buildings

MDPI

Article

Methodology for Continuous Improvement Projects in Housing Constructions

Patricia del Solar Serrano *, Mercedes del Río Merino and Paola Villoria Sáez

Escuela Técnica Superior de Edificación, Universidad Politécnica de Madrid, 28040 Madrid, Spain; mercedes.delrio@upm.es (M.d.R.M.); paola.villoria@upm.es (P.V.S.)

* Correspondence: patricia.delsolar@upm.es

Received: 18 September 2020; Accepted: 31 October 2020; Published: 3 November 2020

Abstract: Several authors have studied construction defects, but no studies were found implementing best practices and control strategies through the implementation of continuous improvement projects. This article shows a procedure based on Continuous Improvement Projects, which can be used in building constructions, and it is structured into four phases: Plan, Do, Check, Act, following the PDCA Quality Cycle. In addition, the method developed was specified for ceramic tiling execution and was further implemented in three building projects of Spain. The results obtained concluded that the proposed Procedure can be used by construction professionals who are concerned about improving the quality of construction. In addition, the implementation of the Procedure managed to reduce around 45% the costs derived from the defects caused during the ceramic tiling execution, due to the best practices incorporated in the Procedure. A slight increase in the number of defects was also found, motivated by the thorough inspection conducted when the Procedure was applied. Therefore, the Procedure (incorporating the lessons learned) must be implemented so that by learning, gaining experience, and incorporating best practices, the goal of zero defects can be achieved.

Keywords: construction defects; housing; ceramic tiling; continuous improvement; quality control; quality management

1. Introduction

The objective of every company must be to achieve "zero defects" in their products, which will result in greater customer satisfaction and expectations [1,2]. Achieving zero defects has many advantages, such as: achieving good quality products, improving customer's satisfaction, reducing repair and rework costs and increasing both productivity and competitiveness, because products can be sold at a lower price whilst keeping profit margins due to the reduced production costs [3].

It is not possible to work towards achieving zero defects in construction without continuous improvement projects forming part of the routine. As such, it is fundamental to know what we are doing wrong and to attack the root causes in order to prevent the repetition of the same mistakes.

In order to work on continuous improvement, it is essential to incorporate the widely-known Deming Cycle, created by Shewart and disseminated by Deming: PDCA (Plan, Do, Check, Act). Such integration involves the participation of everyone, from senior management to the very last employee, through continuous improvement projects [4–6].

Continuous improvement projects involve the implementation of the PDCA Quality Cycle in company activities and processes [7]. It is possible to apply it generally or to focus all efforts on an area where an opportunity for improvement has been detected. The main benefits of implementing continuous improvement projects in a company is that they promote constant insertion of small incremental improvements and achieve better results in regard of efficiency and quality of the final product [8].

However, when trying to apply continuous improvement in the construction sector, many issues appear because of two main reasons: (1) the type of products—i.e., buildings—which are unique and non-serialized, and (2) to the nomadic nature of the sector, where the working environment changes for every project. These specific characteristics of the construction sector highlight the huge differences between this sector and other industries when it comes to implementing quality aspects. [9,10].

Several authors have studied construction defects, providing reliable information about the most recurring defects, helping to increase productivity and implement strategies to achieve zero defects [11–20].

Other studies analyzed defects in specific construction activities of the building process, such as the adhesion flaws of exterior ceramic tiles (façades) and the shortcomings of all of the professionals involved in building wet rooms [21,22]. These studies identified the major defects produced and gave advice to reduce them.

Lee at al. [23] investigated the defects found in residential buildings. Analysis was performed on 7554 defects in 48 residential buildings, covering seven construction elements/activities: reinforced concrete, masonry, finish, mechanical, electrical, and plumbing, door and windows, furniture, and miscellaneous. For reinforced concrete, broken items and water leaks due to cracks or damage represented the most severe defects, while malfunctions and installation problems were the most recurrent defects found for mechanical, electrical, and plumbing.

Moreover, studies dealing with the building finishes and more specifically with ceramic tiling execution have also been found. Silvestre and De Brito [24] developed a procedure to control the ceramic tiling execution. More recently, Del Solar Serrano et al. [25] conducted a research to identify the most recurrent defects found in residential buildings of Madrid, Spain. As a result of this study, 25 main types of defects were detected and highlighted as most recurrent. From the total defects analyzed, most of them (87.5%) occur during the execution process, whereas almost half are caused by or derived from improper grout preparation or faulty application.

Additionally, several works were found defining best practices to avoid or prevent defects in a specific construction activity, but these best practices were not included in the procedures of the Internal Quality Assurance System (SGIQ).

Nevertheless, despite the aforementioned studies, no references were found implementing continuous improvement projects in housing construction.

2. Objectives

The main and first objective of the research presented in this article is to develop a Procedure to implement continuous improvement projects in housing constructions.

A second objective is to apply the Procedure specifically for the construction activity of ceramic tiling execution.

Finally, the third objective is to implement the Procedure of ceramic tiling execution, in three residential buildings. Results before and after its implementation were obtained in order to measure the efficiency of the proposed Procedure.

3. Methodology

The following three-stage method was used to answer the three objectives of the research (Figure 1).

