Contributions to rework prevention in construction projects

DOCTORAL THESIS

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Summary

Literature usually suggests that construction organization can reduce the costs derived from rework implementing quality management systems. Most common challenges and obstacles that construction organizations face during the implementation process and use of quality management systems are related to "how" the information can be recorded in an effective way, and "what" can be done with the recorded information.

The aim of this dissertation is to focus on improving the defects recording process in the construction industry, and to propose methods and tools to use defects recorded on-site to prevent and reduce rework in the construction industry.

The dissertation starts with the development of a conceptual model used to characterize defects. The current model is based on previously existing models and their adaptation to the context of the Spanish residential building sector. The model is based on the enumeration of the parameters that allow characterizing defects. The final model includes 6 parameters, with a list of standardized words and their definitions.

The pre-established vocabulary lists are based on existing classification systems proposed by recognised organisations, authors and research reports, but then adapted to the Spanish context. However, in terms of defects, no standardised list exists. For this reason a taxonomy of defects is further developed for the Spanish construction sector. The aforementioned taxonomy consists of 15 main categories and 19 subcategories.

The dissertation continues with the development of a methodology to track defects in the construction industry and its implementation in an IT tool called MoBuild. The obtained tracking system is based on images and tags. The strengths the abovementioned tracking system is to record information in a structured way and enable further statistical analysis of the recorded information. The new approach implemented in the MoBuild application allows practitioners to reduce the time of the recording process, facilitating the implementation of quality management systems, such as ISO 9000 in construction organizations.

Furthermore, research proposes a quantitative methodology for dealing with potential adverse quality risks during the pre-construction stages of residential buildings and other similar types of constructions. The strength of this methodology lies in the fact that it helps designers to explicitly consider on-site quality during the design process. Designers can compare several design alternatives during the design phase, and determine the corresponding overall quality risk levels of a construction project without their creative talents being restricted. The methodology is especially worthwhile for those less-experienced designers who lack the required skills and knowledge to recognize quality risks in developing optimal designs.

The methodology also serves as an assessment tool for construction companies. It can be used to measure the potential quality risks of construction projects and its subsequent construction activities. The suggested methodology also allows construction companies to optimize their on-site performance in the quality domain during the planning and preparation stages.

Finally, this dissertation analyses the quality perceived by the end users during the post-handover stage. Different statistical methods are used to demonstrate the usefulness of the recorded data for the construction organizations. The aim is to highlight the essential role that records play in the operation of a quality company, in particular by providing essential evidence of the operation of quality systems.

The aforementioned statistical analysis determines the type of defects detected; the elements affected by defects; the areas where defects are detected; which subcontractors produce defects; the source of the detected defects; the origin of the detected defects and; the influence of the building type and its characteristics in the number of defects detected.

The analysis demonstrates that the most common defects identified are: missing items (small elements) and/or tasks (painting and plastering); poor finishing of the floor and wall surfaces in rooms and wet areas, which can be attributable to a lack of protections during construction; and incorrect installations, mainly related to the plumbing and sanitary systems, mechanical and electrical trades. The research also reveals that the most common defects identified by customers at post-handover were derived from bad workmanship and were related to construction errors and omissions. No defects were caused by poor design as they are mainly detected and resolved during the construction, or become apparent after some years of use. Finally, the statistical analysis shows that clients detect more defects in apartments than in detached houses even though apartments have a smaller gross floor area. The results are used to determine strategies for the quality control and supervision tasks.

The dissertation concludes by outlining the main contributions of this research. The subjects that exceed this dissertation's scope are commented on and proposed as future work.

Key words: Rework; Defects; Post-handover defects; Housing; Spain; Defects' mitigation; Quality control; Tracking system; Prediction method; Element; Area; Subcontract; Source; Origin.

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List of Acronyms

CS	Case Study
FRI	Family Risk Index
ISO	International Organization for Standarization
IT	Information Technologies
MEI	Materia/element/item
QMS	Quality Management systems
QRI	Quality Risk Index

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Chapter 1

Introduction to the thesis

1.1 Introduction

This chapter provides an introduction to this thesis as a fulfilment for the title of Doctor by the Technical University of Catalonia. Relating to the field of rework in construction companies, it states the problem, outlines the main aims and objectives of the research project and sets out the scope of the work, its limitations and delimitations. The overview of the methodology implemented, as well as the description of the structure of this dissertation are also included.

1.2 Problem statement

Global economic competition has compelled many organisations to explore all possible options for improving delivery of their products or services (Drucker 1994).This trend has also become apparent in the construction industry, and especially nowadays with the global economic crisis, with clients expecting a better service and projects that closely meet their requirements. This has forced the industry to become more efficient, more integrated and more attractive, both in the eyes of society and of its potential workforce (Bowden 2006).

Rework can adversely affect the performance and productivity of design and construction organization (Love 2002a). In addition, rework has significant influence in cost and schedule overruns (Love et. al 2010). Other parameters such as project sustainability as well as safety can be affected negatively by reworks (Ilozor et al. 2004).

Rework, on average, contributes to the 52% of the total cost overrun incurred and can increase schedule overrun by 22% (Love 2002). Rework costs have been found to range from 5% to 20% of the contract value in construction and engineering projects with design scope changes rework accounting for as much as 50% of the rework that occurs (eg., Barber et al. 2000; Love and Edwards 2004). These variations appear as a result of differences between definitions, in particular scope, data collection methods used and whether rework is calculated as a proportion of the project or contract value (Love and Edwards 2004).

Although literature usually suggests that design and construction companies can reduce the costs of rework implementing quality management systems (Jaafari 1996; Lomas 1996; Rounce 1999; McFallen 2000), some authors such as Love (2003a) reported that there is no significant negative correlation between the firms' quality management systems use and rework costs in the projects in which they were involved.

Quality Management Systems (QMS) force organizations to make a register with the different incidences and to analyse them. However, document requirements for management systems are regarded as onerous, bureaucratic, inefficient, ineffective and divisive; and even if there is acceptance for a degree of formality, staff regards systems as a burden and hindrance to getting their job done (Griffith 2008). The current approach to track quality information on-site is time-consuming and relies heavily on repeated data entry (Dong 2009). Although in the recent years construction information management has greatly benefited from advances in Information and Communications Technology (ICT), the construction industry is still using the traditional method, which is paper-based and supported by pictures (Chen 2011). As noted by Guerriero et al. (2011) it is a fact that design and construction professionals want to capture information on site to write reports faster or to improve communications.

Another important issue in the implementation of Management Systems (MS) is that the site staff do not fully understand MSs to be real and holistically beneficial to both the project and company; thus remaining lost to a simplistic compliance and checklist culture (Gangolells 2009). Moreover, Love (2003) noted that design and construction companies do not have the tools and techniques to carry out quality and learning practices.

The conducted research deals with the two main issues that appear in the implementation of a QMS: "how" to record information in an effective way, and "what" to do with the recorded information. Traditionally, the house building industry uses defects as a main indicator to measure quality (Auchterlounie 2009). The present dissertation will focus on improving the defects recording process in the construction industry and will propose methods and tools to use defects tracked on-site to prevent and reduce rework in the construction industry.

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1.3 Aims and objectives

The aim of this dissertation is to improve the recording process of on-site defects data and to provide tools and techniques to use tracked defects on-site to prevent and reduce rework in the construction industry. The objectives of this dissertation are listed beneath:

Objective 1:

To determine the parameters required in order to characterize a defect in the Spanish residential building sector

Objective 2:

To determine which are the current methodologies used in the construction sector to capture information on-site

Objective 3:

To propose a method to track construction data on-site

Objective 4:

To develop and test a methodology for defects prediction for the Spanish residential building, using preconstruction information such as memory, budget, or quality plan

Objective 5:

To identify quality risks related to the construction process through a process-oriented approach

Objective 6:

To determine the factors which impact on construction defects perceived by the final users in Spanish residential buildings

Objective 7:

To propose measures to reduce defects perceived by the final users in the Spanish residential buildings

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1.4 Scope of the research, limitations and delimitations

This document includes all the relevant information required to meet and justify this dissertation's aim and objectives. This dissertation includes a literature review that deals with all topics addressed throughout the dissertation.

In the Problem Statement section, the semantic problem about rework concept and their consequences is presented. For this reason the dissertation incorporates an extensive discussion about the different concepts related to rework in order to distinguish between the different descriptors.

This document includes the definition of a model that can be used to characterize defects based on lists of pre-established vocabulary such as type of defect, location, etc. The different procedures and techniques that are used in different countries and regions does not allow the reuse of existing classifications for other specific situations. Against this backdrop, the dissertation includes the definition of the list of words of all the model parameters for the defects characterization for the Spanish housing construction. Those lists are based on existing classification systems obtained through the literature review. However, in terms of defects, no existing standardised list was found. For this reason, the thesis includes the development of a taxonomy of defects for the Spanish construction sector. Such taxonomy was developed taking the context of the Spanish construction sector into account. Moreover, further application of the classification in other countries will be evaluated. The dissertation also includes the validation of the aforementioned taxonomy.

The dissertation also includes a set of interviews, both in Spain and Luxembourg, conducted in order to know and understand the different methods used by design and construction professionals to track onsite information as well as the definition of a methodology to track construction information on site. Furthermore, the methodology is implemented on an IT tool called MoBuild to validate the methodology. The validation includes an analysis of the IT tool's usability and the utility. However, the programming tasks conducted on the IT tool are outside of this dissertation.

This research includes the development of a methodology to predict construction defects during the preconstruction stage. The scope of this section includes the development of a process-oriented model that can be used to support construction organizations on the identification and assessment of quality risks during the preconstruction stage using the available information in this stage.

The developed methodology considers the construction processes that relate with Spanish residential buildings, including single-family houses, multi-family dwellings and other similar types. This methodology can be used in other countries when the construction process and construction methods are similar to the Spanish ones. However, this research excludes other types of buildings since construction processes can vary significantly. For the same reason, the methodology only refers to new-start construction projects.

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The boundary of the developed methodology includes the analysis of the potential on-site technological quality risks. It does so without taking into account human and organizational factors, potential risks that may have occurred during the materials' manufacturing phase or those that could occur later, during the building's lifespan. Therefore, latent defects are not taken into account. The methodology takes into account the potential quality risks that can be produced as a consequence of on-site activities. Therefore, quality risks derived from office tasks are not considered within the methodology. Potential quality risks produced as a consequence of bad design are also not taken into account.

With the purpose to determine the factors that contribute on construction defects apparition, the dissertation includes a statistical analysis of those defects perceived by the final users in Spanish residential buildings. The analysis is focused on those defects that arise after the building handover. In addition, the most typical defects, the most affected areas, and the trades with a higher amount of defects are identified. The relationships between the different parameters are also studied. Finally, the influence of building type in defects apparition is also analysed. The quantification of the cost of defects and the temporal deviations of a project due to defects falls out of the scope of this dissertation.

1.5 Overview of the research methodology

The research methodology directs the course of activities to be undertaken during the research. To achieve the research's aim and objectives, the activities were planned as illustrated in Figure 1.

In order to help the reader understand the research context, this dissertation starts with a literature review.

Later, a model to characterize defects is developed through an extensive literature review. The conceptual model is composed of all the parameters that allow practitioners to define a defect. The model includes standardised vocabulary which has been pre-established to assist the data recording and allow the statistical analysis.

The pre-established vocabulary lists are based on existing classification systems proposed by recognised organisations, such as the OMNICLAS and the UNICLASS, authors and research reports, but later adapted to the Spanish context. However, in terms of defects, there is no existing standardised list. For this reason, the only parameter that required a particular work towards determining specific nomenclature was the type of defect.

The taxonomy of type of defect starts with the development of a first taxonomy draft developed through the literature review. The first draft was discussed and improved through a series of workshops done by a panel of experts. After that, the taxonomy is validated using a set of structured interviews with construction industry professionals. Furthermore a case study is used to demonstrate that the taxonomy is able to classify all defects.

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The tracking system for defects in the construction industry is developed using the process presented by the ISO 9241-210 standard. The process proposed by the ISO standard begins with an understanding of the context of use. Then, it proposes to determine the user and organizational requirements. Finally, ISO standard incorporates the evaluation of design solutions as a way to modify the design until the needs of users are met. To understand the context of use a set of interviews using a structured survey was used. The results of the interviews are also used to determine the functional requirements. Finally, the methodology to track defects is defined and implemented in an IT tool to be validated through a set of experiments to be carried out in real situations with real end users.

The methodology to predict construction defects in the preconstruction stage has two main blocks. The first one is the development of a risk register. A process oriented approach is used in order to identify the construction defects in the preconstruction stage. The second bloc is the evaluation of the quality risks. Such evaluation is obtained by simple aggregation of all points awarded to each criterion.

Finally, the analysis of construction defects to demonstrate the usefulness of the defects data for the design and construction companies is presented. For this purpose, a set of statistical methods are used to determine factors that contribute to defects. In addition, the most typical defects, the most affected areas, and the trades with higher number of defects are identified. The relationships between the different parameters are also studied. Lastly, the influence of building type in the defects apparition is analysed. The statistical methods used are: Chi-square test, Pearson's parametric correlation, Anderson-Darling test, normal probability plot correlation coefficient, t test, and typical descriptive statistics (mean, standard deviation, standard error mean, and confidence interval).

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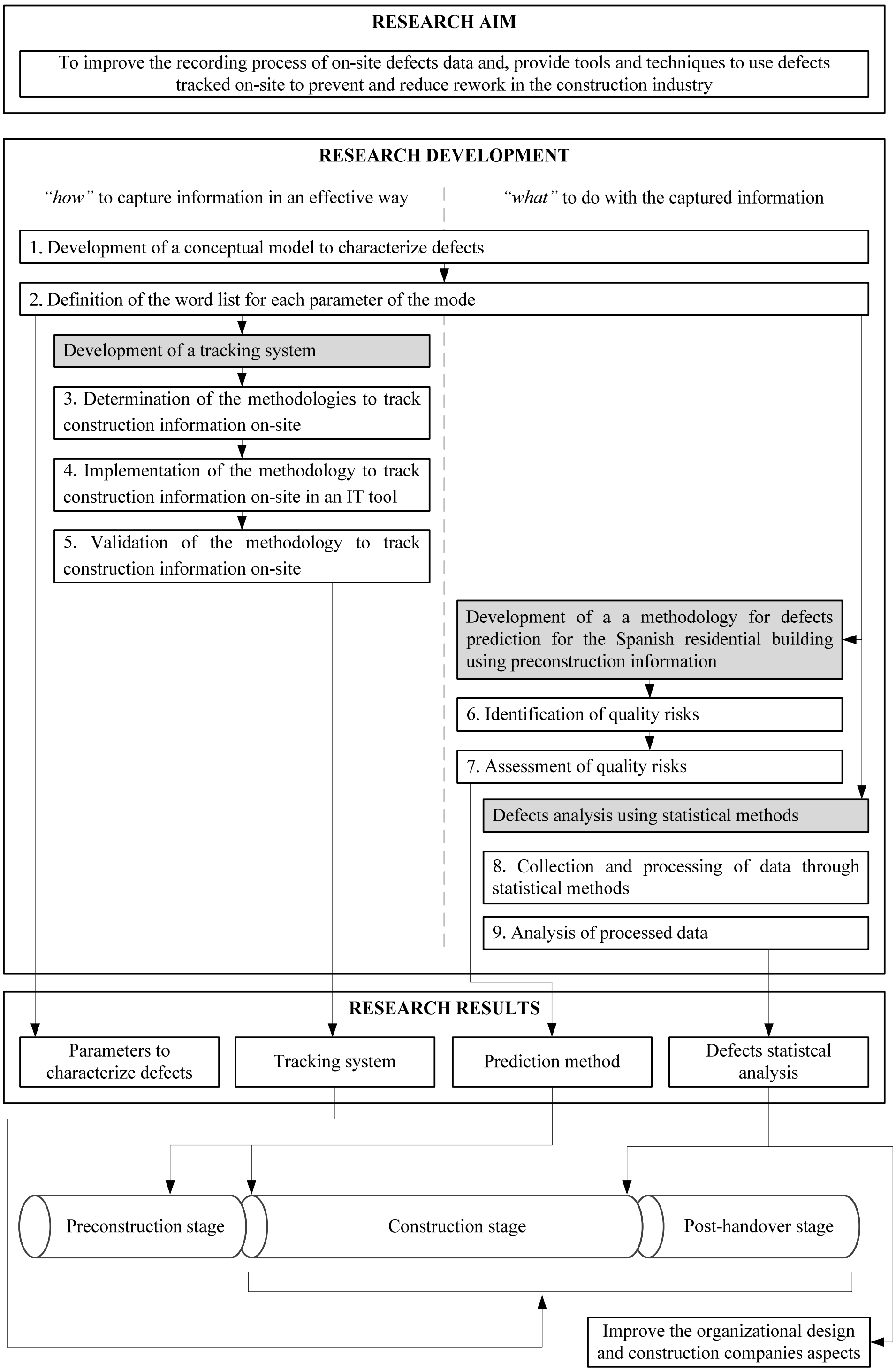

Figure 1. Overview of the research methodology

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1.6 Thesis structure

The document is structured by 7 chapters and 2 appendices. Figure 2 illustrates the outline of this dissertation. The chapters are as described below:

Chapter 1 provides an introduction to this thesis, presenting the problem statement, the main aim and objectives of the research and sets out the scope of the work, its limitations and delimitations. The overview of the implemented methodology as well as the description of the structure of this dissertation, are also included.

Chapter 2 presents a critical literature review covering all subjects that will be addressed in this thesis. The results obtained in this chapter serve as justification of the research undertaken within this thesis. In addition the parameters to define a defect are included.

Chapter 3 details the work undertaken in order to develop a taxonomy for construction defects. The chapter includes the validation of the taxonomy, and a case study to demonstrate the taxonomy usefulness.

Chapter 4 presents the results of the interview about the user methods and technologies used to track defects on the construction sector and the construction industry requirements for a tracking system. With these results, the creation and validation of a tracking system for defects in the construction sector is presented.

Chapter 5 is aimed at developing a methodology to predict construction defects in the preconstruction stage. This chapter describes the work undertaken in order to develop and validate the methodology used to identify construction defects during the preconstruction stage.

Chapter 6 is aimed at demonstrating the usefulness of defects as a source of information. This chapter presents a protocol to analyse construction defects. This protocol is used to analyse a set of data, to obtain the parameters that affect post-handover defects. Finally this information is used to obtain conclusions on how to reduce the post-handover defects.

Chapter 7 concludes with the summary of the key findings of the research as well as explaining how the project contributes to knowledge and practice. It also presents areas suitable for further research.

Appendices A to B include additional supporting material which evidence the undertaken research

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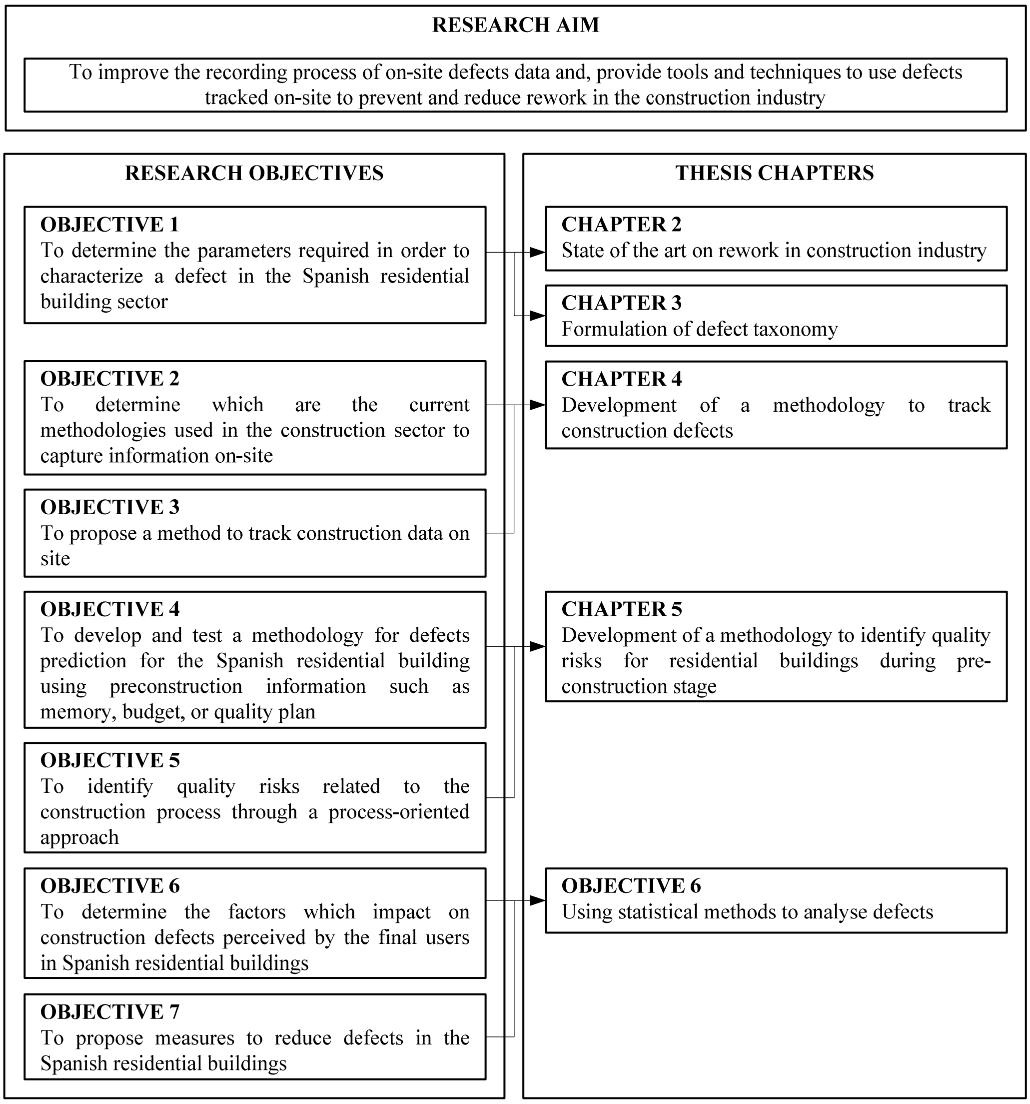

Figure 2. Thesis outline

Chapter 2

State of the art on rework in construction industry

2.1 Introduction

This chapter exposes the findings of a literature review carried out to gather work and thoughts of academics, experts and practitioners within the subject field. First, it briefly examines the different words used as synonymous of rework. Later, it focuses on defects and analyses the concept of "defect" and the implications that it has in the Spanish residential buildings.

This chapter also discusses the importance of the standardization to analyse defects in the construction industry. Different ways to classify defects are presented. Outlining the different ways of classifying defects serves as a starting point to define the conceptual model to characterize defects in the Spanish residential building sector. The Appendix A presents the final word list used in this dissertation.

Moreover, this chapter examines the on-site tracking systems used in the construction industry and explores the different technologies and methodologies used for this purpose. In addition, the chapter explores the concept of defect prevention during preconstruction stage and the most common scopes, strategies and degrees achieved in its implementation. Finally, the chapter details the most common strategies to analyse defects in the construction sector.

This chapter serves as a justification of the research undertaken within this project and establishes the bases of the research.

2.2 Terminology definition

In the building industry, words like “error”, “fault”, “failure”, “defect”, “quality deviation”, “non-conformance”, “quality failure”, “snag”, “rework”, are used interchangeably to describe imperfections in constructed buildings (Mills et al. 2009; Georgiou et al. 1999; Josephson et al. 2002; Love 2002b; Sommerville and McCosh 2006). These words are emotive terms and mean various things to different people, but always suggest that the client involved has had an unsatisfactory solution (Ilozor et al. 2004). The lack of differentiation between the terms used can lead to inaccurate and incomplete measurements, cost determination, and possibly inappropriate strategies for reducing their occurrence (Mills et al. 2009). However, these words have semantic differences.

