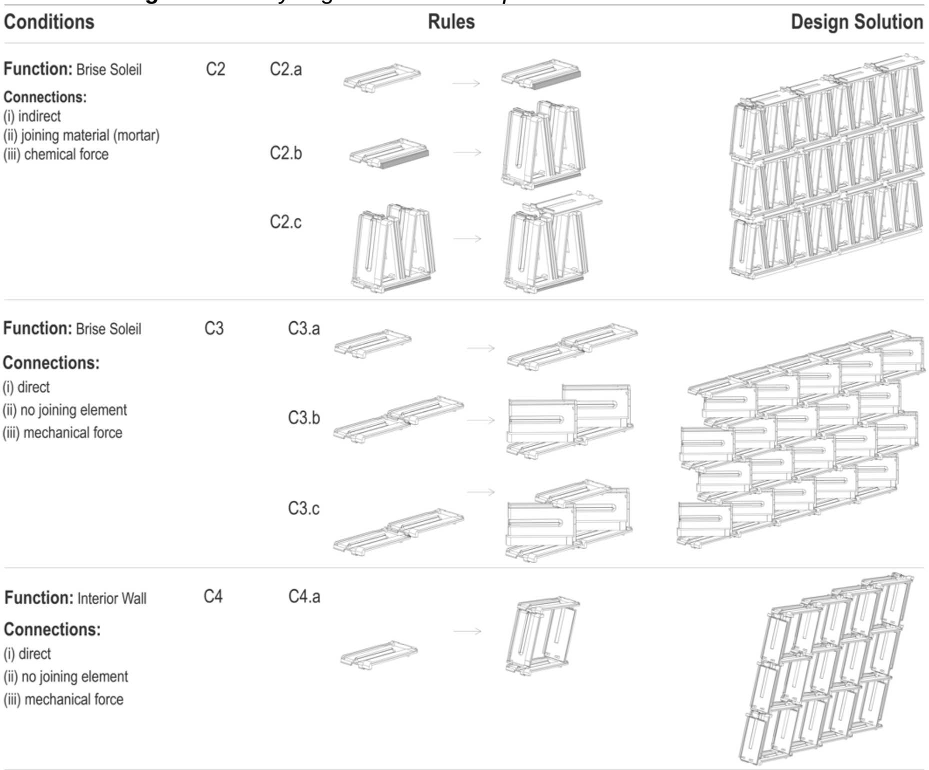

Figure 1. Analytic grammar of *a corpus* of ceramic roof tile walls (Continued)

4 Assessment

4.1 Compliance of connection types with guidelines for disassembly

The reversibility of a connection is defined by the inexistence of damage in both the elements connected and the accessories establishing the connection after the disassembly. The combination of the use or not of joining elements (whether the connections are direct or indirect as described above), with the type of joining element (none, joining material, section, or component) and the type of force applied to establish the connection (mechanical, chemical, or physical) determines the degree of reversibility.

For the purpose of assessing the reversibility of the connections used in the inferred rules and to guide the development of new rules with more suitable connection types, a classification based on the combination of the properties of connections was developed, classifying connection types from less suitable to more suitable for reuse: (i) direct permanent connection (e.g. two elements are connected by physical forces used in connections such as welding, inducing damage at disassembly and therefore not allowing reuse of elements); (ii) indirect connection with chemical joining material (e.g. two elements are connected permanently with accessory jointing section or material such as adhesives or mortars, inducing damage at disassembly and therefore not allowing reuse of elements) (iii) direct integral connections between two pre-formed components (e.g. two elements are fixed by the shape of interlocking interfaces by mechanical forces, allowing reuse of elements but with assembly and disassembly constraints); (iv) indirect connection with accessory fixing component (e.g. two elements are connected with mechanical accessory fixings that can be removed, but allowing reuse of elements with assembly and disassembly constraints); and (v) direct connection by mechanical forces (e.g. two elements are connected exclusively by mechanical forces used).

According to the previous classification, the rules A1, B1, B2, C1 and C2, use mortar as joining material i.e., have a connection type classified as (iii) indirect connection with chemical joining material that does not comply with the reversibility required from DfDM-A guidelines. The disassembly process would result in some damage of the ceramic roof tiles and destruction of the connection material, and therefore the solution for the connection must be changed. Only rules C3 and C4 would not constitute barriers to the recovery of ceramic roof tiles for future reuse as they constitute a direct connection without any accessory and comply with the requirements of DfMA-D.