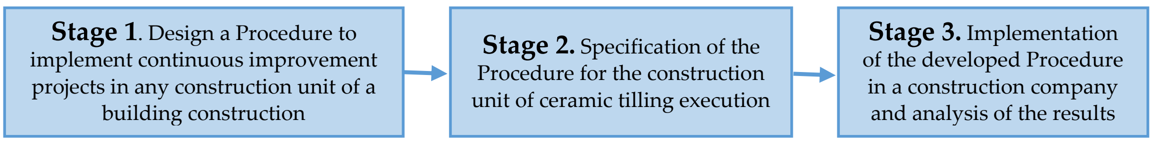

Figure 1. Scheme of the methodology.

3.1. Stage 1. Design a Procedure to Implement Continuous Improvement Projects in Any Construction Unit of a Building Construction

The purpose of implementing continuous improvement projects in building projects is to attack the root causes of the defects, reducing them as a key measure to achieve the success of the improvement project and to achieve building projects with zero defects. For this, the proposed Procedure follows the recommendations of Ishikawa [4], by using the Deming-Shewart's Quality Cycle (PDCA), and it is structured into the following four phases: Plan, Do, Check, Act.

In addition, the Procedure includes:

- the definition of the tasks or activities to be carried out in the Continuous Improvement Project;
- the specification of the members of the team, which will be involved in the continuous improvement project, as well as their responsibilities;
- a series of preventive measures or best practices (BP) for each construction unit; and
- a way to measure the efficiency of implementing continuous improvement projects.

3.2. Stage 2. Specification of the Procedure for the Construction Unit of Ceramic Tilling Execution

In the second stage, the Procedure defined in stage 1 is applied in a specific construction activity, the execution of the ceramic tiling, because it is one of the areas in which the largest number of incidents and defects are recorded (87.5% of the total incidents) and it is responsible for around 90.1% of the total final repair costs [25].

3.3. Stage 3. Implementation of the Developed Procedure in a Construction Company and Analysis of the Results

The specific Procedure developed in the second stage is implemented in a Spanish construction company during the execution of three building projects, with a total of 193 dwellings. These three buildings have similar construction features: high-rise residential buildings with a medium level of quality and were built by the same construction company.

During the implementation of the Procedure, data regarding the defects as well as the main areas of improvement were recorded and analyzed.

4. Results

The results obtained in the three stages of the study are summarized below.

4.1. Procedure to Implement Continuous Improvement Projects in Any Construction Unit of a Building Construction (Stage 1)

As indicated in the methodology section, the Procedure proposed will: define the tasks or activities to be conducted in the Continuous Improvement Project; define the team who will be involved as well as their responsibilities; include a series of preventive measures and a way to measure the results obtained.

4.1.1. Tasks or Activities to Be Carried Out as Part of the Continuous Improvement Project

The tasks can be grouped into four phases following the Deming-Shewart Quality Cycle, as shown in Figure 2, and are detailed below.

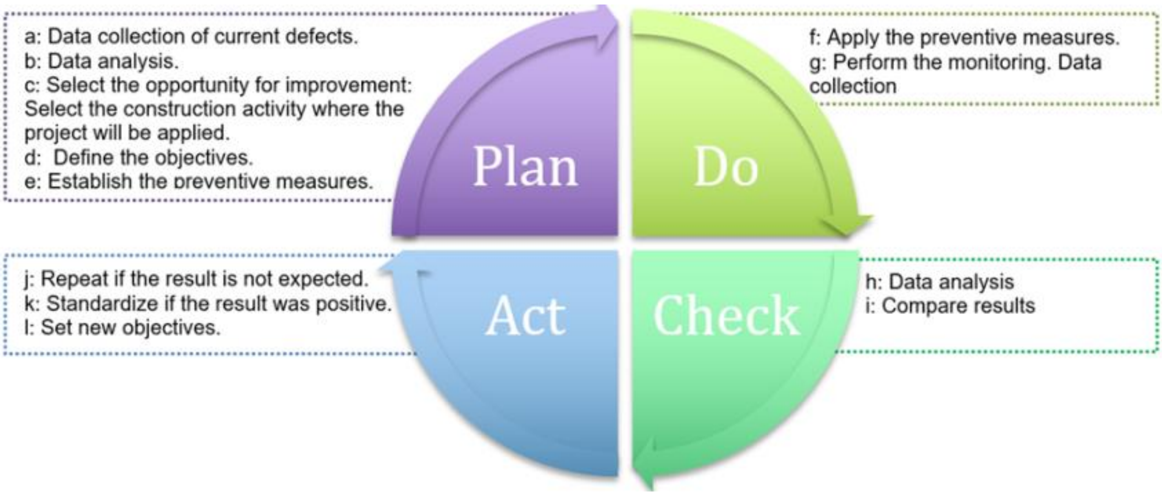

Figure 2. Scheme of the Continuous Improvement Project tasks/activities.

Plan Phase

In this phase, the construction activities which need to be improved will be identified. Then, the opportunities for improvement will be chosen, the objectives defined as well as the preventive measures.

a. Data collection of current defects: This involves inspecting the residential buildings in order to collect data concerning the number and types of defects so it can be further analyzed. The data is documented on a data collection sheet that has been specifically designed in order to feature a list of defects which are easy to analyze and cluster. In order to simplify the data collection and further analysis, a checklist template containing the most common defects is recommended.
b. Data analysis: Once the defects have been recorded and classified according to the type of defect, they can be organized using a Histogram, which classifies the defects according to the number of defects by construction activity. This will help the team to know which construction activity produces the greatest number of defects and therefore requires priority action. This Histogram is created in accordance with the Law of Pareto (Pareto Diagram), which provides information to determine the frequency or relative importance of different items and helps to organize and rank them in terms of importance [26]. Therefore, applying the Pareto Law with the data collected in phase [a] will help to highlight the construction activity responsible of over to 80% of the defects.
c. Select the opportunity for improvement: Selection of the construction activity where the Continuous Improvement Project will be applied. Once the data has been analyzed and the Pareto Diagram created, a meeting with the team is needed to decide in which of the construction activities (responsible of over 80% of the defects), the continuous improvement project will be implemented.
d. Define the objectives: The objectives are set using the values of two quality indexes, i.e., the incident volume quality index (VQI) and the repair cost quality index (CQI), which are calculated using equations 1 and 2, respectively. These indexes are used not only to define the target or objective, but also to measure the results of the improvement project.