Non-conformance is a word used by ISO 9000:2005 to define “the failure to fulfill a requirement”. ISO 9000:2005 defines defect too, as “the non-fulfillment of a requirement related to an intended or specified use”. However, Davis et al. (1989) considers that no practical difference between non-conformances and defects exists.

Battikha (2008) considers that “non-conformance occurs when the finished state of a project and/or its components deviates from established requirements and necessitates decisions to be made regarding their acceptance and/or rectification”.

Atkinson (1987) provides a clear distinction between a failure and a defect: “A failure is a departure from good practice, which may or may not be corrected before the building is handed over. A defect, on the other hand, is a shortfall in performance which manifests itself once the building is operational.” However, Wardhana and Hadripriono (2003) define failure “as the incapacity of a constructed facility or its components to perform as specified in the design and construction requirements”.

Davis et al. (1989), Farrington (1987) and Burati et al. (1992) preferred the word deviation, rather than failure or defect (which are commonly used in manufacturing industries), and used the definition provided by Davis et al. (1989): “Product or result that does not fully conform to all specifications requirements does not necessarily constitute an outright failure”.

Chew (2005) define defect as a resulting from failures in function, performance, statutory and user requirements. On the other hand, Georgiou et al. (1999) suggest that the simplest and most comprehensive definition is that provided by the Oxford English Dictionary, which defines a defect as “a shortcoming or falling short in the performance of a building element”. This definition has been legally validated by the case of Schuller AG v. Wickman Machine Tools Sales Ltd (Dorter and Sharkey 1990). The CIB Working Commission W86 (1993) also supports the above by defining a defect as "a situation where one or more elements do not perform its/their intended function(s)". Watt (1999) improves the definition and considers that "defect is the term used to define a failing or shortcoming in the function, performance, statutory or user requirements of a building, and might manifest itself within the structure, fabric, services or other facilities of the affected building".

Another term used as a synonymous of defect is snag. Sommerville and McCosh (2006) defines snags with two key points: those defects which are "absorbed" during the construction/building process and which are usually corrected before practical completion; and, those which are "visible" to the contractor and home buyer once the home is deemed ready for occupation. This word is rarely used within construction literature even though it is a "common" terminology within the UK construction industry. However, the term post-handover defect is also used to describe those defects that are still remaining after handing over the building but only during the liability period, which usually lasts 12 months (Forcada et al. 2012).

To describe those defects that appear during the occupancy of the building the term latent is also used (Chong and Low 2006). Georgiou (2010) distinguishes between those defects derived from the construction process and those defects that occur as a result of poor maintenance.

Although error and defect can be considered as synonymous (Manrique et al. 2007), error is commonly associated with human action (Lopez et al. 2010; Love et al. 2009), while defect that is referred to elements (Chong and Low 2006). Reason and Hobbs (2003) provides the most accepted definition of error is ". . . an outcome that essentially involves a deviation of some kind, whether it is a departure from the intended course of actions, departure from a path of actions planned toward a desired goal or deviation from the appropriate behavior at work."

In the building industry it is common to use rework as a synonymous of defect, although these definitions vary. Once a defect occurs, and it is rectified then this can be known as rework, which is defined "as the unnecessary effort of redoing an activity or process that was incorrectly implemented the first time" (Love and Edwards 2005) (Love 2002). Ashford (1992) includes repair, as rework and defines repair as "the process of restoring a non-conforming characteristic to an acceptable condition even though the item may not still conform to the original requirement". Construction Industry Development Agency (1995) defined rework as "doing something at least one extra time due to non-conformance to requirements". Rogge et al. (2001) define field rework as "activities in the field that have to be done more than once in the field or activities which remove work previously installed as part of the project." COAA (2001) defines rework as the "total direct cost of redoing work in the field regardless of initiating cause" and also states that field rework does not constitute change orders (for new work), off-site fabricator errors, or off-site modular fabrication errors(Fayek et al. 2004). Han et al. (2011) considers rework as non-value adding effort or non-value adding activity because is a waste effort.

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Consequently, rework is a consequence of a detected defect. It is noteworthy that rework also includes items such as design errors/changes, which do not necessarily result in defects (Mills et al. 2009). For this reason, in this work, rework is not considered a synonymous of defect.

Although the term defect is often used in the design stage, deviation, failure, and fault are also common terms. During construction, defect is the most common term used, but other words such as anomaly or deviation are also used. It is important to emphasize that the authors prefer the word defect to non-conformance, which is proposed by ISO 9000. Although ISO 9000 stresses that is important to distinguish between non-conformance and defect, some authors (as for example Davis et al. (1989)) consider that there exists no practical difference between non-conformances and defects in building industry domain.

The liability period is generally considered to be immediately after handover; however some studies include the liability period to include the construction and occupancy stage. However, many differences in terms of defects exist between these different stages (Sommerville and McCosh 2006; Forcada et al. 2012). Both snag and post-handover defect are used to define imperfections during the liability period.

Referring to the operational stage (or maintenance or occupancy stage) defect or latent defect are the most common terms used.

For the purposes of the research reported in this thesis, the definition of a defect proposed by Watt (1999), as noted above, is adopted.

2.3 Rework and defects

Rework is an endemic problem in building construction projects and is an area of research that has received limited attention (Love et al. 2004). Historically, research conducted has predominantly focused on rework in building construction projects (e.g. (Josephson and Hammarlund 1999; Love and , Heng Li, Peter 2000; Love and Edwards 2005)) with only limited studies examining its incidence in civil infrastructure (Love et al. 2010; Fayek et al. 2004; Burati et al. 1992). Recently some studies about rework are applied in special projects such as offshore platforms (eg. Love et al. 2011).

According to Love et al. (2010), rework costs are a major contributor to cost and schedule growth in building construction projects. However, due to the lack of differentiation between the terms used in the literature is difficult to quantify its incidence.

For example, in terms of costs, Love et al. (1999) found rework direct costs to be 3,15% of the contract value in Residential projects and 2,4% for industrial buildings; Josephson et al. (2002) findings revealed that the costs of rework for the case study projects were 4.4% of the construction values of the observation period; Love (2002b) sampled 161 projects and found the mean direct

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and indirect rework costs were found to be 6,4 and 5,6% of the original contract value; Mills et al. (2009) found defects represent 4% of the contract value of the new dwelling or renovation; Fayek et al. (2004) throw a literature review ranged the rework costs from 2% to 12%. However, Fayek et al. (2004) conclude a variety of methods have been utilized to calculate this percentages. Love and Edwards (2004) reported the variations in the rework's costs estimation derive as a result of differences in definitions, in particular scope, data collection methods used, and whether rework is calculated as a proportion of project or contract value.

In terms of schedule growths, Love et al. (1999) found rework schedule growths to be 11,6% of the contract value in Residential projects and 22,7% for industrial buildings; and Love (2002b) found the mean schedule growths were found to be 20,7%.

As a result of rework, other adverse consequences can appear such as reduced profit, loss of market share and reputation, increased turnover of management and workforce, lower productivity, higher costs, and all too frequently, costly litigation between participants over responsibility for overruns and delays Love and Edwards (2004).

In addition, some author reported undesirable consequences at human level. For example Love et al. (2011) reported that rework can produce demotivation in workers.

Rework includes different concepts and is difficult to attribute which are the consequences of the different concepts. When a defect becomes apparent, it has to be solved and produces a rework. For this reason this dissertation assumes that defects produce all consequences that rework produce.

2.4 Defects in residential buildings: Spanish context

Although, quality management in the residential sector has received considerable attention as result of defects (Ilozor et al. 2004; Mills et al. 2009), defects have become an "accepted part of the building process" (Mills 2009). Numerous studies have been conducted to highlight the factors affecting the quality of housing (Chong and Low 2006; Johnsson 2009). However, the volume of research specifically related to quality in new-build private housing has been limited (Georgiou et al. 1999; Ilozor et al. 2004; Sommerville and McCosh 2006; Mills et al. 2009).

Different interpretations and perceptions of quality by customers and builders may often lead to conflict and disputes after a dwelling is handed over. A contractor may have delivered a dwelling by assuring technical quality regarding the foundations and structural integrity, but not functional quality regarding the paintwork and aesthetics (Craig et al. 2010).

In Spain, research on housing defects has been limited and confined to the studies undertaken by Castro and Montero (1995), the *Asociación Española para la Calidad en la Edificación - ASECE* (Spanish Building Association for Quality) (2011). Castro and Montero (1995) carried out a survey of 2,000 homeowners and revealed that 48% of constructed dwellings that were less than 10 years old had significant quality-related problems such as movement of floor tiles, unevenness of walls and ceilings, cracks in the walls, and roof drainage. The ASECE (2011), on his “Perceptions of Quality in buildings” survey among 1,400 professionals of the construction sector, concluded that the quality warranties introduced by the *Ley de Ordenación de la Edificación* (Building Regulation Act) (Jefatura del Estado, 1999) are positive for the quality of construction works. Noteworthy, housing complaints decreased from 24.7% in 1995 to 8.9% in 2009 (INC 2009).

In Spain, the Ley de Ordenación de la Edificación (Building Regulation Act) establishes compulsory warranties to ensure that buildings meet basic requirements with regard to functionality, general safety and structure, fireproofing, and use and habitability (Jefatura del Estado 1999). Despite the introduction of this act, defects in newly built dwellings remain common, particularly with respect to their structural condition (INC) 2009. Consequently, this has resulted in customers becoming increasingly dissatisfied with the builders.

No study quantifies the costs of defects in the Spanish building industry. However, the impact of defects can be estimated taking into account that the construction industry still accounts for 10.5% of gross domestic product and the housing sector represents 26.2% of the total construction output (Asociación de empresas constructoras de ámbito nacional 2011), and considering that defects represent 4% of the contract value of new dwellings or renovations (Mills et al. 2009). Assuming these hypotheses defect costs would be nearly 0.11% of the Spanish GDP, which would amount up to US $ 1.5 billion

2.5 Standarization of defects

Through implementation and promotion of standardized methods regarding the processes associated with quality, builders may realize that it is possible to attain a goal of ‘zero defects’. Striving toward this goal will bring to fruition a plethora of tangible benefits which include repeat business, increased sales and profits, and lead to employee and subcontractor satisfaction (Leonard and Taggart 2010).

Usually data pertaining to defects is difficult to obtain (Georgiou 2010; Yung and Yip 2010), and even when accessed the information is not standardized. In order to analyse the data a standardization process is required. It is necessary for the data to be organized, possibly re-formed and expanded where necessary to enable in useful data for research purposes to be extracted (Georgiou 2010).

The research carried out by Mills et al. (2009) is an example of this problem. Mills obtained his data from HGF, the Victorian Government insurance organization. Mills explains: “unfortunately due to the cumbersome manner in which the HGF database was designed it became very difficult to draw any firm conclusions. The HGF database was sorted into defects that contained only one defect code; there were 11,652 records included in the analysis." To avoid this problem and enable further analysis of this rich data source Georgiou (2010) proposes the use of classification systems such as that developed by Georgiou et al. (1999).

The country and region specific construction procedures and techniques in Spain make the use of existing classification systems not feasible. Georgiou (2010) suggested that some knowledge and understanding of local construction practice is also desirable. Mills et al. (2009) and Georgiou et al. (1999) focused their research in typical residential buildings from Victoria in Australia; and Trotman (1994) and Watt (1999) focused their research in typical buildings from United Kingdom, both obtaining different defect classifications.

2.6 Classification of defects in the building industry

In the building industry, different approaches to classify defects exist: by its severity, by construction stage, by type, by cause, etc.

Georgiou et al. (1999) suggests classifying defects into major and minor categories, taking into account the severity, classifying the defect as technical, aesthetic or functional. Technical meaning when the workmanship or material of an element reduces its capacity to fulfill the functional performance of a structure; aesthetic, when the appearance of a material or building element is adversely affected or; functional, when a dwelling fails to function in its intended manner.

Sommerville and McCosh (2006) propose to classify snags in technical, omissions and aesthetic. Technical meaning when workmanship, material or design of an element of the building reduce its ability to function properly; omissions, for parts of a home that are simply "omitted" or; aesthetic, when the performance of a building element is adversely affected.

Georgiou (2010) distinguishes between defects due to the construction process, or to natural degradation related to a lack of maintenance by the occupants of the house.

Other criteria used by authors to classify defects are: the type of defect (Mills et al. 2009; Georgiou 2010; Georgiou et al. 1999; Trotman 1994; Watt 1999), the affected element (e.g. Georgiou et al. 1999; Chong and Low 2006; Chong and Low 2005), the affected material (e.g. Chong and Low 2006), or the failure mechanisms (e.g. Chong and Low 2006), and nature(e.g. Porteous 1992).

Other authors analyse the type of defects focusing on one building area, element or construction trade and created their own classifications. For example Tang et al. (2004) focus his research in the concrete construction trade; Chew (2005) in wet areas; Chong and Low (2005) in floor elements; Karim et al. (2006) in area of work, trade and subcontractor packages; Manrique et al. (2007) in tilt-up irregular concrete panels that are constructed on-site using concrete slabs and wooden

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formwork; Mills et al. (2009) in footings, water proofing, plumbing and sanitary construction trades and; Johnssona and Meilinga (2009) in timber module prefabrication buildings.

Another criteria used to characterize defects is the defect cause (Karim et al. 2006) and origins (Josephson and Hammarlund 1999). Various defect tracking and cost coding systems also incorporate the causes of these defects as for example Davis et al. (1989).

Finally, some authors use the human error causes to classify construction defects (Atkinson 1999).

2.7 On-site tracking systems

The typical defect management process involves a site inspector conducting an inspection in the construction site, who documents the discovered defects and then s/he delivers the formally documented to the relevant organization (e.g., architect, builder) to be solved Dong et al. (2009). It is important to clarify the site inspector role could be taken by different actor of the construction process as for example constructor, project manager, architect, engineering manager,…

The communication and information/record management process in the construction industry is still heavily based on traditional methods of paper transfer (Craig & Sommerville 2007).

Different technological innovations are proposed in the literature in order to reduce this time-consuming process. Battikha (2002) suggests a computer-based system to support quality management. The recording process is still manual but the information is managed with a computer program or intranet. The main goal of this system is to deal with information and consequent decision-making processes pertaining to defects distresses of construction projects for the detection of problems and/or their prediction; the diagnosis of their root causes, and the specification of appropriate remedial, corrective and/or preventive actions.

Craig & Sommerville (2007) designed a hybrid electronic/paper-based snagging management system. The underlying concept is to create a digital interface using pen and paper (which are intuitive to most people). Such technology combines the digital pen and paper with e-mail and IT systems.

Another kind of innovation is based on mobile computing. Currently available mobile computing technology is a rather obvious way to improve the field work and enhance the productivity of construction management (Dong et al. 2009). The implementation of mobile devices in construction has focused primarily in project management, schedule management facility inspection and field reporting applications (Dong et al. 2009). Several kinds of mobile devices have been adopted at construction sites. Kimoto et al. (2005) developed a mobile computing system using personal digital assistants (PDA) to assist architects and construction managers to inspect the results of construction works and to monitor the progress of projects. Sunkpho et al. (1998) developed a Mobile Inspection Assistance (MIA) system, which is a wearable computer system that helps bridge inspectors to collect multimedia information in the field and provide the inspection report. Lipman (2004) used a Virtual Reality Modeling Language (VRML) on a mobile handheld computer to visualize 3D structural steelwork models in the field. Kim et al. (2008) developed a PDA and wireless web-integrated system for quality inspection and defect management of apartment housing projects. Data is collected using the PDA and is stored in an online database. Dong et al. (2009) developed a telematic digital workbench, a horizontal table top user interface that integrates mobile computing and wireless communication to facilitate synchronous construction site to office collaboration. The on-site crew uses a handheld mobile device to collect defect information and transfers the information to the design office through wireless communication by sending the information to a database listener. The design office visualizes in a horizontal tabletop the location on the site with the 3D model server.

There are several specific mobile commercial tools to track construction defects such as DFECTX, Defects by Eyi app or IDMS.

Usually, commercial software is based on filling in forms. The length of the forms often compromises its usability. Using large forms in PDA or Smartphones can cause problems that can be increased by environmental factors. For example, Guerriero et al. (2011) notes that contrast and screen luminosity could be a problem while using PDA or Smartphones outdoors, under bright sunlight.

2.8 Defect prevention during preconstruction stage

ISO 9001:2008, in section 8.5.43 (preventive action procedure), remarks the need to establish methods to predict the potential non-quality which will enable appropriate actions to be taken for eradicating their causes and preventing their recurrence and/or their occurrences (Battikha 2008). The removal or mitigation of the failure mode is the most cost effective method since the analysis is performed at the early stage of a system (Zeng et al. 2010).

During the preconstruction stage, project managers are responsible for drafting preproject and quality management plans. For this reason, they should be aware of the different potential costs that rework may cause when they are preparing such documents (Hwang et. al 2009). Developing tools that bring awareness to the project managers of the potential quality risks will support the implementation of ISO 9001:2008 in construction companies and help organizations to improve their quality performance.

Several techniques, methods or models to risk analysis are described in the literature. (Khan 1997; Reniers 2005; Aven et al. 2006; Zayed 2008; Marhavilas 2008; Zongzhi 2010). Nevertheless, all of these risk analysis have the same structure: Risk identification, risk assessment, Risk mitigation.

Risk identification is the first step of risk management process is risk identification. It includes the recognition of potential sources of risk and uncertainty event conditions in the project and the

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clarification of risk and uncertainty responsibilities. It is accomplished by a structured search for a response to the question – What events may reasonably occur that will impede the achievement of key elements of the construction project (Zayed 2008).

In the identification step generally are evaluated independent construction project parameters. The identification can be done by different strategies. For example (Willams 1994) evaluated the likelihood of occurrence and the impact with the scale low, medium or high. (Gangolells et al. 2010) used the probability of occurrence and the severity of consequences to evaluate the health and safety risks for every construction process. Gangolells et al. (2010) and Gangolells et al. (2009) used scale, probability and duration of the impact probability and consequences to evaluate the environmental impact for every construction process.

Generally, as a result of the identification a risk register is created. Conventionally, a risk register has two main roles. The first is that of "a repository of a corpus of knowledge", and the second one is to "initiates the analysis and plans that flow from it" (Willams 1994). As is noted by Allan and Yin (2011), risk register contains relevant information of a risk; the most prominent ones are the impact and the probability of occurrence.

The second step is the risk assessment. Risk and uncertainty rating identifies the importance of the sources of risk. Traditionally risks are assessed with probability of occurrence and severity of risk impact. However when this parameters are used in the identification, authors propose to use other parameters. For example (Willams 1994) proposed to analyse the probabilistic costs, the temporal uncertainties, and the risk of not achieving. (Gangolells et al. 2009) used the exposition to evaluate the health and safety risks. (Gangolells et al. 2010) proposed to use the exposition for the health and safety risk assessment.

The final step is the risk mitigation. Mitigation establishes a plan, which reduces or eliminates sources of risk and uncertainty impact to the project's deployment.

There have been few studies on the analysis of potential quality deviations during the preconstruction stage but they all have focused on qualitative analysis. Of the literature reviewed, the approaches of Meca and Masera (2001), Roger et. al (2001), Manawazi (2004) and Han et. al (2011) are among the most noteworthy.

Meca and Masera (2001) developed a preliminary system to forecast non-conformities of the construction process (Failure Mode Effects Analysis, FMEA). The methodology consists of evaluating non-quality risks of the different work packages, identifying their causes and effects by evaluating their complexity level, aptitude for failure and importance level.

Rogge et al. (2001) in his research involved management and coordination parameters that are not accessible during preconstruction, and Manavazhi (2004) and Han et al. (2011) oriented their research into design problems.

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2.9 Defect analysis as learning source

ISO 9000:2005 establishes eight quality management principles: Focus on your costumers; Provide leadership; involve your people; Use a process approach; Take a systems approach; Encourage continual improvement; Get the facts before you decide; Work with your suppliers.

Defects should be understood as a source of information. Defects can be used as facts to improve the construction methods and process and reduce defects. Learning to reduce defects will lessen the impact of such overruns and would improve project performance, safety, profitability (share value and dividends) and reputation. However, despite increasing customer dissatisfaction, house builders have neglected to listen to the "voice of their customer", which has resulted in defects continuing to manifest at post-handover (Mills et al., 2009; Auchterlounie and Craig 2010).

Viewing defect prevention as a continuous process rather than a product of certain activities or behaviours, involves the exploration of people, organization, and project management system to map dependencies and interfaces that influence the defect prevention process. Furthermore, a process view implies that learning from defects is a collective capacity that can produce individual, organizational and interorganizational defect prevention practices. Given the complexity of the project environment the production of a collective capacity would involve the learning processes of the entire project team. (Adapted from error prevention (Lopez et al. 2010))

Different authors studied defects in real cases and reported the significant factors that contribute to defects (Josephson and Hammarlund 1999, Georgiou et al. 1999, Ilozor et al. 2004, Chew 2005,Chong and Low 2005, Chong and Low 2006, García and de Brito 2008, Mills et al. 2009, Georgiou 2010). To determine these factors different statistical methods are used, the typical are: multiple regression, correlation analysis.

As is noted by Yung and Yip (2010) the availability of data in terms of quality is difficult. When real data is not available, some authors used survey as a source of information. Surveys are a good tool to obtain information; however when the survey pretends to caught opinions a subjective component exist and it has to be taken into account.

For example, Olubodun and Mole (1999) evaluated the influencing factors of defects in public housing in the UK. The source data was obtained from 45 questioners answered by 45 practitioners. The results of that research have to be understood as the opinion of those practitioners and not a fact.

Another resource used by the literature is the utilization of recognized quality assessing tools as for example CONQUAS. CONQUAS is a registered trademark in Australia, Hong Kong, Singapore and the UK (Ling 2005). The CONQUAS system was essentially developed to assess contractors in public sector building contracts. It have three objectives: first, to have a common quality evaluation system for construction projects; secondly, to provide an objective and measurable system for quantifying the quality standards of building construction; and finally, to facilitate the

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systematic assessment of quality standards, within specific time and cost limits and in the process, raise the level of quality in construction (Pheng et al. 1999). The assessment consists in three main parts: Structural works, Architectural works, Mechanical and electrical (M&E) works. The assessment is based on past experiences.

Ling (2005) used surveys and CONQUAS score of 107 projects to identify variables that significantly affect quality scores of design-bid-build and design-build projects, and construct models to predict quality scores in each type of project. The parameters of the resulting model are general parameters of the project such as ownership of building or design completion when budget is fixed. These models to predict the likely quality scores in new projects can be used during at planning and design stage.

Different strategies are used to determine defects factors. Although defects data of construction projects is the most objective data, the difficulty to obtain data makes that authors use other strategies such as surveys, opinion surveys or scoring systems. Differences between the results of different studies remain in the scope of them. In consequence whatever study carried out has to define its boundary conditions to be understood and compared with other studies.

2.10 Summary

There is an existing semantic problem involving the different words used to refer to rework. This problem is basically caused by the different approaches proposed for authors that usually, can be grouped into three general approaches: technical/product, human and project.

Defects and non-conformities are the typical words used when the studies are based on technical/product approach. Although ISO remarks that defect and non-conformity are not synonymous, in the construction sector non-conformities and defects can be considered synonymous. On the other hand, in human and project approaches the word used is error, that is related with human actions and its deviation from the appropriate behaviour at work.

Rework can be considered the global word because include different concepts such as defects, non-conformities, cost associated with redoing portions of work that incorporate or interface with additional or missing scope, and errors.

As it is demonstrated in previous sections, in rework field, it is necessary to define properly the term of rework and delimit its scope to avoid confusions and misinterpretations.

Rework affect the construction process at three levels: project level, increasing costs and schedule; company level, decreasing productivity and worsen its image and; human level, affecting workers motivation.

This dissertation will focus on defects to reduce rework and all negative consequences of rework, assuming a direct relationship between rework consequences and defect consequences.

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Different approaches are used in the literature to classify and characterize defects. Non standardized classification exists to characterize defects. It is need to establish which parameters will be used in this research to characterize defects and define the list of words adapting previous classifications.