4.2 A transformation grammar for a DfMA-D roof tile wall system

For the definition of a roof tile wall SG that integrates DfMA-D principles the following operations were performed: (1) Rule A1 was changed to R1 so that instead of being aggregated with mortar, tiles are simply laid down —type (v) connection, direct connection by mechanical forces. (2) The initial rules, B1, B2, C1, were changed to R3, R4 and R6. The mortar was replaced by wooden battens that could also be recovered from disassembled roofs. Unlike mortar, battens constitute reversible connections and reuse of all components becomes possible—type (iv) indirect connection with accessory fixing component. (3) Rules C1 and C2 were changed to Rule 7 and Rule 8. In the initial part one of the horizontal tiles was removed so that no connections were needed—(v) connection, direct connection by mechanical forces. (4) Rule C3 e C4 were not represented because no change was made as a direct connection was already used. (5) A new rule R2 was created. The tiles simply lay using the profile shape of the previous for interlocking—(iii) direct integral connections between two pre-formed components. (6) Rule B1 was changed to R5. A gap between tiles was created originating a "perforated" wall for lighting and ventilation. The mortar was replaced by wooden battens — type (iv) indirect connection with accessory fixing component. (7) R9 is a new rule created from scratch where the goal was to create a wall of great mass without using any type of connecting element. To provide stability, the modules are phased out from row to row—(iii) direct integral connections between two pre-formed components. Due to space restrictions Figure 2 only illustrates some of the rules.

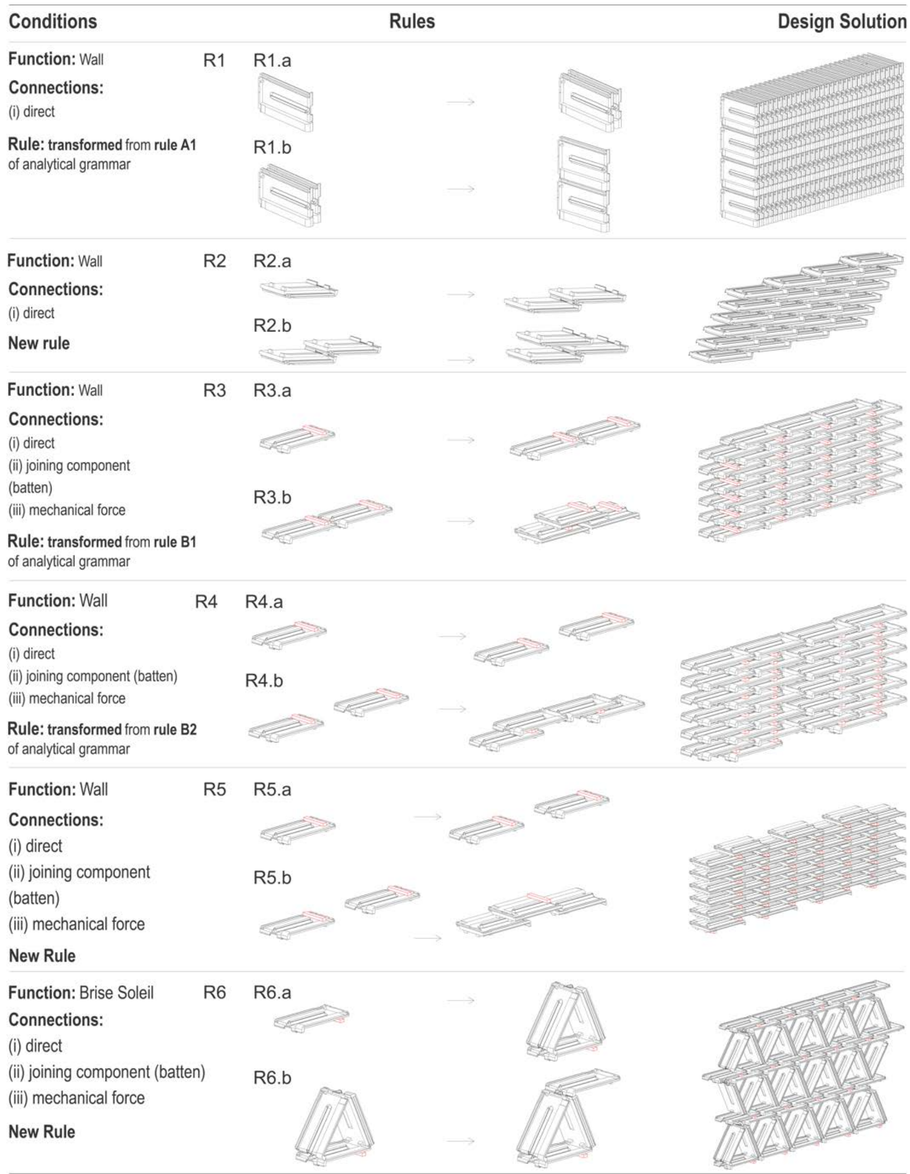

Figure 2. Transformed grammar of *a corpus* of ceramic roof tile walls (rules R1 to R6)

Figure 3 illustrates design solutions derivate from the final SG, demonstrating the combination of different rules with parametric variations.