$$VQI = \frac{number\ of\ detected\ defects}{number\ of\ inspected\ dwellings} \quad (1)$$

$$CQI = \frac{cost\ of\ repairing\ the\ detected\ defects}{number\ of\ inspected\ dwellings} \quad (2)$$

If the company does not have previous records of these quality indexes from similar housing projects, they have to be calculated. For this, the data collected, classified, and analyzed in the tasks "a", "b" and "c" is used to calculate the quality indexes (VQI and CQI). These indexes will be the initial indexes and will serve as reference values to compare the quality indexes obtained in future similar housing projects of the company. If the company already has information of the quality indexes obtained in previous similar housing projects, they are used straightforward as a reference or minimum objective to be achieved (or improved) in the housing project under inspection.

e. Determine the preventive measures: In order to prevent recurrent defects—which have been previously identified as key issues requiring action in task "c"—it is necessary to establish the implementation and monitoring criteria that will prevent the defects from occurring. For this, several documents "Implementation Protocols" and "Monitoring Sheets" are created for the different stages of the construction process.

    - Implementation protocols: It must be the shortest possible document and refers to the regulations and recommendations for a correct execution.
    - Monitoring sheets: it is important to monitor and control the activities conducted throughout the production process, from receiving and using the materials to the handover of the completed construction. For this reason, the following monitoring sheets are proposed:
        - Monitoring sheet for receiving the materials: this sheet details all of the requirements that must be fulfilled by all of the materials which are necessary for the execution of the construction activity under inspection and should be in accordance with the applicable UNE standards;
        - Monitoring sheet for the execution: the proposed sheet covers the regulatory requirements, the manufacturers' recommendations and good construction practices to be performed during the execution of the construction, i.e., when the laying out, when storing the materials, the protection required in the event of adverse weather conditions, etc.; and
        - Monitoring sheet for the handover of the completed construction work: the proposed sheet has a checklist format in order to facilitate the classification of the detected defects. The sheet seeks to standardize data collection by different experts during the handover of the completed construction activity, establishing a single set of common criteria which enables and simplifies the statistical processing of the data.

The Quality Department of the company should incorporate these documents into the company's procedures and the Production Department will implement them in the different building projects.

Do Phase

f. Apply the preventive measures identified in the Plan phase: It is necessary to incorporate the criteria established during the Plan phase and set out in the technical documentation produced strategically to reduce or eliminate the defects which have been selected, in the company's quality and production procedures. Additionally, it is important to consider specific staff training courses.

g. Perform the monitoring and control during the execution of the works. Data collection: Using the monitoring sheets designed in the Plan phase (task "e") in each of the different stages of the construction process (receipt of material, implementation, and handover of completed work). Record and file the monitoring performed for subsequent analysis.

Check Phase

h. Data analysis: This is a similar task to that performed during the Plan phase in order to identify the defects and select the opportunity for improvement. It is necessary to classify and organize all the defects recorded and obtain the Pareto Diagram which will identify the defects making over 80% of the defects, in terms of volume and cost.

i. Compare results: Using the Histogram and Pareto Diagram produced in the previous task "h", it is necessary to establish the VQI and CQI quality indexes achieved in the specific development or developments in which the continuous improvement project is being applied. These indexes must be compared with the reference indexes established in the Plan phase (task "d") to objectively determine whether a significant improvement has been obtained in reducing or eliminating the defects.

Act Phase

j. Repeat if the result is not what intended and implement another improvement cycle and decide whether the objectives are to be maintained or adapted to the new reality.
k. Standardize if the result was positive, so that the measures are consolidated in the company's procedures and applied to all building projects. If the level of quality drops over time, it is highly recommended to conduct a research to analyze what is causing the deviation and the root cause of the problem. In order to be sure that the process is standardized, it is fundamental that the data is analyzed and that the VQI and CQI quality indexes offer the same or better results than those achieved when the decision to standardize the process was taken.
l. Establish new objectives: Once the process has been standardized, it is necessary to look for another opportunity for improvement and set up a new continuous improvement project.

4.1.2. Team Formation and Responsibilities

It is essential to assure the company's commitment and participation in the project [27]. In order to ensure that the whole company participates in the continuous improvement project, it is necessary to form a team composed by representatives from those departments which may benefit from the improvements achieved with the project, i.e.: Management (M); Quality Department (Q); After-sales Department (AS); and Production Department (P).

Each department shall name a representative, except the production department, which in addition to appointing a middle-management representative, shall appoint a Technical team (T) of experts which will perform the monitoring and inspection tasks. This technical team can be composed by members of the construction company staff or external experts specialized in monitoring and inspection. This team must be sized according to the needs of the building projects in which the result of the continuous improvement project is to be measured.

It is very important that each person is clear of their role in the project in order to ensure that it is implemented correctly. The roles and responsibilities are defined in the Responsibilities Matrix Table 1.