The defect recording process is a very arduous task. In the last years some innovations as IT tools have been proposed to make that process lighter. However, practitioners are still using traditional methods (paper based).

Following ISO 9001 standards, the organizations need to establish methods to predict the potential non-quality/incidences prediction. The prediction of the defects in preconstruction stage, together with prevention actions, can be very useful to reduce the amount of rework during the following construction stages. Despite of that, not so many authors focus their studies on this field.

Another key point according to ISO 9001 is the usefulness of the defect data, especially o help companies to continual improvement. Defect data has to be understood as a source of information that can help companies to improve its productivity. Unfortunately most of times defect data is not available to develop studies. Thus some authors base their studies in surveys. However it is important to remark that surveys could have a subjective component that should be taken in to account.

2.11 Implications of the results

The aim of the thesis is to contribute to the reduction of rework in the Spanish residential buildings. The concept of rework is very broad and this dissertation is focused on defects to reduce reworks.

This dissertation uses the Watt's (1999) defect definition: "a failing or shortcoming in the function, performance, statutory or user requirements of a building, and might manifest itself within the structure, fabric, services or other facilities of the affected building"

To characterize a defect this dissertation will consider the following parameters:

- Defect type
- Construction process affected
- Source of the defect
- Origin of the defect
- Construction element affected
- Construction location affected

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The definition of the pre-established list of words included in each of the parameters can be found in the Appendix A. The different lists of words are based on pre-existing classifications and adapted to the Spanish industry. However, in terms of defects a standardised list does not exist, and all classifications are adapted to a specific country. For this reason, Chapter 3 defines a list of standardized words which refer to defects for the Spanish residential buildings.

Different technologies and methods used to improve the on-site defect tracking system process are proposed in the literature. In addition, some innovative technologies are available in the market. However, a study on the current methods and technologies used in the construction industry to track defects does not exist. For this reason, Chapter 4 includes a set of interviews conducted in order to determine which are the currently used processes in the construction industry to track defects, which information they use and which are the limitations of the current technology. With that information a new method to track defects is developed and implemented in an IT tool.

During the preconstruction stage some construction information is not yet available; for example the designer or project manager usually do not know which workers will do the specific jobs, or which is the organization of the construction company. For this reason, the methodology has to be based on the available information. Chapter 5 presents the development of a methodology in order to identify construction defects during the preconstruction stage. The methodology is implemented in a case study to show its potentialities.

Although the construction information about defects is difficult to obtain, this dissertation will avoid surveys to determine factors that contribute to defects due to the associated subjective issues. This dissertation will focus on data coming from client complaint forms from four Spanish builders' database to later conduct the analysis of defects. In this way, the dissertation will follow the ISO 9000 principals: Focus on your customers; encourage continual improvement and get facts before you decide. The results of this analysis will demonstrate the usefulness of this type of data for the construction industry.

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Chapter 3

Formulation of defect taxonomy

3.1 Introduction

This chapter describes the work undertaken in order to meet the thesis' aim and individual objective 2 stated in Chapter 1. This chapter presents the creation and validation of a taxonomy of defects for the Spanish residential building sector. First, using the literature review presented in Chapter 2 about defects classification, an initial draft of the taxonomy is developed; to be later discussed and improved in a series of workshops conducted by a panel of experts. Afterwards, the final classification is validated throughout two activities. The validation starts with the evaluation of the epistemological adequacy and reusability of the proposed classification system. Such evaluation is performed by conducting experts' interviews. Finally, defects' data coming from 3 developments is classified to ensure that all defects can be classified using the taxonomy.

3.2 Research methodology

The methodology used in this chapter to develop the defects' taxonomy for the Spanish residential building sector has 2 steps: Defects classification system development, and validation. The following figure presents the research methodology used in this chapter.

	Defect classification system development		Validation of the classification	
Methods	Literature review (Initial defect list)	Workshops	Expert interviews	Classify real data (Defects from three building developments captured during the construction and posthandover stage)
Aim	- Obtain an initial defect classification to be discussed in the expert workshops	- Discuss the intitial defect classification and obtain the final defect classification - Define all words of the defect classification	- Test if the defect classification is clear and intuitive, and contains all relevant words - Test if the classification can be used in diferent domains -Test if experts classify defects with the same classification word	- Test if the classification can be used to classify construction and posthandover defects - Study the differences between construction and posthandover defects

Figure 3. Research methodology to develop defects taxonomy

Defect classification system development

No standardized Spanish defect classification system currently exists. Therefore, the defect classifications proposed by Mills et al. (2009), Georgiou (2010), Georgiou et al. (1999), Trotman (1994), Watt (1999) and, Johnssona and Meilinga (2009) were used as the basis to develop a first defect classification for the Spanish context. In addition, defects reported during the construction of 20 buildings in Spain between 1999 and 2009 were analysed to complete the list.

Then several workshops were carried out by a panel of experts to discuss and improve the proposed system. The panel of experts was composed by practitioners specialized in construction management with special interest in quality: two professors from the Department of Construction Engineering at the Univestitat Politècnica de Catalunya, two managing directors of Spanish construction companies specialised in housing and one quality coordinator from a Spanish construction company specialised in housing and public buildings.

Participants were encouraged to critique the taxonomy of the classification system, and suggest modifications. During the workshops experts suggested, modified or added terms. Finally experts agreed the definitions of each classification category.

Validation of the classification

The validation was undertaken through two activities: interviews with experts, classifying data coming from 3 developments and experimental validation.

Interviews with experts:

Eight face-to-face structured interviews were undertaken to evaluate the epistemological adequacy, reusability and reliability of the classification system. Interviewees were 6 site managers, and two quality inspectors with a minimum of 10 years experience. Face to face interviews were selected to capture the comments and feelings of the interviewees, and to clarify the terms of the classification system, if necessary.

The interview was structured in four different sections (see appendix B.1 Taxonomy defects' validation). The aim of section one and two was to evaluate the epistemological adequacy (the degree to which the classification resembles the cognitive sentence) and the reusability of the classification system (The degree in which the classification system can be reused in other situations). For this purpose a survey with 6 questions that practitioners had to range from 1 to 6 was conducted, being 6 the most favourable in each case. The questions were based on the criteria proposed by El-Diraby and Kashif (2005).

The aim of section three was to assess the reliability of the classification system. Interviewees were asked to classify 20 construction defects, using the proposed classification system, and provide comments on the suitability of the term used for each case, as well as the difficulty of classifying each defect. This construction defects were selected randomly from a Spanish contractors defects' database. To avoid interference with language differences, defects were shown using pictures. To measure the degree of agreement among all interviewees kappa statistic test was used.

Finally, in the fourth section an open question was proposed with the aim to get expert's opinion on the proposed classification system.

Classification of data

The goal of this validation activity is to check if the taxonomy is able to classify all type of defects that arise and are resolved during construction, and those defects that still remain at handover when the majority of the controls are undertaken.

For this purpose, a total of 1,138 defects were identified, analysed and classified using the best term from the proposed classification system.

Defect data was collated from three building developments defects forms from one Spanish builder. The number of dwellings within each of the seven developments identified ranged from 40 to 126. The building developments were constructed between 2006 and 2007. The size of the dwellings within each building development ranged from 70 to 130 square meters and contained between three and eight floors. Table 1 identifies the main characteristics of the analysed developments.

Table 1. Building characteristics

Development	nº of dwellings	m2	nº floors	Building characteristics	Cost [€]	Year
Development 1	40	6.996.36 (GF 3.184.31 + F 3.762.05)	4 GF + 3	1, 2 and top floor with balconies; Concrete structure; Continuous foundations; Inverted roof; Bricks façade.	4,605,260.27	2007
Development 2	50	10.522,75 (GF 2.456,60 + F 8.066,15)	GF + 10	Ground Floor: Commercial area; 2 to 10 and top floor with balconies; Concrete structure; Continuous foundations ;Inverted roof; Façade: bricks and ventilated façade with ceramic boards	7,939,378.05	2007
Development 3	128	20.985,00 (GF 4.351,00+ F 16.634,00)	2 GF + 5	Reticular framework; Slurry walls; Flat traditional roof and sloped roof with sandwich panels; Bricks façade.	11,793,007.98	2006

3.3 Proposed defect classification system

The categories of the ensuing classification system include different types of defects with common aspects. The classification system is organized into a reduced number of categories (15) so as to be functional (Mills et al. 2009), and to facilitate statistical analysis. Some of these categories include subcategories to specify the particulars of each category. Table 2 presents the developed taxonomy and, A.1 Defects' classification system for construction industry presents the resulting classification system with the definition and examples of each category and subcategory.

The first classification system proposed by the research team and discussed in the workshops included one level category with 30 categories. However, experts considered that the classification was not functional to use. During the workshop discussions experts proposed to create a classification system with two levels. In the main level general words were included; and in level two, more specific concepts were included. For example, for the category "Affected functionality", experts proposed to divide the category in two subcategories taking into account the severity: defects that produce an element that has to be changed or those where the element can be repaired. For this reason this category was divided into two subcategories: "Disabled", in which the material/element/item has to be replaced because its functionality is completely affected; and "Bad operation", in which the material/element/item has no need be replaced because its functionality is partially affected, but it has to be repaired.

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Table 2. Developed taxonomy of defects

Category 1	Category 2
Affected functionality	Disabled
	Bad operation
Inappropriate installation	-
Biological action and change	-
Broken / Deteriorated	-
Chemical action and change	-
Detachment	-
Soiled	General
	Stain
Flatness and levelness	-
Misaligned	-
Missing	Item
	Work
Stability / Movement	Collapse
	Landslip
	Cracking
	Excessive deflection
	Excessive structural vibration
Surface appearance	Bumps
	Dips
	Uneven
	Hit/Scratches
	Efflorescence
Water problems	Excess moisture
	Entrapped water
	Water ingress
Tolerance errors	-
Others	-

The aim of the classification system is to include all defects produced in all construction processes of a residential construction, unlike other authors who developed classifications for specific construction process. For example Silvestre and Brito (2010) developed a classification system for inspecting adhesive ceramic wall or floor tiling, or Tang et al. (2004) that developed a classification system for defects produced in the concreting process.

In comparison to other classification systems, the word workmanship was not used to avoid misunderstandings. During the workshops, experts noted that some practitioners could understand workmanship as a cause or a consequence but not as type of defect (Georgious 2010, Josephson and Hammarlund 1999). Other authors such as Johnssona and Meilinga (2009) propose to use the word erroneous instead of workmanship. With the aim of objectivity, not defining cause or attributing blame, experts proposed to include two categories instead of workmanship: “affected functionality”, relating to defects such as door scrapes on floor and; “inappropriate installation” relating to elements that are not installed following the project specification or client needs.

In the literature some authors use elements as a defect. For example, Chong and Low (2006) include urinal sensor as a defect to indicate that the urinal sensor is not properly working. This

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issue was largely discussed during the workshops. Experts considered that the classification only had to include the variable types of defects to be coherent.

Other classifications such as Manrique (2007) include plural words. In the proposed classification system the experts suggested to include only singular words to standardize the vocabulary.

During the workshops the convenience to include concepts such as worms attack or other biological interaction with the building was discussed. Experts remarked that these kinds of defects are not typical during the construction and post-handover defects, because the development mechanism is slow. In addition, due to the Spanish construction methods, this kind of defect is very unusual.

Another largely discussed category was “Chemical action and change”. This category includes all defects produced by the interaction between chemical elements and compounds that make up materials used in and around buildings; and the constant action of people, processes and environment. These interactions involve or result in chemical reactions, where materials undergo in a kind of chemical change resulting in the formation of new compounds. Some examples of this type of chemical action are the corrosion of metals or the carbonation of concrete (Watt 1999). Experts noted that this type of defect, as well as “Biological action and change”, is unusual in construction stages because in most of cases it is a consequence of other defects and the reaction mechanism is slow.

Although experts consider that “biological action and change” and “chemical action and change” categories mainly appear during the operational stage, they were included in the proposed classification system to embrace the whole lifecycle of the project.

“Soiled” is a category included in any defect classification. Experts remarked that during the construction stage it is known that all construction sites are dirty and this is not understood as a defect. However, when the final user gets the product dirtiness in the elements, it can be understood as a defect, specially stain which is difficult to remove. For this reason, experts finally decided to include this category.

To define incomplete tasks or elements a “missing” category was included. Incomplete was the term chosen initially as it is used in other classification systems (Georgiou et al. 1999). However during the workshops some practitioners reported that from their perspective “incomplete” refers to a task, and excludes items. Johnssona and Meilinga (2009) use the terms missing and unfinished. The panel of experts preferred missing task to define those unfinished parts of the building. For this reason the “missing” category provides two subcategories (task and item) to indicate the type of incompleteness.

The “water problems” category was subdivided into “excess moisture”, “entrapped water” and “water ingress”. Although “water ingress” category could be divided into more specific defects (e.g. leaking in roof, leaking shower base) as did Mills et al. (2009), authors preferred not to create more sub-categories.

3.4 Validation

3.4.1 Interviews

Interview results regarding the epistemological adequacy are considered positive as it can be observed in Table 3.

Table 3. Interview results regarding the epistemological adequacy

	Mean
Do all concepts have a clear and unequivocal meaning?	4.4
Does the taxonomy provide a vocabulary that matches the intuition of the experts?	4.5
Are all the concepts in the taxonomy relevant?	5.1
Does the taxonomy cover all relevant concepts that may be relevant for any task, method and construction type?	4.4

Interview results regarding the reusability of the classification system revealed that the proposed classification system is only suitable for the Spanish housing construction environment due to its dependence on the local construction processes, and the construction type (Table 4). This conclusion agrees with Georgiou (2010) who suggests that some knowledge and understanding of local construction practice is also desirable to study defects in the construction industry.

Table 4. Interview results regarding the reusability of the classification

	Mean
Does the classification depend on the construction tasks and methods used in each country/region?	5.12
Does the classification depend on the type of construction (housing, public building, etc.)?	5.25

For example, neither defect in wood nor in precast structures was analysed to create the classification because they are not used in the Spanish housing Construction Industry. However, these kinds of structures are very usual in other type of buildings such as schools (Pons 2010). In future research the classification system will be tested to analyse defects in other countries with different construction process and different types of buildings.

The reliability was checked by inviting interviewees to classify 20 defects and rate the appropriateness of the term used to define each defective situation. Then, the statistic kappa was used to measure the nominal scale agreement among the different raters. The agreement between the raters was almost perfect as it can be noted in Table 5. These results reveal that the classification system is clear and the terms are well defined.

Table 5. Kappa test for the results of classifying defects

No. of Cases	No. of Reviewers	Kappa	SE (k)	Range (95% confidence interval)	Rating
20	8	0,821	0,013	0,846-0,796	Almost perfect agreement

Finally, an open ended question was included with the aim of obtaining the practitioners opinion regarding the proposed classification system. Most of the practitioners agreed on the terms used in the classification system, although they stated an exhaustive read of each definition was necessary before applying it. This was an expected comment as some categories include multiple subcategories, and some terms define several potential defects. Another interesting suggestion was the possibility of expanding the classification system, and determining the specific defects for each construction trade.

Interviewees suggested the implementation of this classification system in existing or new defects tracking systems. These systems are helpful to record defects information, and quantify the non-value added tasks in the construction process due to defects, however all experts agree that currently the tracked information is not structured and it is difficult to analyse. The use of standardized vocabulary during the tracking/recording process reduces the time spent to analyse data and extract conclusions, and allows the development of statistical analysis (Mills et al. 2009).

Practitioners consider defects as a source of information, and some experts used the word “professionalize” during the interview. It appeared as an unexpected result because construction industry traditionally accepted defects as a part of the building process (Mills et al. 2009). Some practitioners consider that with the current economical situation the Spanish construction industry needs to improve the productivity and increase the reputation. It may be caused by the fact that some construction companies started measuring their productivity due to the economical situation. In fact, only when organizations begin to measure (and therefore really understand) their rework costs, will they fully appreciate the economic benefits of achieving quality Love (2002a). However, learning to reduce defects will not only improve the productivity; it will also lessen the impact of such overruns, and would improve project performance, safety, profitability (share value and dividends) and reputation.

The classification had a good acceptation between the interviewed practitioners, who agreed that the proposed defect classification system can be used to develop related studies analysing housing defects in Spain, addressing the causal mechanism of defects, and their interrelationships (Love et al. 2011).

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Defects should not be considered as the final consequence of a chain of events that cause costs and schedule increases (Love et al. 2004). Defects must be understood as a cause and consequence and reciprocal or looped in their relationships. The interviewees considered that the proposed classification system could be a good starting point to define the complex interaction between variables that contribute to defect occurrence, and to observe any specific cause and effect relationship that may exist.

3.4.2 Data classification

Table 6 presents the distribution of defects both during construction of the building and at post-handover. This analysis revealed that the majority of defects remain at handover (90.86%).

Currently, the Spanish construction standard (CTE, 2006) regulates construction processes and techniques to ensure that buildings meet basic requirements with regard to functionality, general safety and structure, fire-proofing, and use and habitability. This fact, together with the standardization and repetition of tasks in the housing industry, results in a reduced number of defects during the construction of the building. However, at handover, when most of controls and inspections take place, many minor functional defects such as omissions are detected and resolved.

Although the number of construction defects is less than those remaining at handover, the significance and consequences of construction defects is greater. During construction the most common defects are “Inappropriate installation” (31.73 %), “missing item” (23.08%), “surface appearance” (13.46%) and “flatness and levelness” (10.85%). While the most common defects detected at handover are “missing item” (55.80%), “dirty” (27.95%) and “affected functionality” (5.90%).

Table 6. Case study: defects’ distribution

	Construction defects		**Post-handover defects**	
	nº of defects	**%**	**nº of defects**	**%**
Affected functionality	5	4,81%	61	5,90%
Inappropriate installation	33	31,73%	19	1,84%
Biological action and change	-	0,00%	-	0,00%
Broken / Deteriorated	6	5,77%	17	1,64%
Chemical action and change	-	0,00%	-	0,00%
Detachment	-	0,00%	-	0,00%
Soiled	2	1,92%	289	27,95%
Flatness and levelness	11	10,58%	36	3,48%
Misaligned	-	0,00%	-	0,00%
Missing	24	23,08%	577	55,80%
Stability / Movement	3	2,88%	-	0,00%
Surface appearance	14	13,46%	32	3,09%
Water problems	2	1,92%	1	0,10%
Tolerance errors	-	0,00%	-	0,00%
Other	4	3,85%	2	0,19%
Total	104	9,14%	1034	90,86%

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From this analysis, it can be concluded that within each term of the classification system, different defective situations are considered depending on the stage of the project. For example, “missing items or tasks” during construction include omission of bars in the reinforcement or omissions of concrete joints, while at handover this defect term mainly refers to the omission of a doorknob, second layer of paint or polishing works, which are easier to resolve.

During construction stage examples of “Inappropriate installation” defects are concrete slab reinforcement bars installed in the incorrect concrete layer, bad location of joints in relation to other fixtures, or poor concrete mixture ratios. However, very few of these types of defects remain at handover.

The majority of “surface appearance” defects during construction are bumps because the painting works being commenced before the surface was dry, honeycombs in exposed concrete elements, uneven surfaces such as uneven color, ground, margins, and wood with an uneven grain. However, handover defects included in this category are mainly hits on finished unprotected surfaces.

“Flatness and levelness” defects are normally detected during construction and involve all surfaces being significantly irregular and/ or with excessive sloping; for example, slabs or walls too inclined.

Although during construction the natures of defects is basically technical, and at handover the nature of the defects are aesthetic or technical, the classification is useful for both situations. Chong (2005) reached the same conclusion when analysing and comparing the defects that occurred during construction and 2-6 years after initial occupancy, and found that the defects at both periods were very different but had similar descriptions.

We can conclude from this case study that it is possible to classify defects using the presented classification system.

3.5 Conclusions

The chapter presents a defects’ taxonomy for the Spanish residential building sector. The taxonomy is composed by 15 main categories. The validation of the classification system revealed that the classification concepts are clear and with an unequivocal meaning, using a vocabulary that matches with the intuition of the domain experts. All relevant concepts are included in the classification and it covers all the relevant tasks, methods and subdomains. Kappa test results revealed that the classification system is clear and the terms are well defined.

The classification system was developed taking into account the characteristics of the Spanish residential building sector. The interviewees considered that the classification cannot be used in other domains, but it could be used as a starting point to develop defects’ classification systems for other domains.

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The validation revealed that nowadays, Spanish construction companies are realizing the benefits of tracking and analysing defects for the continuous improvement imposed by ISO 9001:2008. Many companies track defects but do not analyse them because it is time consuming, they lack tools and techniques, and they do not have structured database information on defects with standardized vocabulary. For quality management systems to be successful, organizations should measure defects and analyse the associated costs.

The defect classification system proposed in this chapter will enable companies to implement it in their tracking systems, it will help understanding the nature of defects, and it will facilitate the development of strategies to reduce and/or prevent them. In this way this classification is the basis for the rest of the dissertation chapters.

As demonstrated in the case study, structuring defects information using the proposed classification system provides relevant and valuable comparisons and statistical data. This issue is presented in chapter 6.

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Chapter 4

Development of a methodology to track construction defects

4.1 Introduction

This chapter presents the work undertaken to meet objective 2 and objective 3 stated in Chapter 1 of this dissertation. This chapter is aimed to develop a methodology to track construction defects and validate it. First, the author determines the procedures that are currently used in the construction industry to track defects, which information is used, and which are the limitations of the current technology. Secondly, a methodology to track defects is developed and implemented on an IT tool called MoBuild. Finally, the methodology implemented on the MoBuild application is tested through case studies.

4.2 Research methodology

The methodology used in this chapter to define and implement a tracking system for construction defects is based on ISO 9241-210. The ISO 9241-210 standard outlines user-centred design as a process for interactive system development with the focus to enhance usability of that system. The proposed process by the standard begins with an understanding of the context of use and incorporates evaluation of design solutions as a way to modify the design until it meets the needs of users (Figure 4).

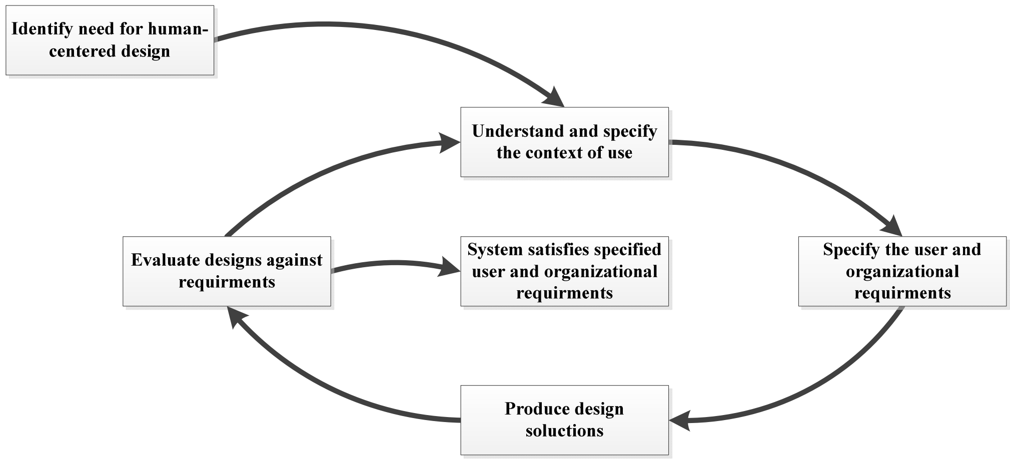

Figure 4. Activities of User-Centred design proposed by ISO 9241-210

This chapter starts with an industry survey to determine why practitioners are still using the traditional method to record defects (paper based). With the industry feedback, a methodology to track defects in the construction sector is defined and, in addition the requirements of the IT tool where the methodology will be implemented to facilitate the recording task will be defined. The programming task of the application is not in the scope of this dissertation. The programming task was done by the Centre de Recherche Public Henri Tudor (Luxembourg) where the PhD candidate performed a research stage. As a result of this, an application for smartphones called MoBuild v0.2 was obtained. The validation of the application was done together by Tudor and the author of the dissertation. The tool usability and the utility validation are included in this PhD, together with a new list of requirements to develop a future industrial prototype of the tool (Figure 5).