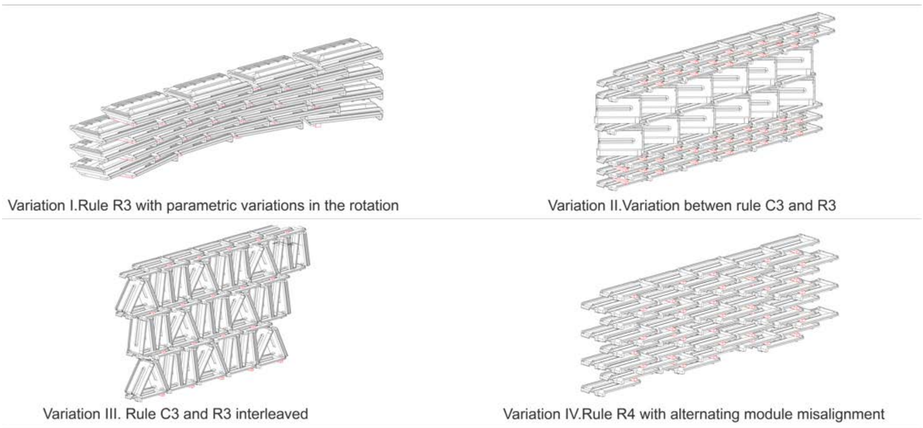

Figure 3. Roof tile wall design solutions encompassing the subsequent application of a set of rules of the Shape Grammar - Variations I, II, III and IV

5 Parametric model

A computational model was implemented in Grasshopper—Visual Programming Language that interacts with modelling software Rhinoceros Considering—with the aim of: (1) creating a pseudo interpreter of the SG rules to automate the generation of design solutions; (2) extending the design process achievements to the assembly and disassembly stages by robotic fabrication techniques. It is a good practice to use modularization strategies in scripting. The subdivision of a complex code into less complex modules, provides a more clear and readable structure, which will be beneficial in subsequent editions. Therefore, modularized groups of components not only keep the model manageable, but also ensure that each of these groups would correspond as much as possible to a grammar set rule. For this reason, each set of rules were implemented in modules in accordance with the surveyed case studies. These initial modules emulate the shape rules for the formal arrangement of the roof tiles, considering the connections and sequence of assembly. Whenever there were variables with parametric behavior, it was considered the use of interactive components to ease the user interaction. A second part of the model automates the gathering sequence of application of the roof tiles, simulating an assembly process that starts in the lower layers toward the upper sections of the wall. This module intentionally tries to implement the behavior and conditions of the assembly on site. A final set of modules incorporate the translation of the assembly process to robot programming language, through KUKA|prc—a library for robot simulation implemented in Grasshopper environment by Johannes Braumann and Sigrid Brell-Cokcan (2015). The choice of this computational ecosystem is since, in future works of this research, is expected to use the 6-axis robotic arm KUKA KR 120 R2700-2.

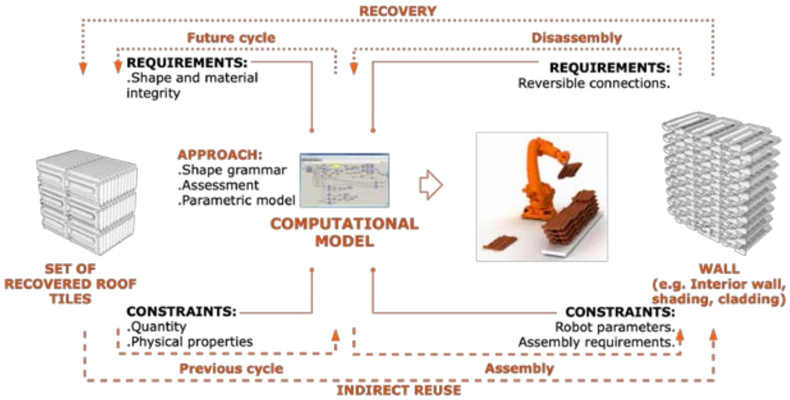

Figure 4. Proposed DfMA-D process for indirect reuse of ceramic roof tiles

6 Conclusion

The paper explores new methods for the reuse of ceramic tiles meeting the goals of circular economy in the building industry. Namely, the inference of a SG from existing examples of design walls of ceramic roof tiles and its subsequent transformation to comply with DfMA-D connection guidelines.

More rules can be developed in order to enrich the grammar pattern composition outputs. Also, guidelines for DfMA-D are broader than the reversible connections, therefore future works to be developed should include compliance with requirements such as ease of access or independence necessary for disassembly or maintenance.

Further the implementation of the SG into parametric design, integrating robotic assembly processes, was illustrated in order to test its application to non-regular design solutions. A deeper analysis on the assembly and disassembly stages through the use of robotic fabrication techniques will be addressed in future works.

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