Table 1. Responsibility allocation matrix.

Phase	Task/Activity	Teams/Members				
		M	Q	AS	P	T
Plan	a: Identify potential problems. Inspection of the dwellings and development of the list of incidents	I	A	S	I	R
	b: Data analysis	I	A/S	R	I	-
	c: Select the opportunity for improvement: Selection of the construction activity where the Continuous Improvement Project will be applied	R	R	R	R	-
	d: Define the objectives. Determine the quality indexes: Incident volume quality index (VQI) and repair cost quality index (CQI).	I	A/S	R	I	-
	e: Establish the preventive measures: technical documents to prevent flaws and control the execution of the construction works.	I	A/S	R	I	-
Do	f: Apply the corrective measures. Distribute the technical document and workers' training	I	A/S	I	R	-
	g: Perform the monitoring and control during the execution of the works. Data collection	I	A/S	I	R	R

Table 1. *Cont.*

Phase	Task/Activity	Teams/Members				
		M	Q	AS	P	T
Check	h: Data analysis: Analysis of the defects. Determine the quality indexes: Incident volume quality index (VQI) and repair cost quality index (CQI).	I	A/S	R	I	-
	i: Comparison of the results. Comparison of the Index Quality obtained in task h with the initial one (obtained in task d)	I	A/S	R	I	-
Act	j: Repeat if the result is not what intended	R	R	R	R	-
	k: Standardize if the result was positive	R	R	R	R	-
	l: Establish new objectives	R	R	R	R	-

M: Management; Q: Quality department; AS: After-sales department; P: Production department; T: Technical team; R: Responsible person/Implementer; S: Supervisor; A: Advised; I: Informed.

4.1.3. Measurement of the Effectiveness of the Procedure

Lastly, to measure the results—once the Procedure has been implemented—the two indexes VQI and CQI are calculated with equations 1 and 2, respectively.

4.2. Procedure for the Construction Unit of Ceramic Tilling Execution (Stage 2)

In the **Plan phase**, it was chosen to apply the Procedure defined in Section 4.1 for the ceramic tiling execution, because according to Del Solar Serrano et al. study [25] it is one of the construction units were the largest number of incidents and defects are usually recorded. In addition, the Procedure focuses on the ten most recurrent defects of ceramic tiling execution found by Del Solar Serrano [25], and more specifically those defects which are responsible for greater repair costs (Table 2).

Table 2. Quality indexes of reference given by the construction company (data from [25]).

Common Defects in Ceramic Tiling	Quality Indexes of Reference	
	VQI	CQI
Replacement of tiles on the side or rim of the bath or shower tray.	0.16	17.51 €
Occasional replacement of tiles due to an error in the layout/cutting of the tiles.	1.02	91.46 €
Replacement of tiles due to a layout error, excessively thick joints or joints that do not coincide.	0.05	9.09 €
Replacement of several tiles due to poor condition.	0.05	9.09 €
Occasional replacement of tiles due to lipping.	0.31	6.15 €
Replacement of several tiles due to multiple lipping.	0.09	17.24 €
Replacement of several tiles due to unevenness.	0.03	5.64 €
Replacement of grout due to poor execution.	5.30	89.26 €
Fill in around water outlets.	1.54	7.63 €
Occasional replacement of damaged tiles.	1.11	22.13 €

Subsequently, the objectives are defined. The objectives to be met are set using the quality indexes, VQI and CQI, given by the construction company, which were calculated with the average data obtained from previous construction works, specifically data obtained from a total of 625 dwellings of seven building constructions, where no continuous improvement projects were implemented. The previous construction works had similar construction features to the three buildings analyzed here (in the third stage), i.e., they were built in Madrid by the same construction company and have similar building components and equivalent quality.

Then, the preventive measures are determined and the Protocols and Monitoring Sheets specific for ceramic tiling execution are designed (Tables 3–5). These documents include a summary of the legislation as well as several experts' recommendations for the execution of ceramic tiling. It also includes the criteria and checklists needed to control the ceramic tiling execution for incoming materials, execution, and handover.

The complete sheets contain a detailed description of each point and due to their length, they have been summarized. Additionally, empty rows are included at the end in order to be able to add other items.

Table 3. Monitoring sheet for incoming materials for ceramic tiling.

	Items to Be Checked	**Compliance (Y;N;N/A)**	**Observations—Corrective Action**
Ceramic tiles	The tile displays an appropriate reaction to fire The tile displays adequate resistance to slipping (Rs) The tile is Class: _____ in accordance with the recommendations of Regulation EN 14411:2006 (Annex N) The tile surface is easy to clean and disinfect. The ceramic parts are resistant to frost. The tiles display adequate mechanical resistance in areas exposed to static or dynamic loads. The tile displays adequate resistance to chemical attack. Features CE marking. Features EU declaration of conformity.		
Gripping material	It coincides with the product recommended by the manufacturer for their tiles and appropriate for the base on which it is to be applied. Features CE marking. Features EU declaration of conformity.		
Grouting material	The manufacturer's recommendations for use and application have been met. Features CE marking.		
Other	Provision has been made to stock surplus material for future replacements. At least 1%.		

Y: Yes; N: No; N/A: Not applicable.

Table 4. Monitoring sheet for the ceramic tiling execution.