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	Tracking system definition		Validation of the tracking system
Methods	Literature review	Interviews with structured survey	Testing tool
Aim	- Understand and know the current technology to track defects on site - Understand and specify the theoretical context of use	- Identify the current processes used by the construction industry to record defects - Understand and specify the practical context of use - Define user and organizational requirements	- Test if the new approach to track defects can be implemented in the practitioners' work practices - Test if the designed solutions meets the user requirments

Figure 5. Research methodology to develop the tracking system

Tracking system definition

In order to identify the current processes used by the construction industry to record defects, a set of 27 interviews were carried out. The interviews were conducted in Luxembourg and Spain. In Luxembourg 12 interviews were conducted, whereas in Spain 15.

A structured survey was used for the interviews, including the following topics: recording process (Method and information), transferring information, managing information. Finally, an open question was included to encourage practitioners to explain the processes that they are using and which are their current problems (see appendix B.2 Processes currently used in the construction industry to track defects).

Practitioners were selected under the following criteria: more than 10 years of experience in construction sector and involvement in construction defects inspections.

The interviews were divided into four sections: recording data on-site, manage data, use of data and, information to characterize defects.

Using the results of the interviews and taking into account the current technological limitations, a methodology to track defects is defined based on a mobile computing system, using Smartphones to assist the construction supervisors. Finally the methodology is implemented in an IT tool called MoBuild.

Validation of the tracking system

A validation protocol was designed to test the new approach to track construction defects. Steps followed during the validation were:

- Step 1: Initial meeting to know how the company is tracking defects.

- Step 2: Define the taxonomies to be uploaded in the application depending on the case study.

- Step 3: Second meeting to explain how Mobuild v0.2 works.

- Step 4: Testing period

- Step 5: Final meeting. A structured interview was used with the following sections: Utility and Usability, in order to evaluate the experience. (see appendix B.3 Questionnaire about Mobuild testing)

With this protocol, the author does not plan to validate the CRTI-web (server) part. Author particularly wants to test the new approach to track defects on-site, as well as to validate the Mobuild v0.2 prototype. Moreover, the experiments are considered pilot-projects, allowing the users to test the prototype during a long period of time (4-6 weeks). The aim is not to gather quantitative feedback, but to get qualitative results and to evaluate the potential of implementing such application in the practitioners' work practices.

4.3 Interview and survey analysis

Practitioners were asked about the tracking practices used in their companies. The results (Table 7) show that practitioners are still using paper to record information on site in both countries. In addition, some companies in Spain do not track defects. IT tools such as PDA or Smartphones are not usually used to track defects.

Table 7. Methods to track on-site

	Luxembourg	**Spain**
	% of use	**% of use**
Paper	90.90	64.29
Paper with pre-established format	0.00	21.43
IT tool	9.10	7.14
Nothing	0.00	7.14

Practitioners believe that current commercial software is useful to automate data entry. However, practitioners feel that such tools only allow introducing descriptions or filling in large forms, making them useless for the construction site. Sometimes the information in the forms is useful as forensic data, but irrelevant for defect solving. Another problem noted by practitioners is the light reflection due to contrast and screen luminosity of the PDA or Smartphones under direct sunlight.

Practitioners prefer to use paper annotations. In both countries, notes taken on paper are always accompanied by pictures. Usually, practitioners use drawings or notes over pictures to characterize

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defects. This practice is more extended in Spain than in Luxembourg. Finally, in Luxembourg some companies started to use recorded voice to track defects (Table 8).

Table 8. Information to track defects on-site

	Luxembourg	**Spain**
	% of use	**% of use**
Drawings	36.36	42.86
Notes on pictures	27.27	50.00
Text	100.00	100.00
Photo	100.00	100.00
Recorded voice	9.09	0.00
Video	0.00	0.00

Videos are not used in any country to record defects. However, some previous studies (Guerriero et al. 2011) remarked that business experts believe that video could be an interesting tool to record defects.

All practitioners revealed that they do not have an integrated tool to manage defects. All the information that is captured on site has to be transferred manually to another support.

The most used tool to manage and store defects (Table 9) is word/excel or similar software. Both local databases and centralized databases are used in Spain in the same proportion. However, local databases are more frequently used in Luxembourg than centralized databases.

Table 9. Methods to manage and store defects

	Luxembourg	**Spain**
	% of use	**% of use**
Excel/Word	54.55	50.00
Local data base	36.36	21.43
Centralized database	9.09	21.43
Nothing	0.00	7.14

Only one company is relying on cloud computing technology, using the Evernote application. Evernote is not a specific tool to track defects, but is a tool to capture, store and share information; such as notes, pictures, web pages, screenshots.... It allows practitioners to capture onsite information and share it with their colleagues. Nevertheless, practitioners who are using this application reported some limitations: first, the application does not allow practitioners to export the information into other platforms which would enable further statistical analysis of most used tags; second, the application does not allow practitioners to add graphical notes to the pictures when they are taken; finally, the management of the user rights is limited.

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As a result of the interviews, it can conclude that some construction companies have started to use IT tools. Nonetheless, most of the companies are still using the traditional method, involving an inspector using paper and camera to annotate the defects. Some additional information such as drawings or notes on pictures is often added. Such data is processed in the main office and later used for defect solving.

Problems such as potential loss of defect information, misunderstandings and unclear instructions among different parties are often caused by manual data collection and transcription (Dong et al. 2009). Moreover, practitioners complained about the traditional method to track defects because it is time consuming. Although the problems of the traditional methods are well known and the practitioners are aware of them, they prefer this method due to its flexibility and it allows them to add all the required information without restrictions. The only limitation is that video information must be added separately.

The recording process requires flexible tools that allow practitioners to add different types of information at different times. As noted by Guerriero et al. (2011), AEC professionals want to collect information on site, write reports in an expeditious manner and improve communication.

Developing tools to facilitate recording defect data and its management could help practitioners to improve productivity, reduce the time of data collection and the managing process.

Table 10 summarize the functional requirements identified for an IT tool to track defects in the construction sector.

Table 10. Functional requirements identified for an IT tool to track defects in the construction sector

Requirement	Description
1	The IT tool shall capture multimedia data (video and picture)
2	The tracked multimedia data shall have the quality enough to communicate the identified construction defect
3	The IT tool, besides to capture multimode, shall capture additional data such as textual notes and graphical annotations
4	The tracked information on-site shall be exported to a data base/excel

4.4 Methodology to track defects

The traditional methodology to track defects is based on textual annotations/forms, where different information may be added; such as pictures, notes on pictures or drawings (Figure 6). The proposed methodology uses pictures as the main entry point. Defect information is completed with tags and other annotations such as text, voice or graphical annotations (Figure 7). It is challenging to characterize a defect using pictures, because in some cases photos are not representative of the

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issue observed on-site. For this reason, tags are introduced to help contextualizing the problem. If necessary, users can add annotations to complete the information.

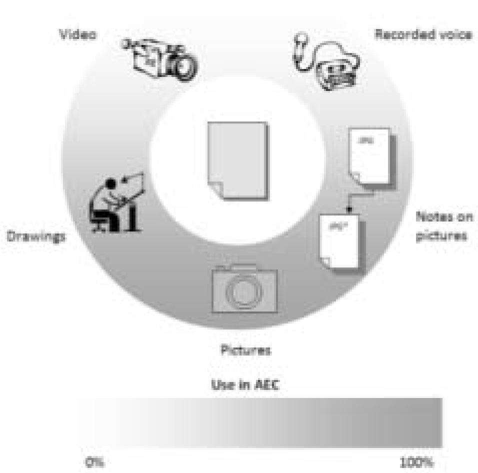

Figure 6. Traditional approach to track defects

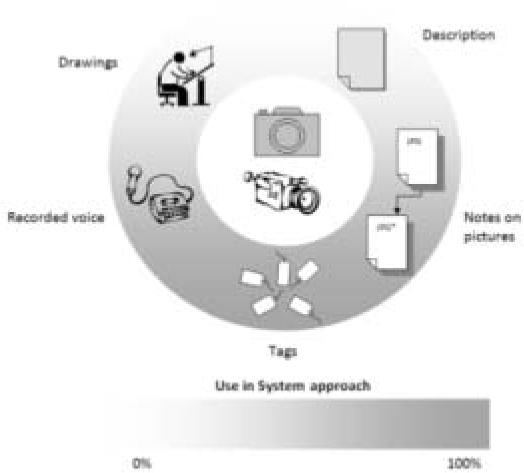

Figure 7. Proposed approach

The added value of using structured tags is to enable further statistical analysis of the recorded information. Tags could be a first step to organize the defect information in order to develop statistical analysis about defects, and study possible strategies to prevent them. It is known that data from construction defects should be considered a source of information. Learning to reduce defects will lessen the impact of such overruns and would improve project performance, safety, profitability (share value and dividends) and reputation.

In the proposed system approach, tags are a list of standardized vocabulary. The lists of standardized vocabulary can have more than 1 level of categories (see example in appendix A.1 Defects' classification system for construction industry). The user cannot modify nor add terms in the list of standardized vocabulary. If the user thinks that there is a need to add or modify the list.

The information captured on-site must be enough to identify and solve the defect. Information about the defects' blame is irrelevant because it can lead to unnecessary discussions (Métayer & Hirsch 2007). In addition, contrast and screen luminosity as a technological limitation must be taken into account. Information such as tags and annotations should be as minimum as possible to facilitate information collection.

The proposed approach to defect characterization, propose using pictures and one tag with the type of defect from an existing classification. Other annotations can be added to complete the information, such as text, voice or graphical annotations.

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To implement this approach in a case study the most important issue is to define the list of tags. Chapter 3 contains the development of a taxonomy to classify defects that could be used to contextualize images.

4.5 Implementation of the methodology in an IT tool

The methodology defined in section 4.4 (Methodology to track defects) is implemented in an IT tool called MoBuild, together with all functional requirements identified in section 4.3 (Interview and survey analysis).

MoBuild v0.2 application is an evolution of MoBuild presented by Guerriero et al. (2011). MoBuild v0.2 has the same functions as MoBuild (picture taking and associated vocal, textual or graphical annotations), but it incorporates the possibility of adding tags. The user can take photographs with his or her Smartphone and then enrich it with annotations. A microphone to associate an audio recording or the keyboard for textual comment can be used. If the comment concerns some areas of the picture, graphical forms (i.e. arrow or rectangle) can be used to highlight the area on the picture (e.g. a malfunction). The added value of using structured tags is to enable further statistical analysis of the recorded information. In MoBuild v0.2, tags are a list of standardized vocabulary. Initially, only tag referred to defect type developed in chapter 3 is uploaded. The user cannot modify nor add terms in the list of tags uploaded to the phone. If the user thinks that there is a need to add or modify the list, of tags the administrator of MoBuild v0.2 must be contacted.

In order to export the MoBuild v0.2 information, two different ways can be used: firstly, the user can send the recorded data (i.e. picture and annotations) by email in order to inform stakeholders about a dysfunction on site, or to his email box for constituting a set of information to be used as a basis for writing the construction report. Secondly, the user can synchronize the information with a web platform to access such information from the office. The web platform allows practitioners to download the pictures and the attached information in different formats to make writing the reports easier.

Table 11. Comparison between MoBuild and MoBuild v0.2

Functionalities	MoBuild	MoBuild v0.2
Take pictures	✓	✓
Take videos	✓	×
Take vocal annotations	✓	✓
Take textual annotations	✓	✓
Take graphical annotations (arrows and rectangles)	✓	✓
Take tags	×	✓
Export tracked information via email	✓ (Pictures and; textual and graphical annotations)	✓ (Pictures; textual and graphical annotations; tags)
Export tracked information through CRTI-web	×	✓ (Data exportation to excel file)

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The application allows sharing photo-based information through email or exporting it to a Web platform, called CRTI-weB (Kubicki et al. 2009). A specific module of CRTI-weB allows the access and management to the photos taken with MoBuild devices and export the information via excel. With that functionality, practitioners are able to carry out statistical analysis of the recorded information.

MoBuild prototype enables managing a large amount of pictures. Four modes are available for consulting the pictures: the user can consult all pictures with the photo gallery, is able to see all picture related to one of his buildings sites (using the map function), can consult all picture related with one of the meetings he has been involved in (using calendar function), or use the function “search” to find a specific picture using the tag searcher.

Figure 3 shows six screenshots of the MoBuild v0.2 prototype developed for the Android platform. Screenshot 1 shows the main menu of MoBuild v0.2. In the main menu several functions are offered: the user is able to search a picture/s using the photo gallery, search (by tags), map (to see a specific construction site), calendar (search for a specific meeting), or take a photo of a defect.

Screenshot 2 shows the interface allowing the user to add annotations in a photo using tags, textual annotations, voice annotations, and to add graphical annotations. The information added by the user can be viewed and modified using the controls previously explained (screenshot 1).

Screenshot 3 shows the interface enabling the user to search pictures by construction site. ”Google© Maps” is used to show construction sites location. Users can add construction sites by placing a pin on the map. They also have to define the radius within which photos will be “incorporated” to the site. If user touches a construction site icon, the application will display the photos of this construction site (screenshot 6). When photos are done outside of one construction site radius, the pictures are displayed separately.

Screeenshot 4 shows the interface enabling user to search pictures by tag. User can select tags and the application will display all pictures with selected tags (screenshot 6).

Screenshot 5 shows the interface enabling the user to search pictures by events. User is able to select special day and the application will display the pictures done during the selected days (screenshot 6).

Finally, screenshot 6 shows the interface presenting the photos’ miniatures. This interface will display all pictures chronologically ordered, or will display filtered by the construction site, tag or day. If user touches a picture icon, the application will display screenshot 2, and user will be able to start reading or adding annotations in the picture.

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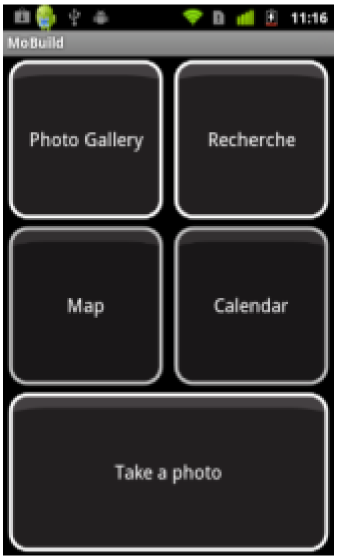
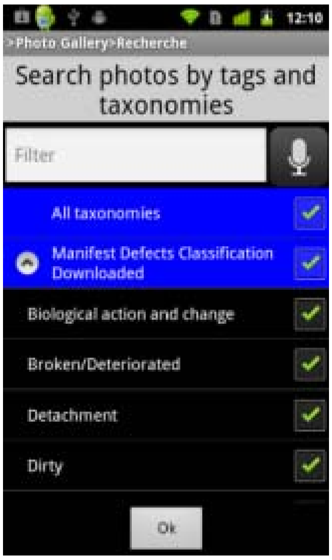


Mobuild screenshoot 1

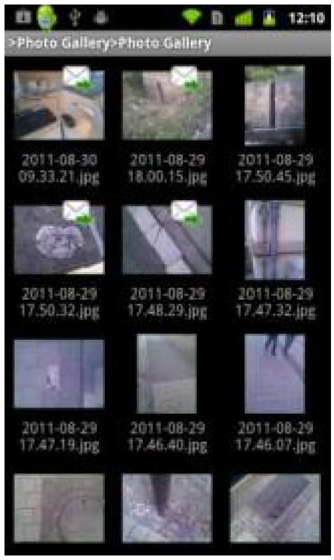
Mobuild screenshoot 2

Mobuild screenshoot .



Mobuild screenshoot 4

Mobuild screenshoot 5



Mobuild screenshoot 6

Figure 8. Screenshots of MoBuild v0.2

4.6 Validation

4.6.1 Use case definition

Use case 1

Case study 1 (CS1) was carried out in a construction company which is specialized in single family houses. The aim of this case study was to use Mo-Build v0.2 to track defects during the construction and handover stage.

In this case study the aim was to track on-site information and manage it. Currently, the company does not have the ISO 9000, but its interest is to ease on-site data collection. The company is tracking construction information using camera and paper-based tools, and they do not have a centralized data-base with the on-site data.

Use case 2

Case Study 2 (CS2) was carried out in an engineering company in Luxembourg. Two engineers used MoBuild v0.2 to track construction-related remarks through photos. A resulting To-Do list was produced after site's visits and sent to concerned practitioners.

Use case 3

Case Study 3 (CS3) was carried out in a public company which is managing the public housing in a city of 220.000 habitants. The aim of this case study was to use MoBuild v0.2 to track defects during the handover stage.

Inspectors must check 5 to 10 dwellings a day. They are currently using paper and camera, but losing a lot of time writing reports and sometimes they lose information.

Use case 4

Case Study 4 (CS4) was conducted in a construction company which replaces and installs buried utilities such as water pipes, gas mains, electric cabling... Initially the aim of this case study was to use Mobuild v0.2 to track defects during the works. But the company also proposed to use MoBuild v0.2 to track the progress of construction processes related with buried utilities, and improving the communication between the work place and the office. The company pursue to provide the client with updated information, offering new services to the client; and to improve the productivity reducing the time of report writing.

Use case 5

Case Study 5 (CS5) was conducted in a construction company which is construction roads. The aim was to test Mobuild v0.2 to track construction defects. But the company also proposed to use Mobuild v0.2 to track the progress of road construction and to track environmental and health and safety incidences.

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4.6.2 Validation analysis

The validation results show that the new approach to track defects has the potential to improve the defects recording process on-site, reducing the information loss between site and office and reducing the amount of time spent to collect data and write the reports compared with current methods used by practitioners. Practitioners appreciate the improvement in the productivity of defects management and, to have the information stored in a structured way. However, practitioners do not know how can be used the recorded information to carry out a continual improvement process.

Practitioners from CS1 did not miss any function in the tool. In fact, practitioners reported that they did not use voice annotations because they felt that it did not add value to his work. However, they felt that if the speech recognition were to be implemented in the tool, it would be very interesting because adding textual annotations would be easier. In fact, the inspection support using speech recognition is not new. Sunkpho et al. (2000) evaluated the possibility of integrating speech recognition into field inspection support systems.

Practitioners reported that sometimes they did not write textual annotations because they were wearing gloves. To solve this problem they proposed two solutions: to implement the speech recognition function to allow practitioners to add more and larger textual comments improving the usefulness of the tool; or to implement the function of adding information on the CRTI-web (server part).

As well, practitioners from CS1 reported that they would appreciate using photos as support when discussing with a subcontractor about problems. In this case they would prefer talking than writing. In general, they estimated that on 70% of the occasions they preferred to talk about the incidences occurred in the construction site by telephone or face to face.

The CS1 results reported extra uses of Mobuild application such as taking photos to ask for technical service information about new equipment implemented in the houses, to remember how an element that will be hidden was built, or just to show that one work is finished… These results suggest that MoBuild has more uses than tracking defects. CS4 and CS5 supported this hypothesis, because the companies asked to introduce not only defect tags, they propose to implement different families of tags to track other information on-site. For example, in CS4, company proposed to add tags to track the construction process, and CS5, proposed to track environmental and health and safety incidences. Further research is required in order to establish potential uses and to propose new experiments to validate it.

The results of CS3 suggest an improvement in the productivity in the defects management. Practitioners spend more time in the construction site to capture the information. On the other hand, the time spent writing the report was reduced, and the amount of time spent to collect data and write the reports is smaller than with the current method. Practitioners reported that they lose a lot of time introducing all the tags. To reduce the recording time practitioners propose to be able to

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pre-establish some initial tags related with apartment identification (eg. Building, floor, dwelling...) and then take all the photos of the defects.

CRTI-web was not in the scope of the validation; however, practitioners reported some interesting points. Practitioners from CS1 and CS2 suggested adding functions to CRTI-web. Practitioner from CS1 suggested improving the information display, adding filters to search for pictures more easily. Practitioner from CS2 suggested implementing a function to attach or modify information in the web page. These suggestions will be taking into account in the further research to improve the CRTI-web.

Table 12 summarize the accomplishment of the initial requirements identified in section 4.4 (Methodology to track defects) and identifies the new requirements derived from the validation. A new prototype would have to be developed and validated. The process would have to be repeated until the IT tool requirements will meet the needs of users.

Table 12. Functional requirements identified for an IT tool to track defects in the construction sector

Iteration	Requirement	Description	MoBuild v0.2
Initial requirements	1	The IT tool shall capture multimedia data (video and picture)	✓ (Except video)
	2	The tracked multimedia data shall have the quality enough to communicate the identified construction defect	✓
	3	The IT tool, besides to capture multimode, shall capture additional data such as textual notes and graphical annotations	✓
	4	The tracked information on-site shall be exported to a data base/excel	✓
Requirements from the first design evaluation	5	Speech recognition	×
	6	Be able to modify tracked information in the server part	×
	7	Be able to add information in the server part	×
	8	Cloud computing synchronisation	×

4.7 Conclusions

In this chapter the results of a survey about defect recording and management processes are presented.

Although available technology and commercial tools allow practitioners to improve the efficiency of defect recording and management process, the results show that AEC practitioners are still using traditional methods based on paper and pictures.

Practitioners noted the need to develop more flexible tools which would implement all the required functions in one single environment.

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This chapter presents a new approach on defect recording and managing. The approach proposes that pictures must be the basis of the system and other information can be added such as tags, voice annotations, graphical annotations and textual annotations. In comparison, the traditional method is based on textual comments and then other information is added to it, such as pictures, drawings etc.

The validation results suggest that the proposed approach could reduce the time of the defect recording process and managing process. In addition this approach can be used in other supervision tasks such as tracking the onsite work performance.

The new approach implemented in the MoBuild application can be used to implement ISO 9000 in construction sites, helping to track and manage the large number of data generated.

The validation process reported that MoBuild v0.2 could be used to track different on-site construction information. The surveys and experiments reported that practitioners are using pictures to communicate on-site information. It is possible to conclude that construction practitioners are in need of tools that would allow them to effectively manage the pictures taken on site, and share them with other practitioners if required.

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Chapter 5

Development of a methodology to identify quality risks for residential buildings during preconstruction

5.1 Introduction

This chapter presents the work undertaken to meet objective 4 and objective 5 stated in Chapter 1 of this dissertation. This chapter presents a quantitative methodology to forecast potential quality risks in new residential buildings at the pre-construction stage where only design information is available. The proposed methodology provides a quality risk incidence index (QRI), which is based on a risk register and calculated using the frequency and consequences of each risk in the different construction activities. It serves as a decision making tool to compare different construction typologies. In addition, the methodology quantifies the quality risk incidence using a family risk incidence index (FRI).

To illustrate the practical use of the proposed methodology, a case study comparing different construction alternatives is presented.

5.2 Research methodology

This chapter is divided in two parts. In the first one, the definition and development of a methodology to predict quality risks for residential buildings during preconstruction is presented. Secondly, a case study is presented to illustrate the practical use of the proposed methodology. The following figure presents the research methodology used in this chapter:

	Methodology definition and development		**Case study**
Method	Development of a risk register	Determination of QRI and FRI	Assessment of different construction activities
Aim	- Identify the quality risks that can apperar during the construction, assessing the impact and the probability of occurrence for each risk in every construction activity	- To evaluate the quality risks and determine which construction activities are more critical in terms of quality risks - To identify which quality risks can be produced to take actions to mitigate it.	- To illustrate the practical use of the proposed methodology

Figure 9. Research methodology to define and develop a methodology to indentify quality risks

Definition and development of the methodology

To identify the quality risks related to the construction of residential buildings, the following methodology is proposed:

- Development of a risk register
    - Construction activities initially considered
    - Inventory of quality risks
    - Identification of quality risks related to the construction activities
- Evaluation of quality risks
    - Quality risk index (QRI) for each trade
    - Family risk index (FRI) for each family of quality risks

Case study

To illustrate the practical use of the proposed methodology, a case is presented. The methodology allows for the simulation of the dangerousness of each construction activity by use of the QRIj indexes and can determine which kind of quality problems may appear by using the FRIj index. A newly built residential building was chosen in order to analyse and compare the quality risks of four different construction methods using the proposed methodology.

The newly built residential building is an isolated multi-family dwelling with six floors and two underground car parks. The building's floor area is 7,198.42 m2 and it contains 31 dwellings. The north facade has windows on all floors, the south facade has windows on the first floor and balconies on the rest of the floors, and the east and west facades have windows on the first floor and balconies and windows on the rest of the floors.

The different scenarios studied using the methodology are:

- residential building built with the typical construction materials used 15 years ago in Spain (concrete structure, continuous foundations, inverted roof, brick facades, internal partitions made with masonry and terrazzo floor);
- residential building built with the materials and technologies being used nowadays (plasterboard in the internal walls, while the rest of the building remains the same as the first scenario);
- residential building built with structural precast solutions (concrete precast solutions in the structure and the rest remains the same as the second scenario);
- residential building built using facade precast solutions (concrete precast solutions in the structure and facades, the rest remains the same as the second scenario).

The characteristics, construction trades, and activities for each option were obtained from the Spanish study on residential building typologies in Spain (Instituto Valenciano de la Edificación 2011).

The QRI and the FRI was determined for each scenario.

5.3 Development of a risk register

Conventionally, a risk register is "a repository of a corpus of knowledge" and "initiates the analysis and plans that flow from it" (Williams 1994). In most cases, a risk register contains relevant information of a risk, including the description of the risk, its impact, its probability of occurrence, owner of the risk, reduction, and mitigation plan (Allan and Yin 2011).

In this chapter the risk register will contain the description of the quality risk, the type of quality risk, the construction activities where this quality risk can appear, its impact, and its probability of occurrence. For this reason, the first step of the methodology is to identify the construction quality risks. To do this, an exhaustive preliminary analysis with a process-oriented approach (Zobel and

Buman 2004) is carried out. A process-oriented approach consists of dividing the work packages or activities into subprocesses or subactivities and assessing their potential risks (Gangolells et. al 2009). As a consequence, inventories of construction activities and subactivities, as well as common quality risks, are required (Figure 10). The establishment of a significance rating is needed to decide which are the significant risks in each construction work package.

5.3.1 Construction activities considered

The first step in a process-oriented approach is to identify the main activities. The main construction activities considered were: (1) earthworks, (2) foundations, (3) structures, (4) roofs, (5) partitions and closures, (6) impermeable membranes, (7) insulations, (8) coatings, (9) pavements, and (10) door and window closures. Each of these main activities was separated into smaller activities steps or subactivities. A total of 219 subactivites were ultimately considered in this initial quality review.

5.3.2 Inventory of quality risks

The second step is to identify all the potential quality risks. In this step, a list of potential quality risks is needed. One of the main quality indicators used by the construction industry has traditionally been the number of technical defects or claims made against the warranty of the quality of a new house (Auchterlounie 2009). Therefore, a list of potential defects will be used as a list of quality risks.

The list of potential defects used in this Chapter is the list proposed in Chapter 3: (1) Affected functionality, (2) Inappropriate installation, (3) Biological action and change, (4) Broken/Deteriorated, (5) Chemical action and change, (6) Detachment, (7) Soiled, (8) Flatness and levelness, (9) Misaligned, (10) Missing, (11) Stability / Movement, (12) Surface appearance, (13) Water problems, (15) Tolerance errors, (16) others.

5.3.3 Identification of quality risks related to the construction activities

The identification step of quality risks evaluates those parameters related to each construction activity (for example execution of concrete structure or execution of wood door and window closures) without taking into account the particularities of each site (such as management activities or worker skills).

The Project Management Institute Standards Committee (PMI 2012) defines risk as an uncertain event or condition that, if occurs, has a positive or negative effect on at least one project objective, such as time, cost or quality. PMI 2012 proposes to evaluate the probability of each risk and its consequence on project objectives. Generally, authors in the reviewed literature use these parameters to assess risks, parameters which are measured with traditional qualitative or quantitative methods (Allan and Yin 2011).

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ISO 9001:2008 does not propose any parameter to predict construction defects. For this reason, the generic parameters, probability of occurrence and severity of risk impact, were used. These criteria are independent of the organisational aspects, management of construction trades, etc.; hence they can be used in this early stage to determine significant quality risks for each construction process (Gangolells et. al 2010) (Figure 10).

Although the best way to quantify risks and their components is by using available statistical information (Hubbard and Evans 2010), when such data is not available, questionnaire surveys are a useful alternative. Data pertaining to defects are either difficult to obtain or do not exist (Georgiou 2010, Yung and Yip 2010). For this reason, a panel of experts is used to identify construction defects using ordinal scales.

To diminish the subjective intrusion during the evaluation of the different parameters during the identification of the quality risks, a four-interval scale agreed upon by the panel of experts at the first meeting was developed for each of the two evaluated parameters.

The probability refers to the frequency of the event that causes the quality incidence. This component was ranged from low probability (rare) to relatively high probability (likely or frequent). The consequences of the quality incidence were scaled taking into account the cost of the repair. In this case, the consequences of a quality incidence were described quantitatively in relation to the repair cost.

In order to calculate the overall significance rating of a quality incidence in a specific construction stage, the four grade scales for the two components of significance are converted into numerical scales (Figure 10).

The overall significance rating of a quality incidence in a particular construction stage was obtained using the following expression:

$$SG_{ij} = P_{ij} \cdot C_{ij}$$

Equation 1. Overall significance rating of a quality incidence in a particular construction stage

where SGij denotes the overall significance rating of a quality incidence i in a specific construction stage j. Pij denotes the probability of occurrence of the incidence, assumed to be 0 (improbable), 1 (not very likely), 2 (likely) or 3 (very likely) and; Sij corresponds to the severity of consequences of the incidence, ranging from 0 (0-100 euros), 1 (100-500 euros), 2 (500-3000 euros) to 3 (more than 3000 euros).

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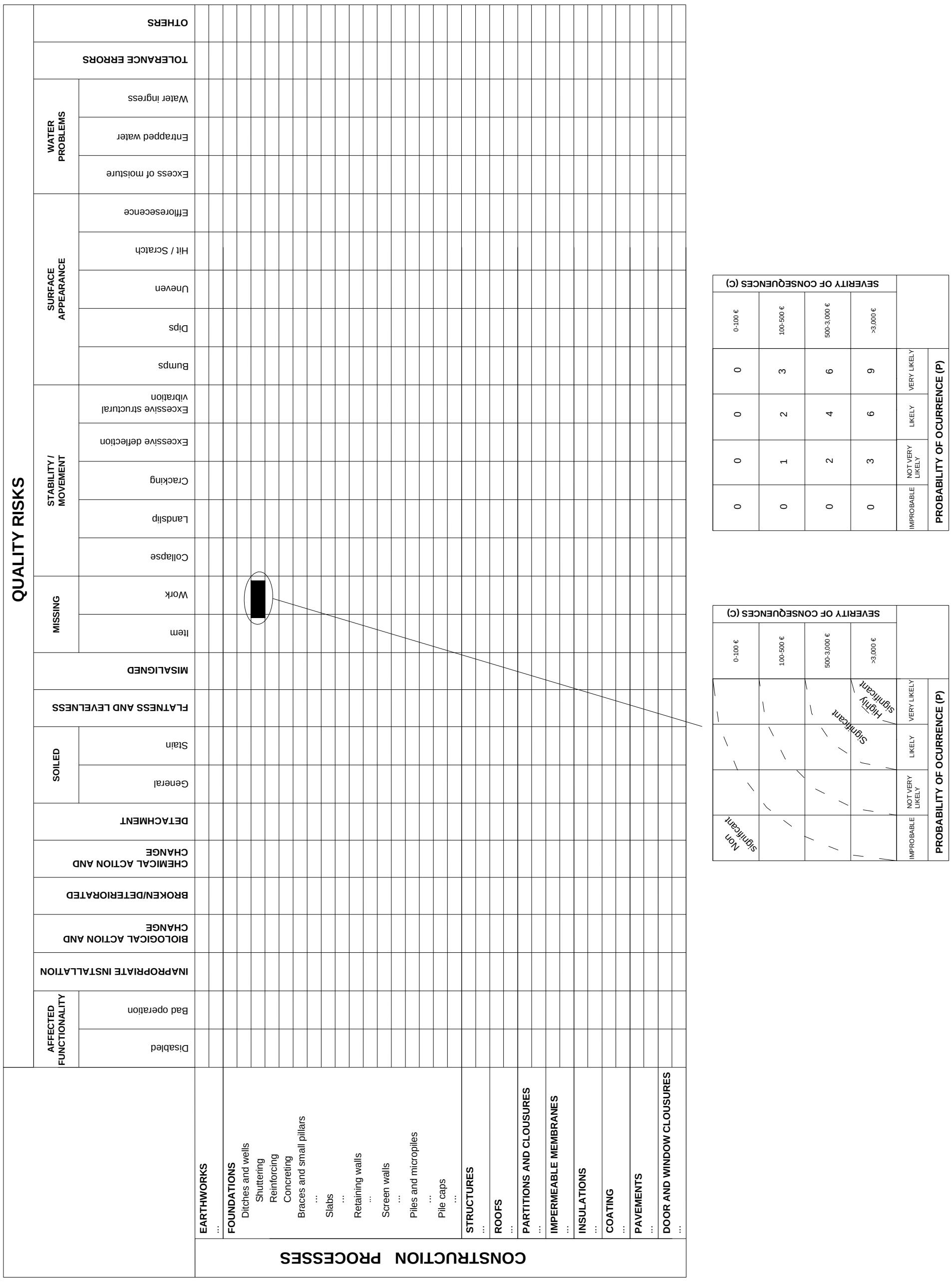

Figure 10. Quality risks identification in a process-oriented using numeric scales for the overall components: probability (P) and severity of conscequences (C). Source: Partially adapted from Gangolells 2010

In this initial identification of quality risks, a quality incidence for a specific construction activity was considered significant if its overall significance rating was higher than 3. Therefore, it makes

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possible to distinguish potential quality risks for each construction activity. In order to make future assessments controllable and effective, many construction risks were aggregated. For example, a unique quality risk was created for all activities that can be the object of missing pieces due to a lack of provisioning such as discontinuous pavements, or discontinuous coatings.

The panel of experts was asked to evaluate each construction defect for each construction stage using the proposed parameters and scales, and determine the potential quality risks. Selection of panellists adhered to the guidelines recommended by Delbecq et al. (1975), Rogers and Lopez (2002), and Gambatese et al. (2008). The consultation panel was composed of 2 architects with more than 10 years of experience as building designers; 2 quality inspectors with more than 5 years of experience in new residential buildings inspections; 3 contractors with more than 15 years of experience in building new residential buildings; and 2 projects managers with more than 10 years of experience in new developments. Finally, two professors specialized in construction quality from the Technical University of Catalonia were invited to participate too.

Different meetings were carried out in order to fill out the survey, whose function was to facilitate data collection. It was represented as a matrix; whose columns were general quality risks, and whose rows were construction activities and subactivities.

As a result of the identification process, a risk register was created. In this case, the resulting risk register indicates the potential quality risks for each construction activity and its impact and probability of occurrence. 148 significant quality risks for construction activities were obtained in 15 different categories. Table 13 and Table 14 display a partial list of these specific construction risks.

Table 13. Specific quality risks for flatness and levelness category

FL-1	Flatness and levelness in on-site preparation and earthworks
FL-2	Flatness in the upper surface of ditches and wells and slab foundations or in the lateral side of retaining walls
FL-3	Inaccurate flatness in interior and exterior vertical closures
FL-4	Inaccurate flatness or levelness in continuous pavements and terrace roofs
FL-5	Inaccurate flatness or levelness in discontinuous pavements and terrace roofs
FL-6	Inaccurate flatness or levelness in metallic auxiliary structures
FL-7	Incorrect levelness of flat roof support
FL-8	Loss of flatness in synthetic pavements and skirting boards
FL-9	Inaccurate flatness or levelness after polishing or tapering pavements

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Table 14. Specific quality risks for general and stain subcategories

General	
DG-1	General dirty production such as wrappers or workers' waste
DG-2	Dust generation in activities involving construction machinery or transport, earthworks and stockpiles
DG-3	General dirt on screen walls due to embedded earth
DG-4	General dirt on elements to be used such as steel reinforcement bars, ceramic elements or tiles, which make adhesion to the corresponding element difficult
DG-5	General dirt on the underneath layers which makes adhesion of the subsequent layers or pieces difficult
DG-6	Dust generation in activities which involve cutting
DG-7	General dirt due to grout and joints execution
DG-8	Dust generation in activities which involve polishing
DG-9	Operations that cause dirtiness at the construction site entrances
Stain	
DS-1	Stains due to fragments or particles in concreting operations
DS-2	Rust staining on concrete elements
DS-3	Staining on brickwork
DS-4	Stains due to operations involving the use of mortar, bonding mortar, plaster or grout.
DS-5	Stains due to operations involving elastomeric pastes and amorphous products such as operations of waterproofing and insulation with amorphous products
DS-6	Stains due to fragments or particles in painting operations carried out with gun
DS-7	Stains due to operations involving the use of glue or other kind of adhesive elements such as discontinuous coatings adhesion
DS-8	Stains of paint and varnish as a result of painting elements with paint roller or paintbrush
DS-9	Stains in finished pavements due to the movement of machinery and cars

5.4 Evaluation of quality risks

In order to calculate the quality risk index (QRI) for each construction trade the following expression was used:

$$QRI_j = \sum_{i=0}^{m} SG3_i$$

Equation 2. Quality risk index (QRI) for each construction trade

where QRIj denotes the overall significance rating of all quality incidences in a specific construction stage j, SG3i denotes the overall significance rating of a quality incidence in a specific construction stage j with a value bigger than 3, and m is the number of families of defects.

In order to determinate which family of risks has the greatest impact during the construction of the residential buildings the following formula was used:

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$$FRI_i = \sum_{i=0}^{n} SG3_j$$

Equation 3. Family risk impact (FRI) for each type of defect

where FRIi denotes the overall significance rating of all construction stages in a specific quality risk i, SG3i denotes the overall significance rating of a quality risk in a specific construction stage j with a value bigger than 3, and n is the number of families of quality risks.

5.5 Case study results and discussion

The results of the simulations are presented in Figure 11 and Figure 12. Figure 11 shows the QRI value for each group of activities for the different options and, Figure 12 shows the FRI values for each type of defect for the different options.

The results show that design decisions are important drivers of building quality as reported by (Chong 2006). For example the use of plasterboards (scenario 2: global QRI 1420) in front of masonry (scenario 1: global QRI 1550) to build the internal residential building partitions helps reduce the QRI 8.39% because plasterboard is a precast solution that involves less construction activities.

The principal benefit of using plasterboard is that it avoids the plastering activities associated with masonry walls prior to paint. Plastering is one of the most soiled activities. This fact is shown in fig (2) where the FRI for the soiled defect category is reduced. In addition, the humidity in the construction site is reduced because plasterboard is a dry-wall. All problems derived from the use of water in the construction site are reduced. On the other hand, the risk related to the affected functionality category increases because plasterboard cannot fulfil the requirements in terms of acoustic insulation or supporting the weight of hanging. In addition, the risk related to tolerance errors increases because plasterboard is not as flexible as masonry walls, and potential tolerance errors can be solved easily with the second one. Using plasterboards in the partitions reduces the QRI index in the partition and coating activities: QRI index from 54 to 36 for partitions, and from 299 to 187 for coatings.

Currently, in the Spanish residential building sector (scenario 2), the most dangerous activity in terms of quality is structure (QRI 258). One way to avoid this problem is to use precast solutions in the structure activities (scenario 3).

Precast solutions are not used in the Spanish residential building industry (Montes 2011). However, in other types of buildings such as schools in recent years, the prefabricated solutions have become very frequent making it possible to reduce the construction time and costs (Pons

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2010). Two different approaches have been analysed: the use of precast solutions in the structure and the use of precast solutions in the structures and the facade.

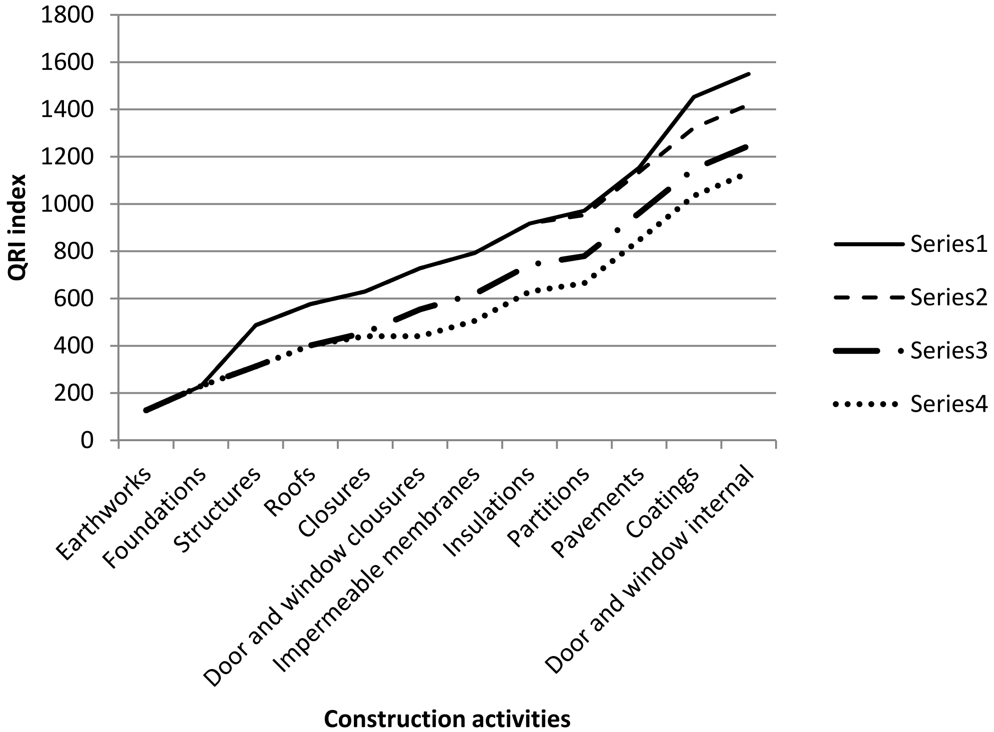

Figure 11. QRI index results for the cases of study

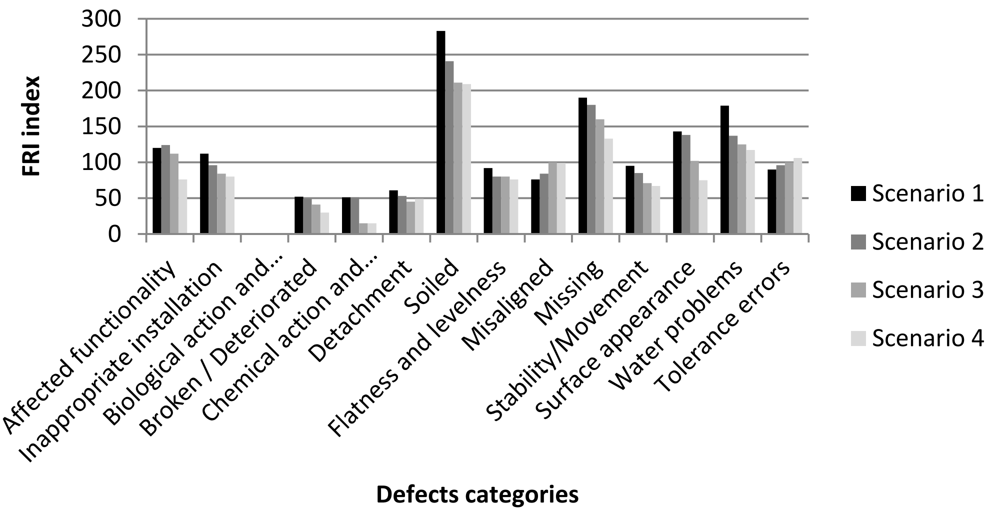

Figure 12. FRI index results for the cases of study

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The use of precast solutions in the structure and use of plasterboard in the internal partitions (scenario 3: QRI 1420) reduces the QRI value 19.61% when compared to scenario 1. The reduction of the quality risk in structure activities decreases from 258 to 84 because the number of construction activities is reduced. The activities related to the formworks, reinforcement, and curing are eliminated. In this way, problems related to the concrete construction process, such as wrong size of reinforcement bars or location of the bars, are eliminated. The FRI index for the inappropriate installation is reduced from 96 to 84 and for missing from 180 to 160. In addition, other kinds of quality problems are reduced. This includes soils in the construction site, where FRI index is reduced from 241 to 211; and the FRI index of the surface appearance defect, which is reduced from 138 to 102. However, not all quality risks are reduced. For example, misalignment quality risk increases from 84 to 100; and tolerance error quality risk increases from 96 to 100. The reason for this increment is that this methodology not only takes into account the frequency of the defects appearance but also its repair cost. The probability of occurrence and the severity of consequences sometimes can be cross-referenced. For example, in the precast solutions problems related to this layout would be difficult to solve. However, the frequency of such layout is low.

The use of precast solutions in the structure and the facade, and the use of plasterboard in the internal partitions (scenario 4: QRI 1132), reduce the QRI value 26.97% when compared to scenario 1. The use of precast facades produces a significant reduction of quality risks if windows are embedded in the precast facades. If not, the reduction of the QRI index is only 20.65%, not too far from scenario 3. The FRI index is reduced for all the construction defect's categories except for the tolerance errors, which increase slightly.

In conclusion, the use of precast solutions reduces the number of activities at the construction site; thus reducing the quality risks related to all categories, except for the misalignment and tolerance errors categories.

The use of the precast solutions implies other benefits at the construction site. This includes, for example: a reduction of the execution time, reduction in costs, reduction of the onsite environmental impacts, and reduction of the health and safety risks.

5.6 Conclusions

Design decisions are important drivers of building quality. However, both designers and contractors would benefit from the knowledge and information about the potential defects of their designs. That would help them choose the optimal design, develop effective quality plans and inspections, choose the proper project organization or determine which skills are needed by the workers; and to establish measures to mitigate quality risks. In this chapter, a quantitative methodology is proposed for dealing with potential adverse quality risks during the preconstruction stage of residential buildings. The strength of this methodology lies in the fact that it will help practitioners to explicitly consider quality risks during the preconstruction stage.

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Designers will be able to compare several construction alternatives during the design phase and determine the corresponding overall quality risk level of a construction project without restriction of their creative talents. The aim of this methodology is to help designers develop optimal designs while taking into account the potential quality risks.

The methodology can also be useful for project managers or construction companies in measuring the quality risks of construction projects, in detecting which project is likely to have more quality risks, and in determining which tasks are most problematic. With that information, project managers and contractors will be able to develop realistic schedules and implement measures to mitigate the quality risks, making the optimization of on-site practices possible. As demonstrated by Hegazy et. al (2011), incorporating rework term into construction schedule analysis could help practitioners optimize the corrective action.

This methodology could also be implemented in a 4D model as a visualisation method of quality risks when planning the execution phase. However, the current data visualization method has to be improved, because visualizing information in a matrix is not very operative. In future research, depending on the necessities of the user (contractor, designer, client, etc.), different visualization options to implement this methodology will be studied.

Currently, the methodology only takes into account the technological quality risks. In the future, the incorporation of human and organizational parameters will also be studied to simulate which defects will appear due to the project's organization. In addition, the possibility of adding different parameters to compare projects with different volume of works and construction activities will be analysed. In this way, construction companies will be able to optimize the resources during the construction of different buildings that are being built simultaneously.