	Items to Be Checked	Compliance (Y;N;N/A)	Observations—Corrective Action
Plan of the layout	Features all elevations. There must not be strips measuring less than 4cm adjacent to doors and windows. Representation of a complete row on patterned flooring. In the case of continuous flooring spanning several rooms, start by laying an initial row that will span the entire surface that is to be paved. The edge of the bath should be established as a criterion for starting with a complete tile from the top of the bath. In kitchens, tiling starts with the decorative row that is positioned between the work surface and the cupboards, using an entire tile both above and below it.		
Preparation of the base and intermediate layers	The base is firm and free of contamination. The base is flat and rigid in the event of using thin-bed adhesives. In the event of using intermediate layers of waterproofing, soundproofing and/or insulation, separation layers should be implemented. Exposed concrete wall bases with metal sheet formwork: must be treated using a primer or by pricking the surface. Brick wall base: it is necessary to render the wall to a minimum thickness of 10 mm, using a rough, smooth or scraped finish. Concrete block wall bases: it is necessary to level out the surface. Plastered and plasterboard wall bases: these surfaces must be treated first with a primer.		
Onsite layout	Structural joints are respected throughout the tiling thickness. Intermediate movement joints are respected throughout the tiling thickness. Movement joints in exterior tiling: minimum width 10 mm. Panels of 9 m^2 to 12 m^2. Movement joints in exterior flooring: minimum width 10 mm. Panels of 25 m^2. Movement joints in interior tiling: minimum width 6 mm. Joints every 8 m at least. Movement joints in interior flooring: minimum width 6 mm. Joints every 40 m^2 or 8 mL. Tile-to-tile joints. Dimension as recommended by the manufacturer.		
Positioning of tiles—flooring	Flatness of flooring measured using 2 m ruler: Tolerance 4 mm. Lipping of less than 2 mm. Any protrusion exceeding 6mm should not form an angle with the flooring that is greater than 45°. Unevenness that does not exceed 5 cm shall be resolved using a slope that does not exceed 25%. In sections measuring less than 3 m, this slope shall not exceed 10%. Temperature of application: between +5 °C and +30 °C. Avoid working at below 5 °C. Received with cement mortar: Bed of sand with a thickness of no less than 2 cm. Dry, clean, continuous grading sand, with a maximum grain size of 0.5 cm. Use of pre-dosed mortar mixed on-site, should never be used more than 2 h after mixing. Received with thin-bed adhesive: this is applied using a trowel in order to obtain an even layer and then it is combed using a toothed trowel in order to obtain the appropriate thickness and flatness.		

Table 4. *Cont.*

	Items to Be Checked	Compliance (Y;N;N/A)	Observations—Corrective Action
Positioning of tiles—walls	Flatness of the wall in all directions, measured using 2 m ruler: Tolerance 2 mm. Check the vertical alignment of the first tile using a plumb-line. Check lipping: Permissible tolerance: 1 mm for joints measuring less than 6 mm, 2 mm for joints measuring more than 6 mm. The tiling will start above the flooring and before it is laid. Received with adhesive. Exterior walls: Apply two coats to the base. Received with adhesive. Interior walls: apply with a trowel using the sharp edge to spread it and the toothed edge for subsequent combing. Check adherence through occasional detachment of tiles.		
Grouting	Application: Once at least 24 h have passed (depending on the weather), when the mortar has started to set. The joint must be perfectly clean before it is filled and sealed. A material intended specifically for grouting must be used, in accordance with UNE-EN 13888:2009. The color of the grouting material matches that chosen.		
Cleanness of cut	A first cleaning must be done before the grouting material starts to set. In the event of special stains or incrustations special cleaning products must be used. Hygiene is ensured when the joints are easy to clean, display low absorption and are resistant to cleaning systems.		
Other	The work is not exposed to adverse weather conditions (rain, snow or wind) which may affect the mixture of the gripping and grouting materials. The surfaces are protected from the sunlight during periods of high temperatures and must be watered. It is not advisable to subject flooring to dynamic or static loads until one month after the installation.		

Y: Yes; N: No; N/A: Not applicable.

Table 5. Monitoring sheet for the handover of completed ceramic tiling work.

	Category of the Defect	Location [a]	Description of the Defect
1	Replacement of tiles in perimeter areas.		
2	Replacement of tiles on the side or rim of the bath or shower tray.		
3	Occasional replacement of tiles due to an error in the layout/cutting of the tiles.		
4	Occasional replacement of tiles due to excessive overhang of drying room floor over the drying room below.		
5	Occasional replacement of tiled flooring due to an error in the layout when changing flooring.		
6	Replacement of several tiles due to a layout error, excessively thick joints or joints that do not coincide.		
7	Replacement of bath or shower tray edging.		
8	Replacement of skirting board cut at door frame or corner.		
9	Replacement of flooring due to shade variation.		
10	Replacement of grout due to a mistake with the color.		
11	Replacement of several tiles due to poor condition.		

Table 5. *Cont.*

	Category of the Defect	Location [a]	Description of the Defect
12	Repair of grout in order to hide the outline of the joints.		
13	Occasional replacement of tiles due to lipping.		
14	Replacement of several tiles due to multiple lipping.		
15	Replacement of several tiles due to unevenness.		
16	Replacement of flooring due to puddling.		
17	Replacement of grout due to poor execution.		
18	Fill in around water outlets.		
19	Clean marks and scratches.		
20	Occasional replacement of tiles due to breakage/chipping.		
21	Receipt of water outlets.		
22	Occasional replacement of tiles due to layout error.		
23	Replacement of tiles due to a deviation in the partition wall.		
24	Replacement of tiles due to their absence behind the door or curtain rail.		
25	Occasional replacement of damaged tiles.		

[a] The room were the defect is detected.