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Chapter 6

Using statistical methods to analyse defects

6.1 Introduction

This chapter is aimed at meeting objective 6 and objective 7 stated in Chapter 1 of this dissertation. This chapter presents an analysis of the defects detected by the final users in residential buildings, in order to propose preventive measures for future projects. The study focuses on the analysis of 2,531 post-handover defects from seven building developments containing 95 dwellings. The chapter answers 4 general questions: i) “which” defects arise during the handover stage; ii) “where” are those defects located; iii) “why” are those defects produced and; iiii) “how many” defects arise during the handover stage. The influence of building type on post-handover defects is also discussed during the analysis. Finally, different strategies to reduce post-handover defects are discussed.

6.2 Research methodology

This chapter aims to analyse the quality observed by end-users in the post-handover stage and to determine whether a significant difference exists between the two main residential building types built by developers, flats, and detached houses. It also aims to identify the influence of different building parameters on the number of defects detected in each building type, and to determine the most common building elements and areas where housing defects are found in the post-handover stage.

The first step was to define the data classification. For this purpose, the conceptual model described in Chapter 2 was used. In addition, building characteristics are included in the data model including: building type, gross floor area of the dwelling, construction cost, number of floors in the building and number of dwellings per development, distance from the contractor's headquarters to the site, and number of rooms per dwelling (Figure 13).

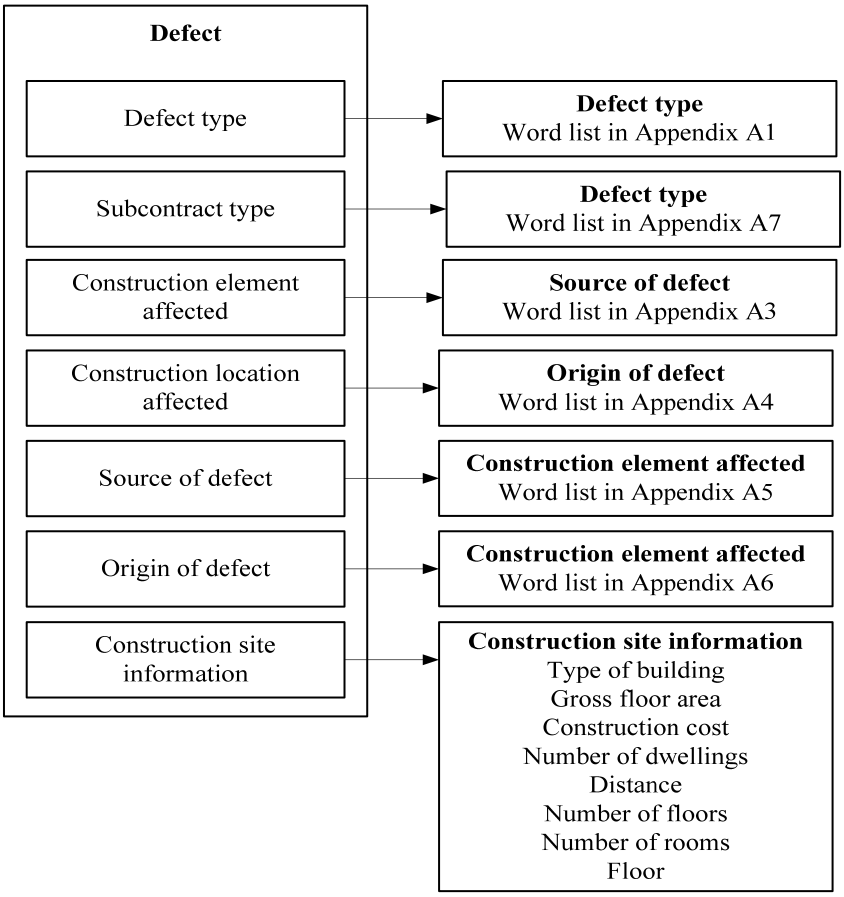

Figure 13. Data structure

The second step was to collect, analyse, and evaluate data from client complaint forms completed following the handover of 95 dwellings provided by several Spanish contractors. The information recorded on these forms was then classified using the structure defined above.

Data on defects was only collected on new flats and detached houses (both common building types in Spain) to ensure that the data was representative of the defects typically found in the country.

The data collected was analysed following the structure defined in Figure 14. The analysis was performed in order to answer the following specific questions:

Q1. Which defects are detected?

Q2. Which elements are affected by defects?

Q3. Does any correlation exist between defect and the element in which the / where the defect is detected?

Q4. Which areas are affected by defects?

Q5. Does any correlation exist between the defect and the area where the defect is detected?

Q6. Which subcontract trade produces more defects?

Q7. Does any correlation exist between the defect and the subcontract trade?

Q8. Which are the sources of defects?

Q9. Does any correlation exist between defect and the source of defect?

Q10. Which are the origins of defects?

Q11. Does any correlation exist between defect and the origin of defect?

Q12. Does any difference exist between the number of defects detected in detached houses and in flats?

Q13. Does any correlation exist between the number of defects and the different construction site information (type of building, gross floor area, construction cost, number of dwellings, distance, number of floors, number of rooms, and floors)?

The statistical analysis was done using Minitab (version 16) and the Statistical Package for the Social Sciences (SPSS) for Windows (version 17.00). SPSS was used to carry out a Chi-square test (χ^2) test. This test was later used to determine the relationship between the type of defect that was identified with the building element, location, subcontract trade, source and origin. In addition, a Pearson's parametric correlation was computed to test the association between variables. This approach made it possible to identify those variables with significant correlations at the 95% and 99% confidence intervals.

Minitab was used to determine the distribution type of the construction defects for each building type by performing the Anderson-Darling test, as well as to determine the normal probability plot correlation coefficient (r). The correlation coefficient (r) was compared with the critical values proposed by Filliben (1975). Minitab was also used to determine the mean, standard deviation, standard error mean, and confidence interval at 95%.

Finally, SPSS was used to identify where any differences between samples might lie by means of a t test. In addition, to test variables' associations with the different characteristics of each building type, the Pearson's parametric correlation was computed. This approach made it possible to identify those variables with significant correlations at the 95 and 99% confidence intervals.

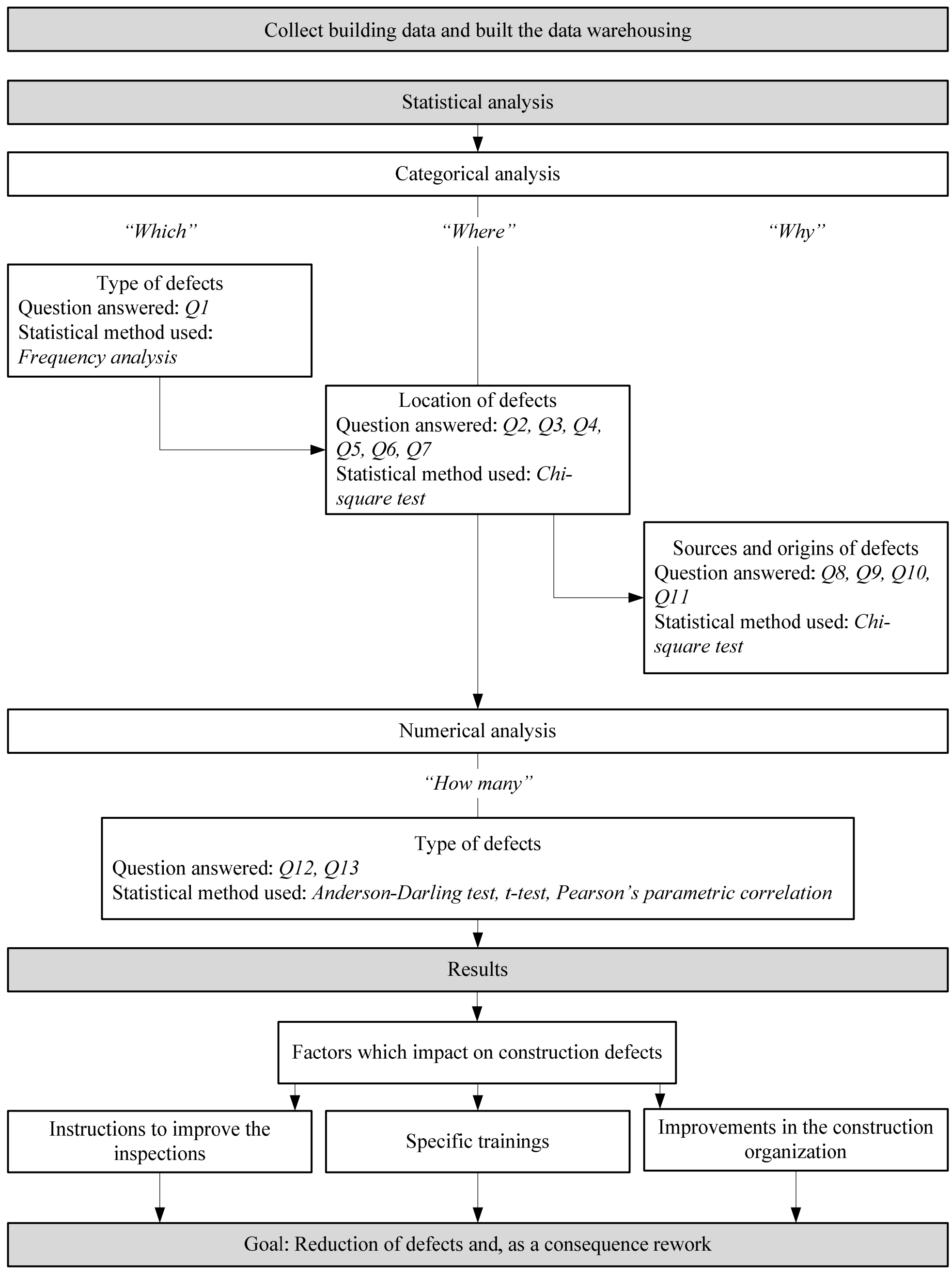

Figure 14. Structure of the post-handover statistical analysis

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6.3 Data collection

Similar to Georgiou et al. (1999) and Mills et al. (2009), data was collected from client complaint forms from four Spanish builders' databases. These databases contained information regarding the buildings and defect characteristics. Seven developments were randomly selected. The amount of dwellings within each of the previously mentioned developments ranged from 24 to 146. The building developments were constructed between 2004 and 2006. The size of the dwellings within each building development ranged from 75 to 130 m2, and from two to eight stories. Table 15 identifies the analysed developments ‘ primary characteristics. These buildings are deemed to be representative of residential construction in Spain as identified by the Instituto Nacional de Estadítica, or National Statistics Institute (INE 2011). This institute specifically analyses economic and social trends in Spain; in several areas, such as construction.

From those seven developments selected, 95 complaint forms where randomly chosen and analysed (each complaint form corresponding to one dwelling): 46 were detached houses and; 49 were flats (Table 16). A total of 2,351 defects were identified and analysed.

Table 15. Building characteristics (Post-handover analysis)

Development	nº of dwellings	m2	nº floors	Building characteristics	Cost [€]	Year
Development 1	81	80	GF + 3	Ground floor with a small terrace, 1, 2, and top floor with balconies; concrete structure, continuous foundations, inverted roof, façade (light prefabricated concrete panels)	6,600,000	2004
Development 2	110	75	GF + 7	Ground floor: commercial area, 1 to 7 and top floor with balconies; concrete structure, continuous foundations, inverted roof, façade (brick and ventilated façade with ceramic boards)	11,800,000	2005
Development 3	30	150	GF + 1	Reticular framework, continuous foundations, flat traditional roof and sloped roof with sandwich panels, brick façade	3,095,009	2006
Development 4	146	90	GF + 4	Ground floor without terrace, 1 to 4 and top floor with small balconies; concrete structure, inverted roof, brick façade	10,403,520	2004
Development 5	30	130	GF + 1	Unidirectional framework, continuous foundations, sloped roof, façade (brick and stone slabs)	6,893,000	2004
Development 6	24	130	GF + 1	Unidirectional framework, continuous foundations, sloped roof, façade (brick and stone slabs)	4,969,636	2005
Development 7	112	85	GF + 6	Ground Floor: commercial area, 1 to 5 and top floor with balconies; concrete structure, isolated foundations, inverted roof, brick façade	9,836,800	2005
Total	533					

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Table 16. Building characteristics per type of building

Building type	No of dwellings	Avarage constuction cost	Avarage gross floor area	Avarage number of floors
Detached house	46	€1,320/m^2	137m^2	GF+1
Flat	49	€1,068/m^2	83m^2	GF+5

6.4 Type of defects

An analysis of the defect data revealed that the most common defects, as noted in Table 17, were: missing item or task (37.1%), surface/appearance (19.5%), and inappropriate installation (16.0%). Missing elements included items such as door handles, whereas missing tasks referred to the neglect of an activity such as painting and plastering. The surface/appearance defects that were identified were found to be attributable to poor finishing of the floor and wall surfaces.

Failure to clean and polish marble and concrete surfaces was also categorized as aesthetic defects. Surface/appearance defects included bumps, surface cracking, dips, stains, and hits. Such defects were likely to have arisen from workers dropping tools or placing heavy equipment on the floor, which caused chips and cracks to occur. Lack of adequate protection for completed work was also found to contribute to defects and often resulted in stains to the surface of floors. The incorrect installation or specification of items such as toilets, TV sockets, radiators, or general purpose outlets, or the wrong specification arose due to a lack of customer involvement during the formative stages of a project. Defects relating to the inappropriate installation of items were classified as technical defects and generally pertained to poor workmanship, material, or design of a building element. For example, floor unevenness (i.e., incorrect laying of tiles) arose due to guidelines not being used during the laying of tiles. However, most defects identified within the defect liability period (DLP) were minor in nature.

Table 17. Defects by Type of defect

Defect type	Number of defects	%
Excess of moisture	19	0.8
Surface appearance	458	19.5
Soiled	237	10.1
Misalignment	123	5.2
Detachment	81	3.4
Missing item or task	872	37.1
Affected functionality	97	4.1
Incorrect installation	376	16.0
Broken	88	3.7
Total	2,351	100.0

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6.5 Location of defects

6.5.1 Analysis of defects by affected element

Table 18 and Table 19 present the distribution of defects by construction elements. These tables show that doors and windows (25.0%), fixtures and fittings (e.g., missing or wrongly specified shower stand, screen, cap tap, inspection hatch cap, door handles, doorstops, grilles, or entry-phone) (18.5%), and interior walls (14.0%) were elements in which most defects arose. Table 20 presents the results of a x^2 analysis that sought to determine the independence of the defect type and the respective element. The analysis revealed that defect type and element were not independent ($p < 0.05$).

It was revealed that door defects were primarily attributable to surface problems as a result of staining, scratches, and bumps. Many functionality problems identified with doors were associated with their misalignment. In several instances, doors were found to scrape the floor or could not be opened properly because of faulty hinges.

Window defects were aesthetic and functional in nature and attributable to minor stains and scratches. Interior wall defects were also surface-related as a result of holes or chips in plasterboard, and in wet areas such as bathrooms, chipped and broken tiles were identified. In the case of functional defects in windows, these arose due to defective joints and incorrect hinges.

Table 18. Defects by Element

Element	**Number of defects**	**%**
Fixture and fittings	435	18.5
Doors and windows	338	14.4
Plumbing and sanitary system (P&B)	31	1.3
General	118	5.0
Mechanical and electrical system (M&E)	82	3.5
Furniture	161	6.8
Exterior works	199	8.5
Internal wall	329	14.0
Door	343	14.6
Ceiling	85	3.6
Floor	230	9.8
Total	2,351	100.0

Building items such as general-purpose outlets (GPOs), TV sockets, and grilles, were found to be significantly associated with incorrectly installed items (r =+0.907, n =533, $p < 0.01$ with two tails, r^2 =0.82). These building items were also found to be significantly associated with bathrooms (r =+0.978, n =533, $p < 0.01$ with two tails, r^2 =0.96) and kitchens (r =+0.919, n =533, $p < 0.01$ with two tails, r^2 =0.84), where the majority of fittings exist. However, building items were also found to be significantly associated with balconies (r =+0.965, n=533, $p < 0.01$ with two tails,

r^2=0.93). It is suggested that this finding could be due to incorrectly installed items such as rails and cornices or to areas where exterior sockets or grills deteriorate due to weathering.

Table 19. Construction element and type of defect

	Element											
Defect	**Item**	**Window**	**P&B**	**General**	**M&E**	**Furniture**	**External wall/rook**	**Internal wall**	**Door**	**Ceiling**	**Floor**	**Total**
Excess of moisture	3	0	5	1	1	1	0	3	0	2	3	19
Surface appearance	42	28	1	56	9	29	45	128	40	42	38	458
Soiled	52	18	3	24	1	9	54	26	19	9	22	237
Misalignment	6	33	0	0	2	11	1	2	67	0	1	123
Detachment	28	8	3	0	6	4	4	12	8	2	6	81
Missing item or task	209	140	11	31	39	70	67	78	97	23	107	872
Affected functionality	7	43	3	0	4	2	0	0	38	0	0	97
Incorrect installation	73	47	4	6	20	32	24	58	67	7	38	376
Broken	15	21	1	0	0	3	4	22	7	0	15	88
Total	435	338	31	118	82	161	199	329	343	85	230	2,351

Interior wall elements were positively correlated with surface appearance defects (r=+0.927, n =533, p < 0.01 with two tails, r^2 =0.86). This finding is similar to the research reported by Johnsson (2009), who revealed that cracks in walls were common at the post-handover stage and tended to occur above windows and doors. Furthermore, defects in interior wall elements were associated with the staining and cracking of tiles in bathrooms (r=+0.912, n=533, p < 0.01 with two tails, r^2=0.83) and kitchens (r=+0.936, n=533, p < 0.01 with two tails, r^2=0.88). Other types of elements adversely affected by defects found in kitchens (r=+0.941, n=533, p < 0.01 with two tails, r^2=0.88) and bathrooms (r=+0.930, n=533, p < 0.01 with two tails, r^2=0.86), and related to furniture that was installed (e.g., cupboards), although they tended to be minor in nature.

Table 20. Chi-square hypothesis test of independence between Element and defect

	Value	**df**	**Asymp. Sig (2-tailed)**
Pearson chi-square	910.81 a	80	0.00
Likelihood ratio	811.35	80	0.00
No. of valid cases	2351		

a. 28.3% had an expected count of <5. The minimum expected count was 0.25.

6.5.2 Analysis of defects by affected area

Table 21 and Table 22 present the distribution of defect locations within a dwelling. The primary areas where most defects were identified were the bedroom (21.7%), lounge (10.5%), and wet areas (bathroom, 16.8%, and kitchen, 15.0%). Table 22 presents the results of a χ^2 analysis that sought to determine the independence of the type of defect and its location of origin. Table 23 revealed that defect type and location were not independent ($p < 0.05$).

Table 22 indicates that many defects were detected in wet areas (bathrooms and kitchens). Although wet areas account for less than 10% of the GFA of a building, defects in these areas can result in significant rework costs (Chew 2005).

The findings identify that 72% of defects that arose from the seven developments were detected inside the dwelling. In the bedroom and lounge areas, defects were attributable to surface/appearance problems and included uneven walls, paint stains, wall or ceiling cracks, and the incorrect installation of tailor-made furniture. In bathroom areas, defects were stains and cracked tiles, unpainted ceilings, unconnected wastepipes, and shower supports. As mentioned previously, such defects are attributable to poor workmanship and a lack of protection during construction. External defects were primarily identified in terrace areas, and in the case of garages, defects were attributable to damp and excessive water penetration.

Table 21. Defects by area

Location	**Number of defects**	**%**
Balcony	164	7.0
Bathroom	395	16.8
Kitchen	352	15.0
Exterior	79	3.4
Garage	86	3.7
General	150	6.4
Bedroom	511	21.7
Hall/corridor	185	7.9
Lounge	250	10.6
Terrace	59	2.5
Common areas	120	5.1
Total	2,351	100.0

Missing element or task defects in bathroom and kitchen areas were found to be significantly correlated (r=+0.912, n=533, $p < 0.01$ with two tails, r^2=0.83). This was because both have similar finishing and installation types. Similarly, defects in bedrooms were correlated with hallways (r=+0.942, n=533, $p < 0.01$ with two tails, r^2=0.89) and lounge areas (r=+0.919, n=533, $p < 0.01$ two tails, r^2=0.84) because they also have similar fittings and finishings.

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Table 22. Area and type of defect

Defect	Element											
	Balcony	**Bathroom**	**Kitchen**	**Exterior**	**Garage**	**General**	**Bedroom**	**Hall/corrid or**	**Lounge**	**Terrace**	**Common areas**	**Total**
Excess of moisture	1	7	1	0	3	0	4	0	0	2	1	19
Surface appearance	16	51	60	7	14	35	134	54	56	6	25	458
Soiled	16	28	20	22	23	46	26	6	22	12	16	237
Misalignment	2	22	22	3	7	0	46	6	12	0	3	123
Detachment	2	24	9	3	0	4	20	5	9	1	4	81
Missing item or task	94	146	126	32	25	39	171	92	89	18	40	872
Affected functionality	3	17	17	0	2	3	28	8	14	00	5	97
Incorrect installation	25	83	83	9	10	21	64	12	39	12	18	376
Broken	5	17	14	3	2	2	18	2	9	8	8	88
Total	164	395	352	79	86	150	511	185	250	59	120	2,351

Table 23. Chi-square hypothesis test of independence between area and defect

	Value	**df**	**Asymp. Sig (2-tailed)**
Pearson chi-square	385.82 a	80	0.00
Likelihood ratio	369.57	80	0.00
No. of valid cases	2351		

a. 26.3% had an expected count of <5. The minimum expected count was 0.48.

6.5.3 Analysis of defects by subcontract trade

Table 24 and Table 25 identify the primary subcontract trades in which defects arose. Partitions, linings and closures, doors and windows (37.8%), coatings (23.6%), services (14.4%), and furniture and devices (10.2%) were identified as problematic areas. Table 26 presents the results of a x^2 analysis that sought to determine the independence of the type of defect and the respective subcontract trade. It was revealed that the defect type and subcontract trade were not independent ($p < 0.05$).

No defects were detected in the earthworks, foundations, or structural subcontracts. This may be due to the quality controls associated with the inspections that are implemented during construction by engineers and builders. If errors do arise, however, then they may arise as latent defects.

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Table 24. Defects by subcontractor type

Subcontract	Number of defects	%
Structure	24	1.0
Services	339	14.4
Maintenance	99	4.2
Furniture and devices	239	10.2
Partitions and linings	240	10.2
Pavement	205	8.7
Painting	555	23.6
Door and window closures	650	27.6
Total	2,351	100.0

Table 25. Subcontract and type of defect

Defect	Subcontract								
	Structure	**Services**	**Maintenance**	**Furniture and devices**	**Partitions and linings**	**Pavements**	**Painting**	**Door and window closures**	**Total**
Excess of moisture	1	7	1	0	3	0	4	0	19
Surface appearance	16	51	60	7	14	35	134	54	458
Soiled	16	28	20	22	23	46	26	6	237
Misalignment	2	22	22	3	7	0	46	6	123
Detachment	2	24	9	3	0	4	20	5	81
Missing item or task	94	146	126	32	25	39	171	92	872
Affected functionality	3	17	17	0	2	3	28	8	97
Incorrect installation	25	83	83	9	10	21	64	12	376
Broken	5	17	14	3	2	2	18	2	88
Total	164	395	352	79	86	150	511	185	2,351

Subcontract trades were significantly correlated with surface/ appearance defects (r=+0.914, n=533, $p < 0.01$ with two tails, r^2=0.83). The subcontract trades of plumbing and sanitary systems and mechanical and electrical systems were categorized as services, and defects that arose from them were found to be correlated with kitchen areas (r=+0.954, n=533, $p < 0.01$ with two tails, r^2=0.91). The subcontract trade of partitions and linings was also found to be correlated with kitchen areas (r=+0.913, n=533, $p < 0.01$ with two tails, r^2=0.83). The partitions and linings of a kitchen wall are primarily constructed using a stud frame and plasterboard lining, and finished with wall tiles. Unevenness between plastered board panels may have a negative impact on the quality of the tiling that is undertaken. The painting subcontract trade was found to be significantly correlated with surface appearance defects (r=+0.921, n=533, $p < 0.01$ with two tails, r^2=0.85), which incurred on internal walls (r=+0.975, n=533, $p < 0.01$ with two tails, r^2=0.95).