4.3. Implementation of the Developed Procedure in a Construction Company and Analysis of the Results (Stage 3)

In the **Do Phase**, the Procedure designed in the Plan Phase (Section 4.2.), is implemented in three building case studies, supervising the ceramic tiling execution in bathrooms, toilets, and kitchens of the dwellings. During the execution of the works, the inspections and control were carried out by the quality technicians of the construction company by filling Tables 3 and 4.

Once the ceramic tiling was fully executed, an external evaluation team carried out the inspection of the dwellings using Table 5. An example of the data collection performed in one dwelling is shown in Table 6.

Table 6. Example of the data collected for one of the dwellings analyzed during the Do Phase.

	Category of the Defect	Location [a]	Description of the Defect
1	Replacement of tiles in perimeter areas.	–	–
2	Replacement of tiles on the side or rim of the bath or shower tray.	–	–
3	Occasional replacement of tiles due to an error in the layout/cutting of the tiles.	Bathroom #1	The tile drill for the drain of the right sink is not covered by the trim.
		Bathroom #1	Irregular cut of the ceramic tile located in the joint of the corner and the door of the washbasin.
		Kitchen	The baseboard located in the corner on the left side of the window is inclined.
4	Occasional replacement of tiles due to excessive overhang of drying room floor over the drying room below.	–	–
5	Occasional replacement of tiled flooring due to an error in the layout when changing flooring.	–	–
6	Replacement of several tiles due to a layout error, excessively thick joints or joints that do not coincide.	Kitchen	The pieces of baseboard located between the radiator and the furnace, are badly set. The thickness of the joints are not regular (one is thicker than the other)

Table 6. *Cont.*

	Category of the Defect	Location [a]	Description of the Defect
7	Replacement of bath or shower tray edging.	–	–
8	Replacement of skirting board cut at door frame or corner.	–	–
9	Replacement of flooring due to shade variation.	–	–
10	Replacement of grout due to a mistake with the color.	–	–
11	Replacement of several tiles due to poor condition.	–	–
12	Repair of grout in order to hide the outline of the joints.	–	–
13	Occasional replacement of tiles due to lipping.	–	–
14	Replacement of several tiles due to multiple lipping.	Kitchen	The baseboard under the exit door to the terrace is not correct. The pieces are not aligned and the setting out of the joint is not correct (one is thicker than the other).
15	Replacement of several tiles due to unevenness.	–	–
16	Replacement of flooring due to puddling.	–	–
17	Replacement of grout due to poor execution.	Bathroom #1	There is a lack of grout in the joints of the walls with the floor.
		Bathroom #1	There is an area near the bathtub with an excess of grout.
		Bathroom #2	There is a lack of grout in the joints of the walls with the floor.
		Bathroom #2	There is a lack of grout in the right-hand side of the toilet.
		Kitchen	The grout is cracked in some areas (corners).
18	Fill in around water outlets.	Bathroom #1	Water outlets are not completed
		Bathroom #2	Water outlets are not completed
19	Clean marks and scratches.	–	–
20	Occasional replacement of tiles due to breakage/chipping.	–	–
21	Receipt of water outlets.	–	–
22	Occasional replacement of tiles due to layout error.	–	–
23	Replacement of tiles due to a deviation in the partition wall.	–	–
24	Replacement of tiles due to their absence behind the door or curtain rail.	–	–

Table 6. *Cont.*

	Category of the Defect	Location [a]	Description of the Defect
25	Occasional replacement of damaged tiles.	Bathroom #2	The pieces around the siphonic boat are hit and brushed
		Bathroom #2	The piece are hit and there is a glob of paste under the sink.
		Kitchen	The baseboard is hit and broken near the washing machine or dishwasher.
		Kitchen	The ceramic tile was hit and it is scratched near the refrigerator area.
		Kitchen	The baseboard is hit and broken near the refrigerator area.
		Kitchen	The baseboard located between the radiator and the furnace is hit and broken.

[a] The room were the defect is detected; – No defects were detected.

The inspections were conducted at the rate of 5 inspected dwellings per day per inspector. The inspections were performed every day until all the dwellings were revised. All the inspections of were conducted and finished within 6 to 19 working days.

Table 7 shows the number of dwellings and defects identified for each building case study. A total of 16,105 defects were detected, corresponding to a rate of 83.45 defects per dwelling.

Table 7. Number of defects detected when the inspections were conducted in the three building case studies where the Procedure was implemented (Do Phase).

Building Case Study	Number of Dwellings	Number of Defects	Number of Defects per Dwelling
A	91	7219	79.33
B	32	4023	125.72
C	70	4863	69.47
Total	193	16,105	83.45

After implementing the preventive measures and the data collection of the Do Phase, the effectiveness of the continuous improvement project is analyzed (**Check Phase**), analyzing whether the objectives set in the Plan Phase were met or not. Tables 8 and 9 show the defects quantified for the works analyzed as well as the quality indexes obtained.

Results in Table 9 show that, after implementing the Procedure of ceramic tilling, the repair cost quality index was reduced around 45%, resulting in greater cost savings. Nevertheless, the volume quality index obtained resulted around 20% above the reference. This can be explained because a more exhaustive inspection is conducted when the Procedure is followed, and therefore more defects are detected. These results show that despite the number of defects were kept similar, the repair costs where significantly lower, probably because the preventive measures focused fundamentally on the defects entailing higher costs.