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Table 26. Chi-square hypothesis test of independence between Subcontract and defect

	Value	**df**	**Asymp. Sig (2-tailed)**
Pearson chi-square	1,501.88 a	56	0.00
Likelihood ratio	1,135.07	56	0.00
No. of valid cases	2351		

a. 23.6% had an expected count of <5. The minimum expected count was 0.19.

6.6 Sources and origins of defects

6.6.1 Analysis of defects by source

64.2% of the analysed defects are derived from bad workmanship, 19.1% due to materials and 15.5% from lack of protection. Only 27 defects (1.1 %) are derived from bad design (See Table 27). This data diverges from the results obtained from defects during the construction stage and also the latent stage. Work undertaken by the Building Research Establishment (1981) over a number of years in the UK indicated that 50% of defects found on construction projects could be attributed to design issues, 40% occurred during the construction phase (as a result of on-site practices), and 10% were due to product failure. In fact, the majority and most significant construction defects such as structural or water proofing defects are caused by poor design (Chong and Low 2005), but are mainly solved during the construction of the building. Lopez and Love (2011) estimated that the mean direct and indirect design error costs are 6.9% and 7.4% of a project's contract value respectively.

Those defects arising from bad design that are not solved during construction are not normally detected during the liability period (post-handover), but are manifested after some years of use. Chong and Low (2006) analysed various latent building defects and concluded that 60% of the defects were preventable with better design, and 33% with better workmanship. Moreover, during inspection of the building clients only notice/observe those appearance defects that are normally a result of bad workmanship. Since design defects manifest themselves much later than workmanship defects, it pays to have better design effort.

Table 27. Defects by source

	Number of defects	**Percentage %**
Design	27	1.1
Lack of protection	365	15.5
Workmanship	1,509	64.2
Materials	405	19.1
Total	2,351	100.0

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Table 28 presents the distribution of defects by source. It can be seen that 88.3% of the defects caused by lack of protection are surface appearance defects (28.2%) and soiling defects (60.1%). Although defects resulting from lack of preservation of finished parts of the building while other activities are being carried out usually become apparent during construction, occasionally they are not resolved and persist until the first occupancy. These defects are mainly stained tiles and door frames, paint staining as a result of poor protection of items such as radiators, and floor damage or broken tiles due to heavy loads from equipment or tools during fit out. Dirty boots of workers can also stain the floor whilst moisture is present (Chong and Low 2005).

Table 28. Contingency table between source and type of defect

Defect	**Source**				
	Design	**Lack of protection**	**Workmanship**	**Materials**	**Total**
Excess of moisture	3	0	14	2	19
Surface appearance	1	103	335	19	458
Soiled	0	222	15	0	237
Misalignment	0	0	123	0	123
Detachment	0	3	76	2	81
Missing item or task	14	3	485	370	872
Affected functionality	0	0	90	7	97
Incorrect installation	8	3	334	31	376
Broken	1	31	37	19	88
Total	27	365	1,509	450	2,351

The analysis reveals that the majority of the defects provoked by workmanship (76.4%) are missing item or task (32.1%), surface appearance defects (22.2%) and incorrect installation (22.1%). In fact, missing item or task defect was found to be significantly associated with workmanship (r = +0.990, n =533, p <0.01 two tails, r^2=0.98) and also with materials (r = +0.927, n =533, p <0.01 two tails, r^2 =0.86). A missing task relates to neglecting to undertake an activity such as painting, wall coating, plaster, tiling, etc. This defect is then mainly related to surface appearance defects. Missing item or task was found to be significantly associated with surface appearance defects (r = +0.821, n =533, p <0.01 two tails, r^2 =0.67). However a missing item includes items such as door handles or imperfect grout, which is mainly related to incorrect installation. However, both of them are classified as functional defects, which are the ones that customers invariably rely upon on to measure the quality of housing (Kang 2006).

Surface appearance defects were also found to be significantly associated with workmanship (r =+0.885, n =533, p <0.01 two tails, r^2 =0.78). Surface/appearance defects are mainly uneven or unsatisfactory finishing of the floor and wall surfaces and are mainly caused by poor workmanship. Most irregularities were caused by unevenness of the screed that received the tiles. These defects were also caused by workers not laying out the floor materials properly; not using proper guiding lines and rushing to finish the job. Failures to polish to shine the marble surface,

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and stains during construction from spillages were other examples of such defects with workmanship sources.

Materials are the main source of missing item or task (82.2%). Surprisingly, surface appearance defects are not caused by problems with materials. This incongruence may be because problems with materials were already detected during construction, or that problems such as rust do not appear just after hand over of the building but are detected after some years of use (Chong and Low 2005; Chong and Low 2006). These results also diverge from those obtained from the study of influencing factors of defects during occupation carried out by (Olubodun and Mole 1999). They concluded that the majority of defects derived from poor workmanship are rot, slab failure, dampness in solid floor, water ingress and damp proofing to walls which are mainly defects that do no appear during post-handover but after some years of occupation. Although detachment, affected functionality and misalignment are defects with less proportion of occurrence at post-handover, they are mainly derived from poor workmanship. 93.8% of detachment defects are related to poor workmanship, mainly because the worker did not fix correctly items such as tiles. 92.8 % of functionality defects are related to poor workmanship. This includes poor installations of ducts, or doors and windows that do not close correctly or scrapes on floor because tiles were not correctly placed. All misalignment defects are also related to poor workmanship.

93.7% of the soiled defects were derived from lack of protection. Soiled defects can be related to general dirtiness of the dwelling at handover, or stains provoked during construction as a result of poor protection. This is mainly caused by the constant rectifications needed during handover.

Although only 20 defects detected were derived from design, it is noticeable that those defects were mainly derived from missing items (50%), incorrect installation (28.6%) and excess moisture (10.7%). As missing items include missing elements and missing activities, some finishing elements were not included in the project, other activities such as floor polishing were also missed. Other design problems were derived from wrong bathroom fittings description and also from bad distribution of the windows, doors and furniture.

Another interesting finding was that workmanship and materials sources were both positively correlated (r =+0.888, n =533, p <0.01 two tails, r^2 =0.79). The majority of the defects provoked by materials are missing items. Sometimes it refers to materials that were not placed such as grilles, handrails, terrace drains, and doorstops but they can also be related to missing elements due to poor workmanship such as baseboards. As mentioned previously no single defect has one single source, at times both workmanship and materials sources are interrelated.

Table 29 presents the results of a x^2 analysis which sought to determine test the independence of the type of defect and the respective source. The analysis revealed defect type and source were not independent ($p < 0.05$).

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Table 29. Chi-square hypothesis test of independence between source and type of defect

	Value	df	Asymp. Sig (2-tailed)
Pearson chi-square	1,887.72 a	24	0.00
Likelihood ratio	1668,44	24	0.00
No. of valid cases	2351		

a. 9 cells (25.0%) had an expected count o f less than 5. The minimum expected count was 0.22.

6.6.2 Analysis of defects by origin

Regarding origin, Table 30 demonstrates that omissions (42.1%) and errors (39.8%) are the major factors that contribute to post-handover defects.

Post-handover omissions refer mainly to activities or parts of the building that are left, whereas construction omissions and errors refer to the result of erroneous construction methods or procedures mainly due to poor workmanship. Errors include both aesthetic defects that refer to the appearance of a building element, and technical defects that occur when the workmanship, material or design of a building element hinders its ability to function properly (Sommerville and McCosh 2006). Under the term damage, those defects caused by a subcontractor or inclement weather are included.

The analysis of this data shows that post-handover defects are mainly those minor defects that are not solved during construction, or appear as a result of attempts to resolve construction defects prior to handover, for example when a plumber fixes a water pipe and gets the wall soiled.

Table 30. Defects by origin

	Number of defects	Percentage %
Change	4	0.2
Damage	423	18.0
Error	935	39.8
Omission	989	42.1
Total	2,351	100.0

Table 31 presents the distribution of defects by origin. Taking into account that design defects are mainly resolved during the construction period or not visible until the operation stage, the majority of defects are related to errors and omissions both during construction or prior to handover, are also related to workmanship.

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Table 31. Contingency table between origin and type of defect

Defect	**Source**				
	Change	**Damage**	**Error**	**Omission**	**Total**
Excess of moisture	0	2	14	3	19
Surface appearance	0	146	241	71	458
Soiled	0	184	10	43	237
Misalignment	0	3	120	0	123
Detachment	0	9	66	6	81
Missing item or task	0	1	37	834	872
Affected functionality	0	1	94	2	97
Incorrect installation	4	3	339	30	376
Broken	0	74	14	0	88
Total	27	365	1,509	450	2,351

The analysis of the data shows that errors mainly provoke incorrect installation (36.3%), appearance defects (25.8%) and misalignments (12.8%). These defects are mainly considered minor defects. Surface appearance defects were found to be significantly associated with errors (r =+0.964, n =533, p <0.01 two tails, r^2 =0.93). Missing item or task defects were also found to be significantly associated with errors (r =+0.891, n =533, p <0.01 two tails, r^2 =0.93) and with omissions r =+0.995, n =533, p <0.01 two tails, r^2 =0.99). Both surface appearance and missing item or task are mainly provoked by poor workmanship. In fact workmanship cause was found to be significantly associated with error (r =+0.926, n =533, p <0.01 two tails, r^2 =0.88) and with omission (r =+0.973, n=533, p <0.01 two tails, r^2 =0.95).

Soiled defects were found to be significantly associated with damage (r =+0.961, n =533, p <0.01 two tails, r^2 =0.93). The majority of the damaged elements that are still visible during the posthandover are not related to functionality or stability, such as damaged structures, but to finishing (surface appearance, soiled and broken) such as plaster or painting stains that damage furniture, doors, windows or floor tiles. As identified previously, these type of defects are mainly caused by lack of protection during construction. In fact, lack of protection was found to be significantly associated with damage (r =+0.964, n =533, p <0.01 two tails, r^2 =0.93).

Finally both materials and omission origins were found to be significantly associated (r=+0.95, n =533, p <0.01 two tails, r^2 =0.90).

Table 32 presents the results of a x^2 analysis, which sought to determine the independence of the type of defect and the respective origin. The analysis revealed defect type and origin were not independent ($p < 0.05$).

Table 32. Chi-square hypothesis test of independence between origin and type of defect

	Value	df	Asymp. Sig (2-tailed)
Pearson chi-square	2,811.23 a	24	0.00
Likelihood ratio	2,856.49	24	0.00
No. of valid cases	2351		

a. 10 cells (27.8%) had an expected count of less than 5. The minimum expected count was 0.03.

6.7 Number of defects

6.7.1 Influence of building type in the number of defects

The Anderson-Darling test was used to determine the type of distribution for each building type.

The *p* value of this test for a normal distribution was not less than or equal to 0.05 for either building type (Table 33). Moreover, the normal probability plot correlation coefficient (*r*) was greater than the 5% critical value in both cases (0.9793 for detached houses and 0.9795 for flats). It can thus be assumed that the defects in both groups have a normal distribution with 95% confidence. Specifically, the number of defects detected in detached houses ranged from 18.68 to 23.32, and the number of defects detected in flats ranged from 23.51 to 33.10, with a 95% confidence interval (Figure 15).

Table 33. Andrerson-Darling test to compare the two samples (Flat versus Detached houses)

Building type	No.	Mean	Standard deviation	Standard error mean	Distribution	*p* value (Anderson -Darling test)	Normal probability plot correlation coefficient (*r*)	95% Confidence interval
Detached house	46	21.000	7.80313	1.15051	Normal	0.375	0.9793	18.68; 23.32
Flat	49	28.306	16.69232	2.38462	Normal	0.103	0.9795	23.51; 33.10

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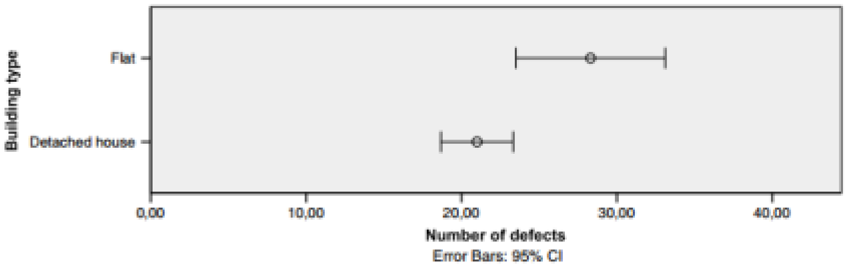

Figure 15. Confidence interval

To determine whether the number of defects varied between detached houses and flats, a *t* test was performed (Table 34).

Table 34. t-Test to compare the two samples (Flat versus Detached houses)

	Levene's test for equality of variances		T-test for equality of means					95% Confidence interval of difference	
	F	**sig**	**T**	**Df**	**Sig (2-tailed)**	**Mean difference**	**Standard error difference**	**Lower**	**Upper**
Equal variances assumed	30.963	0.000	-2.704	93	0.008	-7.30612	2.70241	-12.67256	-1.93968
Equal variances not assumed			-2.759	68.962	0.007	-7.30612	2.64765	-12.58810	-2.02

Levene's test for homogeneity of variances was violated for detached houses and flats ($p > 0.05$), indicating that the population variances for each group were different.

At the 95% confidence level, the number of defects varied significantly by residential building type. It was thus concluded that the number of defects varied significantly between the two samples and that detached houses and flats could not be reclassified into a single category.

6.7.2 Influence of building characteristics in the number of defects

To test whether there was a significant relationship between defects and different construction parameters (gross floor area of the dwelling, construction cost, number of dwellings per development, etc.), a Pearson's (r) correlation was computed. This analysis was used for both detached houses (Table 35) and flats (Table 36).

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Table 35. Correlation matrix for defects and characteristics of detached houses

	Number of defects	**Gross floor area**	**Construction cost**	**Number of dwellings**	**Distance**	**Number of floors**	**Number of rooms**
Defects	1	-	-				
Gross floor area	0.676[a]	1	-				
Construction cost	-0.659[a]	-0.973[a]	1				
Number of dwellings	0.409[a]	0.610[a]	-0.409	1			
Distance	-0.676[a]	-1.000	0.973[a]	-0.610	1		
Number of rooms	0.676[a]	-1.000[a]	-0.973[a]	0.610[a]	-1.000	1	
Number of floors	0.337[b]	0.492	-0.680[a]	-0.390[a]	-0.492	0.492[a]	1

[a]Correlation is significant at 0.01 level (two-tailed).

[b]Correlation is significant at 0.05 level (two-tailed).

Table 36. Correlation matrix for defects and characteristics of flats

	Number of defects	**Gross floor area**	**Constructi on cost**	**Number of dwellings**	**Distance**	**Number of rooms**	**Number of floors**	**Floor**
Defects	1	-	-					
Gross floor area	0.611[a]	1	-					
Constructio n cost	-0.601[a]	-0.920[a]	1					
Number of dwellings	0.526[a]	0.684[b]	-0.571[a]	1				
Distance	-0.328[a]	0.742[a]	-0.477	0.289[b]	1			
Number of rooms	-0.445[a]	0.498[a]	-0.769	0.471[a]	-0.193			
Number of floors	0.441[a]	-0.588	0.858[a]	-0.283[b]	-0.009	-0.936[a]	1	
Floor	-0.083	0.286[b]	-0.206	0.105	0.357[b]	0.030	-0.05	1

[a]Correlation is significant at 0.01 level (two-tailed).

[b]Correlation is significant at 0.05 level (two-tailed).

It should be noted that a positive Pearson's (r) correlation value indicates that when a variable increases, so does the related variable. In contrast, a negative Pearson's (r) correlation value indicates that when a variable increases, the related variable decreases. The r-value was used to calculate the r^2 value, which indicates the extent to which one variable can be predicted by changes in another (Love 2002).

According to the results (Table 35), the number of defects in detached houses was significantly associated with all other variables.

For detached houses, the correlation coefficients revealed that the number of defects was significantly associated with the gross floor area [r = + 0.676, n = 46, $p < 0.01$, two tails and $r^2 = 0.4570$ (45.70%)]. Specifically, the larger the gross floor area, the more defects were detected. Some 45.70% of the variance in defects can be attributed to changes in the gross floor area.

Similarly, the number of defects was also significantly associated with the distance between the contractor's headquarters and the site [r = - 0.676, n = 46, $p < 0.01$, two tails and $r^2 = 0.4570$ (45.70%)]. In this case, too, the longer the distance from the contractor's headquarters to the site, the fewer the defects. Although this is a surprising finding, a detailed examination of the project data revealed that buildings built near the contractor's headquarters were built by the firm's own employees, whereas the work was subcontracted for buildings built far from a contractor's headquarters. As Atkinson (2002) has concluded, there is a strong correlation between defects and management practice. Although the coordination of a large number of subcontractors is a source of defects during the construction process (Karim et al. 2006), most of the defects due to poor subcontractor coordination are detected during the construction and handover stages, when a large number of quality controls are carried out. In general, the defective and incomplete work remaining in the post-handover stage is specialty work, such as painting, cleaning, or the installation of mechanical and electrical appliances, carried out by subcontractors that have already left the site when the quality controls take place.

In fact, the defects detected in each stage of a building's lifecycle [construction, handover, post-handover, and maintenance (Chong and Low 2005)] are different, just as the perception of quality and what constitutes defective work varies between the client, the developer, and the contractor (Georgiou et al. 1999).

The number of defects was also significantly associated with construction cost [$r = 0.659$, $n= 46$, $p < 0.01$, two tails and $r^2 = 0.4343$ (43.43%)]. As expected, the higher the construction cost, the fewer the defects detected. This is not entirely surprising, because it is also true that the higher the construction cost, the more quality inspections and controls are included in the construction process and the better quality the materials and finishes used, which results in a higher quality final product (Georgiou et al. 1999). However, cost is not always directly associated with quality or, more specifically, to the quality observed by clients. According to Georgiou et al. (1999), some building elements vary in quality, but not necessarily in terms of how they work. For example, the porosity and water absorption of floor tiles might affect a building's lifespan even though the tiles function satisfactorily. Indeed, clients may not even notice such latent defects upon entering the building because most building defects do not become visible until 2 years after occupancy (Chong and Low 2006).

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The number of defects was also significantly associated with the number of dwellings in the development [r = 0.409, n= 46, p < 0.01, two tails and r^2 = 0.1673 (16.73%)] and to the number of rooms [r = 0.337, n = 46, p < 0.05, two tails and r^2 = 0.1137 (11.33%)]. However, r^2 was low, indicating that only 16.73% of the variance in defects could be predicted by changes in the development. Likewise, only 11.37% of the variance in defects could be predicted by changes in the number of rooms.

For flats, the floor was also considered. For this building type, the correlation data revealed a significant relationship between the number of defects and all variables except the floor (Table 36).

The data showed that the number of defects was significantly associated with the number of floors in the building [r = 0.441, n = 49, p < 0:01, two tails and r^2 = 0.1945 (19.45%)]. In a flat development, many more dwellings are built with the same characteristics. (In this study, there was an average of 112 flats per development compared with 28 detached houses per development.) The taller the building, the more defects were detected. Although this is a surprising finding and it is often difficult to identify the causes, Atkinson (1999) noted that most defects are related to the people who carry out the construction. More specifically, lack of worker motivation is one of the main causes of building defects (Josephson and Hammarlund 1999). Given that work on flats is more repetitive than work on detached houses, workers might pay less attention to what they are doing out of boredom or carelessness. A detailed examination of the project data showed that flats were subject to a tighter schedule than detached houses and that work on them thus had to be rushed to meet the targets. The fact that workers were working under higher pressure led to more defects in the finished work. The implication of this is that the occurrence of defects cannot be treated in isolation and that any analysis of cause must treat the whole project as a system (Atkinson 1999).

The number of defects was also significantly associated with construction cost [r = 0.601, n = 49, p < 0.01, two tails and r^2 = 0.3612 (36.12%)]. As with detached houses, the higher the construction cost, the fewer the defects detected.

As with detached houses, here too the number of defects was significantly associated with the distance between the contractor's headquarters and the site [r = 0.328, n = 49, p < 0.05, two tails and r^2 = 01076 (10.76%)]. However, only 10.76% of the variance in defects could be predicted by changes in this distance.

The correlation analysis for flats did not show any significant relationship between the number of defects and the dwellings' floor areas. In fact, in contrast to detached houses, the larger the gross floor area of a flat, the fewer the defects detected. This is related to the types of defects clients detect. In flats, many defects are detected in general areas such as the entrance hall, façade, etc. Thus, they do not depend on the dwelling's gross floor area. Moreover, the analysis does not consider the magnitude of the defects. For example, a levelness defect caused by shoddy workmanship is counted as a single defect regardless of the magnitude of the affected element.

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6.8 Summary

The most common defects identified by customers at the handover stage were incorrect or missing grouting in tiles, and fixtures and fittings in toilets. In addition, failure to apply second coats of paint on walls was found to be a problematic area. Typical surface/appearance defects included floor or wall unevenness, stains, mess, and small cracks and marks, primarily caused by lack of protection. Defect types that arose in areas where fixtures, fittings, and finishing touches were similar, such as the kitchen and bathroom (where the walls are lined with tiles), and lounge and hallway areas, were analogous with one another. Unexpectedly, the research revealed a significant association between the interior walls and the balconies. In this case, the use of a sliding door can lead to cracks in the walls next to a balcony, as it can be repeatedly closed with a great deal of force.

A common complaint was related to the incorrect positioning of fittings. A lack of interaction between the customers and contractors about the positioning of items, such as radiators, lead to the occurrence of reworks. Identifying customers' specific needs during the formative stages of construction will improve customer satisfaction and reduce rework. Improving relationships with customers by meeting their immediate needs and expectations may provide a basis for learning about their future behaviours and requirements, which in its turn may reduce the incidence of defects and subsequent rework.

The study also revealed that there is a strong correlation between defects and the people who carry out construction (workmanship), and therefore management practices (inspection/checking, "responsibility" issues, etc). Although most of the construction defects are caused by design problems, clients do not detect them during post-handover, because some defects are already reduced and/or eliminated during construction, and others do not appear until after some years of functioning.

Moreover, the most important defects provoked by poor workmanship (missing items or task and appearance defects) were found to be significantly associated with errors and with omissions, which are the major factors that contribute to post-handover defects. In fact workmanship as a source of defects was found to be significantly associated with errors and with omissions. This is in line with the previous studies that concluded that no single defect has only one source and origin, and that they are sometimes interrelated.

The analysis of 95 Spanish residential buildings showed that clients detect different defects in different types of residential buildings. Clients detect more defects in flats than in detached houses, even if flats have a smaller gross floor area. This suggests that the differences in contractors' and clients' perceptions of quality notwithstanding, contractors observe end user needs more accurately in detached houses than in flats. Building characteristics were investigated to determine whether a logical explanation existed. The lower quality of the materials used in flats in comparison with detached houses, the lack of motivation of those workers in charge of repetitive jobs, and the tighter schedule to which flats are subject, which forces workers to rush, might all be factors influencing the total amount of defects detected by clients. However, other factors beyond the scope of this study may also contribute to the outcome, such as the levels of supervision over the workforce or workers' experience.

Despite the differences between flats and detached houses, in both cases developers meet their production volume goals by offering fixed products in terms of layout and quality specifications. The only choices the client can make are the amount of rooms, the gross floor area, and certain furnishing in the kitchen and bathrooms. Moreover, clients (homebuyers) play a negligible role in defining the functional requirements and quality standards of the dwelling. It is so because the quality standards are set and managed by the contractor. In addition, in Spain, the Ley de Ordenación de la Edificación (Building Regulation Act) establishes compulsory warranties to ensure that buildings meet basic requirements regarding functionality, general safety and structure, fireproofing, and use and habitability (Jefatura del Estado 1999).