Finally, in the Act Phase, based on the lessons learned in the previous phases, the Procedure of execution criteria for the improvement of ceramic tiling consists of:

- a document of execution criteria, which summarizes the regulations and recommendations of experts in the field and which serves as a reference text for specific training courses;
- a matrix of assignment of responsibilities; and
- three execution control sheets: material reception, ceramic tiling execution and ceramic tiling handover control sheets.

Nevertheless, it is necessary to continue implementing new improvement cycles and updating the preventive measures, incorporating other criteria, in addition to the cost, to select the defects on which to act and achieve the objective of zero defects.

Table 8. Volume quality index (VQI) obtained and compared with the index of reference (objective) established in the Plan Phase.

Common Defects in Ceramic Tiling	VQI after the Continuous Improvement [a]	VQI of Reference (Objective) [b]	Difference
Replacement of tiles on the side or rim of the bath or shower tray.	0.15	0.16	−0.02
Occasional replacement of tiles due to an error in the layout/cutting of the tiles.	2.78	1.02	+1.76
Replacement of several tiles due to a layout error, excessively thick joints or joints that do not coincide.	1.00	0.05	+0.95
Replacement of several tiles due to poor condition.	0.00	0.05	−0.05
Occasional replacement of tiles due to lipping.	1.37	0.31	+1.06
Replacement of several tiles due to multiple lipping.	0.02	0.09	−0.06
Replacement of several tiles due to unevenness.	0.00	0.03	−0.03
Replacement of grout due to poor execution.	5.88	5.30	+0.58
Fill in around water outlets.	0.00	1.54	−1.54
Occasional replacement of damaged tiles.	0.86	1.11	−0.24
Total	**12.00**	**10.00**	**+2.00**

[a] Mean value of the quality indexes obtained in the three case studies analyzed. [b] Values set during the Plan phase based on building projects were no continuous improvement procedure was implemented (Table 2). VQI: incident volume quality index.

Table 9. Cost quality index (CQI) obtained and compared with the index of reference (objective) established in the Plan Phase.

Common Defects in Ceramic Tiling	CQI after the Continuous Improvement [a]	CQI of Reference (objective) [b]	Difference
Replacement of tiles on the side or rim of the bath or shower tray.	17.51 €	17.44 €	−0.06 €
Occasional replacement of tiles due to an error in the layout/cutting of the tiles.	91.46 €	249.52 €	158.06 €
Replacement of several tiles due to a layout error, excessively thick joints or joints that do not coincide.	9.09 €	195.90 €	186.81 €
Replacement of several tiles due to poor condition.	9.09 €	0.00 €	−9.09 €
Occasional replacement of tiles due to lipping.	6.15 €	27.34 €	21.19 €
Replacement of several tiles due to multiple lipping.	17.24 €	4.78 €	−12.46 €
Replacement of several tiles due to unevenness.	5.64 €	0.00 €	−5.64 €
Replacement of grout due to poor execution.	89.26 €	99.05 €	9.78 €
Fill in around water outlets.	7.63 €	0.00 €	−7.63 €
Occasional replacement of damaged tiles.	22.13 €	17.25 €	−4.88 €
Total	**275.21 €**	**611.29 €**	**−336.07 €**

[a] Mean value of the quality indexes obtained in the three case studies analyzed. [b] Values set during the Plan phase based on building projects were no continuous improvement procedure was implemented (Table 2). CQI: repair cost quality index.

5. Conclusions

From the results obtained, the following conclusions can be drawn:

- It is necessary to implement continuous improvement projects in construction in order to improve the quality of residential buildings, using similar tools to those used by other industrial sectors such as the Deming-Shewart's quality cycle.

- The objective of these improvement projects must be to achieve, in a medium term, zero defects.
- It has been possible to design a methodology to implement continuous improvement projects in housing constructions, which enables the definition of specific Procedures to be applied in different construction units. The Procedure developed can be easily applied and used by construction professionals who are concerned of improving the quality of the construction.
- The proposed Procedure follows the different phases of the Deming-Shewart's quality cycle and includes:
  - The definition of the objectives, tasks, and responsibilities of each member of the team.
  - Technical documentation of quality and production procedures which helps the construction workers to implement the tasks whilst ensuring a good quality (implementation protocols and monitoring sheets).
  - Training courses for all the staff involved in the project.
  - Assessments to check the efficiency and compare the results obtained after implementing the Procedure.
- The proposed monitoring sheets can be used as checklists in order to facilitate and assure exhaustive inspections of the works.
- It is suitable to control the execution of the construction units and to gradually reduce the number and repair costs of the defects.
- Finally, in the case of implementing similar Procedures in all the construction units of a building, it would lead to significant reductions in post-sale costs, reducing the repair costs derived from correcting defects.

Author Contributions: Conceptualization, P.d.S.S. and M.d.R.M.; Data curation, P.d.S.S.; Formal analysis, P.d.S.S.; Investigation, P.d.S.S. and M.d.R.M.; Project administration, P.V.S.; Supervision, M.d.R.M. and P.V.S.; Writing—original draft, P.d.S.S; M.d.R.M and P.V.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: The authors would like to thank the ARPADA Company, particularly the Department of Environment and Quality and the Department of Projects, for providing the data needed for this study.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Flynn, B.; Schroeder, R.G.; Sakakibara, S. The impact of quality management practices on performance and competitive advantage. *Decis. Sci.* **1995**, *26*, 659–691. [CrossRef]
2. Anderson, N.C.; Kovach, J.V. Reducing welding defects in turnaround projects: A Lean Six Sigma case study. *Qual. Eng.* **2014**, *26*, 168–181. [CrossRef]
3. Milion, R.N.; Alves, T.D.C.L.; Paliari, J.C. Impacts of residential construction defects on customer satisfaction. *Int. J. Build. Pathol. Adapt.* **2017**, *35*, 218–232. [CrossRef]
4. Ishikawa, K. *What is Total Quality Control? The Japanese Method*; Prentice Hall: Upper Saddle River, NJ, USA, 1985.
5. Reed, R.; Lemak, D.J.; Mero, N.P. Total quality management and sustainable competitive advantage. *J. Qual. Manag.* **2000**, *5*, 5–26. [CrossRef]
6. Vásquez-Hernández, A.; Fernando Botero Botero, L. Standardizing system of posthandover defects for the construction sector in Colombia. *J. Archit. Eng.* **2019**, *25*, 05019004. [CrossRef]
7. Moica, S.; Veres Harea, C.; Marian, L. Effects of Suggestion System on Continuous Improvement: A Case Study. In Proceedings of the IEEE International Conference on Industrial Engineering and Engineering Management, Bangkok, Thailand, 16–19 December 2018; pp. 592–596.
8. Martins, M.; Varela, M.L.R.; Putnik, G.; Machado, J.; Manupati, V.K. Tools implementation in management of continuous improvement processes. In *Lecture Notes in Mechanical Engineering*; Springer: Cham, Switzerland, 2019; pp. 348–357.

9. Josephson, P.; Hammarlund, Y. The causes and costs of defects in construction. A study of seven building projects. *Autom. Constr.* **1999**, *8*, 681–687. [CrossRef]
10. Delgado-Hernandez, D.J.; Cruz-Cruz, C.C.; Vences-García, P.Y. Improvement Management Tools in the Construction Industry: Case Study of Mexico. *J. Constr. Eng. Manag.* **2017**, *143*, 05016024. [CrossRef]
11. Gardez, N.; Lopes, N.; de Brito, J.; Sá, G. System of inspection, diagnosis and repair of external claddings of pitched roofs. *Constr. Build. Mater.* **2012**, *35*, 1034–1044.
12. Gardez, N.; Lopes, N.; de Brito, J.; Sá, G. Pathology, diagnosis and repair of pitched roofs ceramic tiles. *Constr. Build. Mater.* **2012**, *36*, 807–819.
13. Neto, N.; de Brito, J. Validation of an inspection and diagnosis system for anomalies in natural stone cladding (NSC). *Constr. Build. Mater.* **2012**, *30*, 224–236. [CrossRef]
14. Pereida, A.; Palha, F.; de Brito, J.; Silvestre, J. Inspection and diagnosis system for gypsum plasters in partition walls and ceilings. *Constr. Build. Mater.* **2011**, *25*, 2146–2156. [CrossRef]
15. Silvestre, J.; de Brito, J. Ceramic tiling inspection system. *Constr. Build. Mater.* **2009**, *23*, 653–668. [CrossRef]
16. Silvestre, J.; de Brito, J. Ceramic tiling in building façades: Inspection and pathological characterizaction using an expert system. *Constr. Build. Mater.* **2011**, *25*, 1560–1571. [CrossRef]
17. Silva, A.; de Brito, J.; Gaspar, P. Service life prediction model applied to natural stone wall claddings (directly adhered to the substrate). *Constr. Build. Mater.* **2011**, *25*, 3674–3684. [CrossRef]
18. Rodrigues, M.; Teixeira, J.; Cardoso, J. Building envelope anomalies: A visual survey methodology. *Constr. Build. Mater.* **2011**, *25*, 2741–2750. [CrossRef]
19. Maraculla, M.; Forcada, N.; Casals, M.; Gangolells, M.; Fuentes, A.; Roca, X. Standardizing housing defects: Classification, validation and benefits. *J. Constr. Eng. Manag.* **2013**, *138*, 585–593.
20. Marín García, D.; Moyano, J.J.; Rico, F.; Nieto, J.E. Automated model to classify defects that affect termination of building elements. *Inf. Construcción* **2017**, *69*, e182.
21. Chew, M. Factors affecting ceramic tile adhesion for external cladding. *Constr. Build. Mater.* **1999**, *13*, 293–296. [CrossRef]
22. Chew, M. Defects analysis in wet areas of buildings. *Constr. Build. Mater.* **2005**, *19*, 165–173. [CrossRef]
23. Lee, S.; Lee, S.; Kim, J. Evaluating the impact of defect risks in residential buildings at the occupancy phase. *Sustainability* **2018**, *10*, 4466. [CrossRef]
24. Silvestre, J.; de Brito, J. Inspection and repair of ceramic tiling within a building management system. *J. Mater. Civ. Eng.* **2010**, *22*, 39–48. [CrossRef]
25. Del Solar, P.; Del Rio, M.; Villoria, P.; Nadal, A. Analysis of recurrent defects in the execution of ceramic coatings cladding in building constructions. *J. Constr. Eng. Manag.* **2016**, *142*, 04015093. [CrossRef]
26. Chang, R.; Niedzwieck, M. *Tools for the Continuous Improvement of Quality (Volumes 1 and 2)*; GRÁNICA: Buenos Aires, Argentina, 1999.
27. Lodgaard, E.; Ingvaldsen, J.A.; Aschehoug, S.; Gamme, I. Barriers to continuous improvement: Perceptions of top managers, middle managers and workers. *Procedia CIRP* **2016**, *41*, 1119–1124. [CrossRef]

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.