In Spain, internal builders' supervision has tended to focus on structural problems as they are the most important and expensive to rectify. Yet, defects of a minor nature, specifically those of an aesthetic nature, generally result in customer dissatisfaction, and adversely impact a builders' business. Thus, it is imperative for builders to focus on satisfying the customer's needs and expectations if they are to remain competitive.

6.9 Conclusions

While legislation is in place to control the subcontracting activities and guarantee the quality of buildings, a significant number of complaints from customers can be found in newly built houses in Spain.

Before handover, when most of the controls take place, builders must ensure that the building meets the basic technical requirements, such as the foundations and structural integrity, but they do not focus on those aspects that related to functional quality, such as paintwork and aesthetics, which are the factors that customers invariably rely upon on to measure the quality of their housing.

Builders are responsible for rectifying aesthetic defects and omissions during the delivery and liability period. Such defects are an inconvenience and contribute to customer dissatisfaction. The defects detected by customers are predominately functional rather than technical in their nature. It is mostly due to customers tend to be technically inexperienced, and thereby being more likely to have a strong emotional attachment with the quality of the product itself and the softer issues of quality. Those defects can be addressed prior to handover. Thus, rectification costs can be reduced and the builder's image and reputation can remain untarnished. However, pressure to deliver a building to customers, and coordination issues with subcontractors, may result in defects emerging

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during the delivery and liability period. Therefore, an emphasis on quality control and supervision of subcontract trades during the final stages of house construction is critical at this juncture to ensure that defects are reduced.

Even though clients are not aware of the quality of many non-visible structural elements or latent defects, and only notice malfunctioning elements, omissions, and aesthetic defects, many defects can still be found in newly built residential buildings that are supposed to be complete. Such entirely avoidable defects are often detected by clients in the post-handover stage, damaging the image and reputation of the contractor and affect end-user's satisfaction.

The large amount and poor coordination of subcontractors, and the sequential, interrelated and standardized construction activities, mean that some professionals are not able to finish their work, or that defective work is detected once they have left the site. It is, then, difficult to rectify the problem, or in doing so other defects might appear. This confirms the need to improve the quality of management and control of work in the critical final stages of completion of subcontract work (before the subcontractor leaves the site).

The large amount of claims from end users must be perceived as damaging to the overall reputation and image of the house building industry. Despite this, builders continue to ignore the issue and continue to handover new homes with high number of defects. This situation is mainly caused by the large amount of subcontractors and the poor coordination between them, as well as the pressure to deliver the building in time.

The determination of the typical locations, subcontracts, and elements in which defects arose in residential buildings provides invaluable knowledge about those areas where builders are likely to make errors or mistakes, or deliberately take shortcuts during construction. This type of analysis can help practitioners to define strict quality controls during construction phases in order to reduce customer complaints. Therefore, from the analysis of the results, the specific issues that need to be addressed include making sure that:

- Elements, primarily in bathrooms and kitchens, are correct (e.g., door handles, shower stands, screens, cap taps, doorstops, and grilles);
- Finishing surface tasks have been conducted (interior walls: painting, plastering; floor: polishing, integrity of the tiles);
- Floors and walls are even and clean;
- Window and sliding door joints are correct;
- Installations are finished (e.g., toilets, TV sockets, radiators, and GPOs); and
- Specifications are correct (e.g., A/C grille sizes, doors open correctly).

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The determination of the sources and origins of defects detected by customers in residential buildings after handover demonstrates the negative impact of re-doing defective work during the final stages of construction. It also provides invaluable knowledge regarding those areas where the construction industry should direct the focus in order to improve the quality of the finished buildings. These measures should include understanding customer expectations and preferences, training programs for workers, specialization of subcontractors and hardening external control prior to handover.

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Chapter 7

Final conclusions

This dissertation has presented different approaches to help construction organizations in reducing rework, focusing their efforts in defects. This chapter summarises the main contributions of this research and their impact on the field of rework reduction. During the research undertaken, interesting questions were raised although they could not be addressed. These issues are presented as possible paths to continue the research on this field.

7.1 Main contributions

The principal findings and implications of this dissertation are presented below, demonstrating how the initial stated objectives have been achieved by the undertaken research.

The first objective of this thesis was to determine the parameters to characterize a defect in the Spanish residential building sector. In this sense, Chapter 2 exposes the findings of a literature review carried out to investigate the different meanings of rework, as well as the importance of the standardization and the different existing classification types. Based on a critical review of the related literature, the parameters to characterize a defect are determined. The main findings obtained from that critical review of the related literature are:

- There is an existing semantic problem involving the different words used to refer to rework. It can lead to inaccurate and incomplete measurements, cost determination, and possibility inappropriate strategies for reducing the rework occurrence.

- The approach proposed by the authors to analyse reworks determines the word used by the authors to refer as a synonymous of reworks. Three different approaches are used by the authors in the literature: technical/product, human and project. Usually, when authors choose a technical/product approach, they use the word defect or non-conformity. On the other hand, in human and project approaches the word used by the authors in the literature is error, and it relates with human actions and its deviation from the appropriate behaviour at work.

- When a study is carried out by a researcher in the rework area, the first step is to define precisely the scope of the research to avoid confusions and misinterpretations.

- Rework includes different concepts, and it is difficult to attribute which are the consequences of different concepts.

- Although learning from past experiences can help reduce defects and their consequences, data is usually not easily available, or it is poorly structured and difficult to analyse. Several structured classification systems for defects exist, but regionally specific construction activities make the data useless for research use.

- Different approaches are used in the literature to classify and characterize defects. The six parameters required in order to characterize a defect are:

    - Defect type
    - Construction element affected
    - Construction area affected
    - Construction process affected
    - Source of defect
    - Origin of defect

- Different standardized classifications about the parameters to characterize defects (elements, area, process, source, and origin) can be found in the literature. These classifications are adapted and reused for the Spanish residential building sector. However, non-standardized classification exists to characterize the type of defect.

To fulfil the objective 1, the development of a taxonomy for construction defects is needed. In this way, Chapter 3 presents the development of a taxonomy for the Spanish residential building sector. The key features of the developed taxonomy are summarized below:

- The developed and validated classification system has two levels. The taxonomy is composed by 15 main categories, and 19 subcategories. Each category and subcategory includes a definition to clarify its meaning.

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- The interviews conducted to validate the classification revealed that:
    - The classification concepts are clear and with an unequivocal meaning, using a vocabulary that matches with the intuition of the domain experts
    - The proposed classification system is only suitable for the Spanish housing construction environment due to its dependence on the local construction processes and the type of construction.
    - The classification system is clear and the terms are well defined.
- When a list of words is defined in order to use them as standardized vocabulary, to avoid misunderstandings it is desirable to define each word properly.
- Such a system, based on real data and practitioners experience, contributes to a better understanding of housing defects. The inclusion of standardized and domain focused classification systems will facilitate the implementation of on-site tracking systems leading to a more effective project management. In this sense, the Spanish construction companies can use this classification in the ISO 9001:2008 implementation.
- Also, this classification system could be the starting point to develop a Spanish standard for effective defect capturing, management, and future analysis. Once data is standardized, statistical analysis can be easily carried out in order to reduce defect occurrences and to enhance project performance levels in the construction industry.
- The taxonomy is useful to classify construction and post-handover defects. However, during the construction phase, the nature of the defects is basically technical, and at handover phase defects are mainly aesthetic or technical in their nature.

The second objective was to determine which are the current methodologies used in the construction sector to capture information on-site. For this purpose, Chapter 2 exposes the findings of a literature review carried out to investigate which are the current processes in the construction industry to capture information on-site. These findings are complemented with a set of interviews presented in Chapter 4. The main findings of this critical review are presented below:

- Construction professionals recognize that defect management is one of the major factors that general contractors have to take into consideration in order to improve project performance.
- Defect management is a much time-consuming task. To solve this problem, different advanced technologies used to improve the defect management process are presented in the literature.
- The development of IT tools could be useful to improve the efficiency of the process to capture information on-site in the construction industry. However, when an IT tool is

developed, usability and utility criteria must be taken into account. In addition, some functional limitations, such as contrast and screen luminosity, have to be taken in to account.

- Although available technology and commercial tools allow practitioners to improve the efficiency of the process of capturing information on-site in the construction industry, the results of the interviews show that construction industry practitioners are still using traditional methods based on paper and pictures.
- Practitioners noted the need to develop more flexible tools which would implement all the required functions in one single environment. The functional requirements obtained from the interviews revealed that:
  - The tool shall capture multimedia data (video and picture)
  - The tracked multimedia data shall be of enough quality to communicate the identified construction defect
  - Besides allowing capturing multimodal information, the tool shall also allow to capture additional data such as textual notes and graphical annotations
  - The possibility of exporting the tracked information on-site to a data base/excel must exist.

The third objective was to propose a method to track construction data on-site. In this sense, Chapter 4 presents a methodology to be used to track construction data on-site. The methodology is then implemented on an IT tool and tested. The main contributions in this area are summarized below:

- The method to track construction data on-site is based on images and tags. This is an organized method to track on-site data information in order to develop statistical analysis about the tracked information, and to obtain valuable conclusions to be used to improve the construction process.
- The method is developed to track defect data information. However, during the validation, some potential uses, such as to report the construction process.
- MoBuild v0.2 validation suggests that the proposed approach could reduce the time of the defect recording process and managing process. In this sense, MoBuild v0.2 can used to implement ISO 9001:2008 in construction sites, helping to track and mange the large number of data generated.
- MoBuild v0.2 needs a new iteration to implement the new functional requirements that arose from the validation. These functional requirements are summarized below:

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  - Implementation of speech recognition
  - Development of a web platform to export the tracked information, and to allow users to modify or add information on the tracked data
  - Implementation of the cloud computing synchronisation

The fourth objective was to develop and test a methodology for defects prediction for the Spanish residential building using preconstruction information. Chapter 5 detailed the development and testing of a methodology to prevent construction defects at preconstruction stage. The key features of the developed methodology are summarized below:

- A quantitative methodology is proposed for dealing with potential adverse quality risks during the preconstruction stage of residential buildings. The developed methodology is based on two steps:
  - Creation of a risk register through an exhaustive analysis with a process oriented approach. The process oriented approach included 219 activities and 15 quality risks.
  - Evaluation of the QRI for each construction trade and the FRI for each family of risks. QRI assesses the quality of each construction trade and FRI assesses the impact of each family of risks.
- The strength of this methodology lies in the fact that it will help practitioners to explicitly consider quality risks during the preconstruction stage in a systematic way. With the presented method, both designers and contractors would benefit from the knowledge and information about the potential defects of their designs.
- The methodology output helps practitioners to choose the optimal design; develop effective quality plans and inspections; choose the proper project organization or determine which skills are needed by the workers; and to establish measures to mitigate quality risks.
- The methodology only takes into account the technological quality risks.

The fifth objective was to identify quality risks related to the construction process with a process-oriented approach. Chapter 5 presents the application of the methodology developed to fulfill objective 4. The methodology is used in the Spanish context using regional construction activities. The key features of this subject are summarized below:

- Instead of providing a standard set of quality risks, the methodology defined to fulfil the objective 4 was used. Therefore, the methodology obtains specific quality risks related to the construction process and it is tailored to regional specificities. Using this approach, the inclusion of quality risks is neither arbitrary nor incomplete.

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- Using the methodology to fulfil objective 4, a total of 148 significant quality risks for construction activities were obtained in 15 different categories.

The sixth objective was to determine the factors which impact on construction defects for Spanish residential buildings. Chapter 6 presents the results of a statistical analysis about the quality perceived by the end users. The statistical analysis is used to determine the factors which impact on construction defects as perceived by the final users in Spanish residential buildings. The key features of this subject are summarized below:

- The most common defects identified at handover stage by costumers were incomplete tile grouting and incorrect fixtures and fittings in toilets. Failure to apply second coats of paint to walls was deemed a problematic issue. Typical surface/appearance defects were found to include floor or wall unevenness, stains, mess, small cracks and marks mainly caused by lack of protections.

- In areas where fixtures, fittings, and finishes were similar, such as the kitchen and bathroom (where the walls are lined with tiles), and lounge and hallway areas, defect types that arose in these areas were analogous with one another.

- No structural defects were identified in this study. This fact suggests that contractors focus their quality control in those structural defects that can cause major consequences during the liability period.

- The sources of defects detected by clients are mainly due to bad workmanship. Only a small portion is derived from bad design.

- Omissions and errors are the major factors that contribute to post-handover defects in terms of origin.

- The number of defects detected by clients in flats and detach house are significantly different. Clients detect more defects in flats than in detached houses.

- The number of defects detected by clients in detached houses has a significant positive correlation between the gross floor area, number of dwellings, number of floors and number of rooms. However, the number of defects has a significant negative correlation between construction cost and distance between the contractor's headquarters and the site.

- Number of defects detected by clients in flats has a significant positive correlation between number of floors. However, the number of defects has a negative correlation between the gross floor area, construction cost, number of dwellings, distance between the contractor's headquarters and the site, and number of rooms.

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The seventh objective was to propose measures to reduce defects in the Spanish residential buildings. Chapter 6 also presents measures to reduce defects in the Spanish residential buildings. The key features of this subject are summarized below:

- Determining the location, subcontract, and element where defects occur in residential buildings can provide invaluable knowledge about areas where builders are likely to make errors, mistakes or take deliberate short-cuts during construction. Thus, emphasis on quality control and supervision of subcontract trades, especially in the areas identified, and during the final stages of residential construction, are critical to ensure that defects are reduced. The specific issues that need to be addressed include the checking that:
    - Elements, primarily in bathrooms and kitchens, are correct (e.g., door handles, shower stands, screens, cap taps, doorstops, and grilles);
    - Finishing surface tasks have been conducted (interior walls: painting, plastering; floor: polishing, integrity of the tiles);
    - Floors and walls are even and clean;
    - Window and sliding door joints are correct;
    - Installations are finished (e.g., toilets, TV sockets, radiators, and GPOs); and
    - Specifications are correct (e.g., A/C grille sizes, doors open correctly).
- Training and education programmes should include feedback from employees, trade partners and customers.

7.2 Current implications of this research

This dissertation focused on the two main issues in the implementation of a QMS: “how” to capture information in an effective way, and “what” to do with the recorded information. Current implications of the research undertaken within this dissertation are summarized below, differentiating between the benefits derived from the dissertation results during the preconstruction stage, construction stage and post-construction stage.

During the *pre-construction stage*, construction organizations can benefit from the results of the dissertation in several ways, as described below:

- The dissertation provides a quantitative methodology for dealing with potential adverse quality risks during the pre-construction stages of residential buildings and other similar types.

- The early identification of quality defects makes it possible for designers to compare several design alternatives during the design phase and determine the corresponding overall quality risk level of a construction project without their creative talents being restricted. The methodology is specially addressed to those less-experienced designers who lack the skills and knowledge required to recognize quality risks in developing optimal designs.

- The understanding of what quality risks can be produced during the construction stage can support construction companies during the selection of appropriate preventive measures to be implemented.

- Information related to the potential quality risks can be used for training purposes regarding defect prevention, and consequently reducing rework by raising awareness of the potential quality impacts in every activity of the construction phase among workers.

- The methodology provides a technique to use the information recorded during the construction stage. The use of the methodology will allow companies to obtain their specific quality risks and adopt learning practices.

During the *construction stage*, the dissertation results can support organizations on the recording process of defects, facilitating the implementation of quality management systems. Moreover, the dissertation provides specific knowledge about the issues that need to be addressed before the building is delivered to the final user.

- The model to characterize defects can be used as a metadata standard to help organizations comply with the ISO 9000 standards for quality systems. Construction organization can meet ISO 9000 requirements for the creation and preservation of reliable, authentic and accessible records. In this way, the model to characterize defects can be implemented in a tracking system tool to record defects. The adoption of the pre-established vocabulary in the recording process will enable further statistical analysis of the recorded information.

- The proposed approach to track defects implemented in MoBuild application can help organizations to implement ISO 9001:2008 in construction sites, helping organizations to track and mange the large number of data generated. Moreover, the tracking system can be used to track other information during the whole life cycle of the building.

- The statistical analysis determined the locations, subcontracts, and elements where defects occur in residential buildings. The statistical analysis provides invaluable knowledge about areas where builders are likely to make errors, mistakes, or take deliberate short-cuts during constructions. This knowledge can be used by the

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construction organizations to improve the quality controls and the supervision of subcontract trades.

Finally, the dissertation results can be used during the *post-construction stage* as a framework for construction organizations to effectively analyse recorded information and to improve the organizational aspects of design and construction companies.

- The dissertation provides tools and techniques to use the recorded information to obtain valuable knowledge to develop training and education programs.
- The dissertation provides tools and techniques to use the recorded data as a source of information for the development of strategies to improve the quality controls and the supervision of subcontract trades.

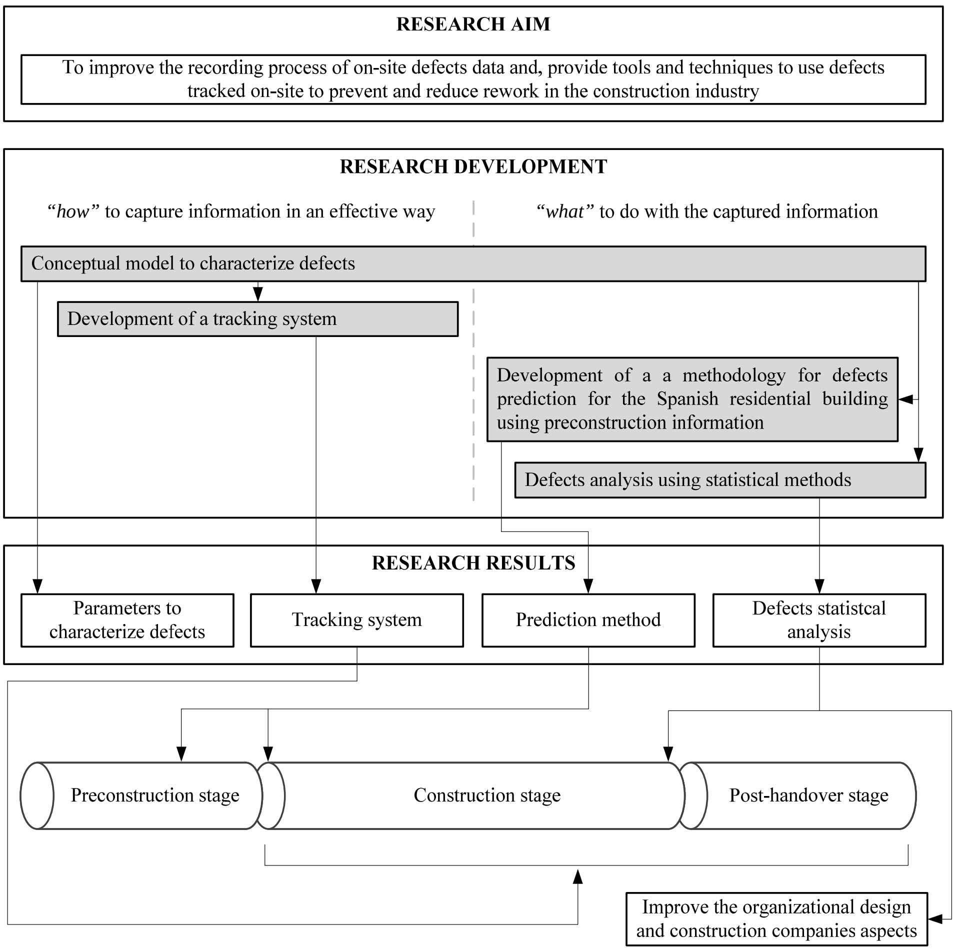

Figure 16. Overview of the research results

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7.3 Further research

Some interesting issues came up during the development of this research; however, they were not addressed in this dissertation, as the level of analysis they would require lays beyond the scope of this dissertation. The most interesting and urgent research questions seeking answers and explanations are listed and described below.

- Use of the defects' taxonomy in other scenarios.

  The defects' taxonomy is validated in the context of Spanish residential buildings. During the validation, the practitioners were asked if they thought that the validation could be used in other domains. Although the taxonomy validation suggests that the taxonomy cannot be used in other domains, the validation in other contexts will allow defining more precisely in which scenarios this taxonomy can be used.

- Improve MoBuild application and include functionalities to the web platform

  During the MoBuild validation some interesting functionalities were proposed by the practitioners. However, most of them require specific developments to be implemented, such as speech recognition to facilitate the introduction of data. Another aspect that needs to be improved is the location of the defect. Currently, the geolocation is only available using GPS, making location impossible inside the buildings. For this reason, it would be interesting to add WiFi location to help positioning the defect inside the building.

  Web platform functions must be implemented in order to manage the tracked information. Examples of these functions are: modifying recorded information, introducing new information, and generating automatic reports.

- Test the methodology to track defects using MoBuild application in other scenarios and domains

  This dissertation tested the methodology implemented in the MoBuild application to track defect data in the construction industry. However, during the tests, practitioners suggested new scenarios where the methodology could be used; for example, to track the construction progress. For this purpose, new scenarios have to be defined including the associated taxonomies, and carry out the testing process.

- Assessment of the quality risks

  Currently, only the technological quality risks are taken into account by the methodology. In the future, the incorporation of human and organizational parameters will also be studied, in order to simulate which defects will appear due to the project's organization. In addition, the possibility of adding different parameters to compare projects with different volume of works and construction activities will be analysed. With this,

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construction companies will be able to optimize resources during the construction of different buildings that are being built simultaneously.

- Quality risk register visualization

  Currently, one of the possible outputs of the methodology is a matrix. Visualizing information in a matrix is not very operative. In order to increase the usability of the methodology outputs, the implementation of 4D models will be studied. The aim is to provide a visualization model that offers guidance to practitioners on the evaluation of the construction quality risks.

- Quality costs

  In order to demonstrate builders and subcontractors the impact of re-doing defective work on their overall profitability, future research will focus on determining the causes and the costs of defects

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Publications

At the examination date, works carried out into the scope of this thesis have been sent or are being prepared to be published in the following research journals, which are relevant in the field of research. The research outputs of each chapter have been sent or are being prepared to be published in journal or conference papers. Figure 17 presents the publication outline.

Journal papers:

- Macarulla, M.; Forcada, N.; Casals, M.; Gangolells, M.; Fuertes, A.; and Roca, X. (2012). Standardizing housing defects: classification, validation and benefits. J. Constr. Eng. Manage., 139 (8), 968-976.

- Macarulla, M.; Forcada, N.; Casals, M.; Kubicki, S.. Mapping construction defects through images. Under preparation.

- Macarulla, M.; Forcada, N.; Casals, M.; Gangolells, M.; Fuertes, A.; and Roca, X.. Identification of quality risks related to the construction process. Submitted.

- Macarulla, M.; Forcada, N.; Casals, M.; Gangolells, M.. Assessment of quality risks related to the construction process. Under preparation.

- Macarulla, M.; Forcada, N.; Casals, M.. Strategies and methods to analyse defects in construction sector. Under preparation.

- Forcada, N.; Macarulla, M.; Love, P.E.D. (2012). Assessment of residential defects at post-handover. J. Constr. Eng. Manage., 139 (4), 372-378.

- Forcada, N.; Macarulla, M.; Gangolells, M.; Casals, M.; Fuertes, A.; and Roca, X. (2012). Post-handover housing defects: sources and origins. In press.

- Forcada, N.; Macarulla, M.; Fuertes, A.; Casals, M.; Gangolells, M.; and Roca, X. (2012). Standardizing housing defects: classification, validation and benefits. J. Perform. Constr. Facil., 26 (4), 433-440.

Papers in conference proceedings:

- Macarulla, M.; Forcada, N.; Casals, M.; Kubicki, S. (2012). Tracking construction defects based on images. ECCPM 2012. Reykjavik, Island. July 25-27, 2012. 723-729.

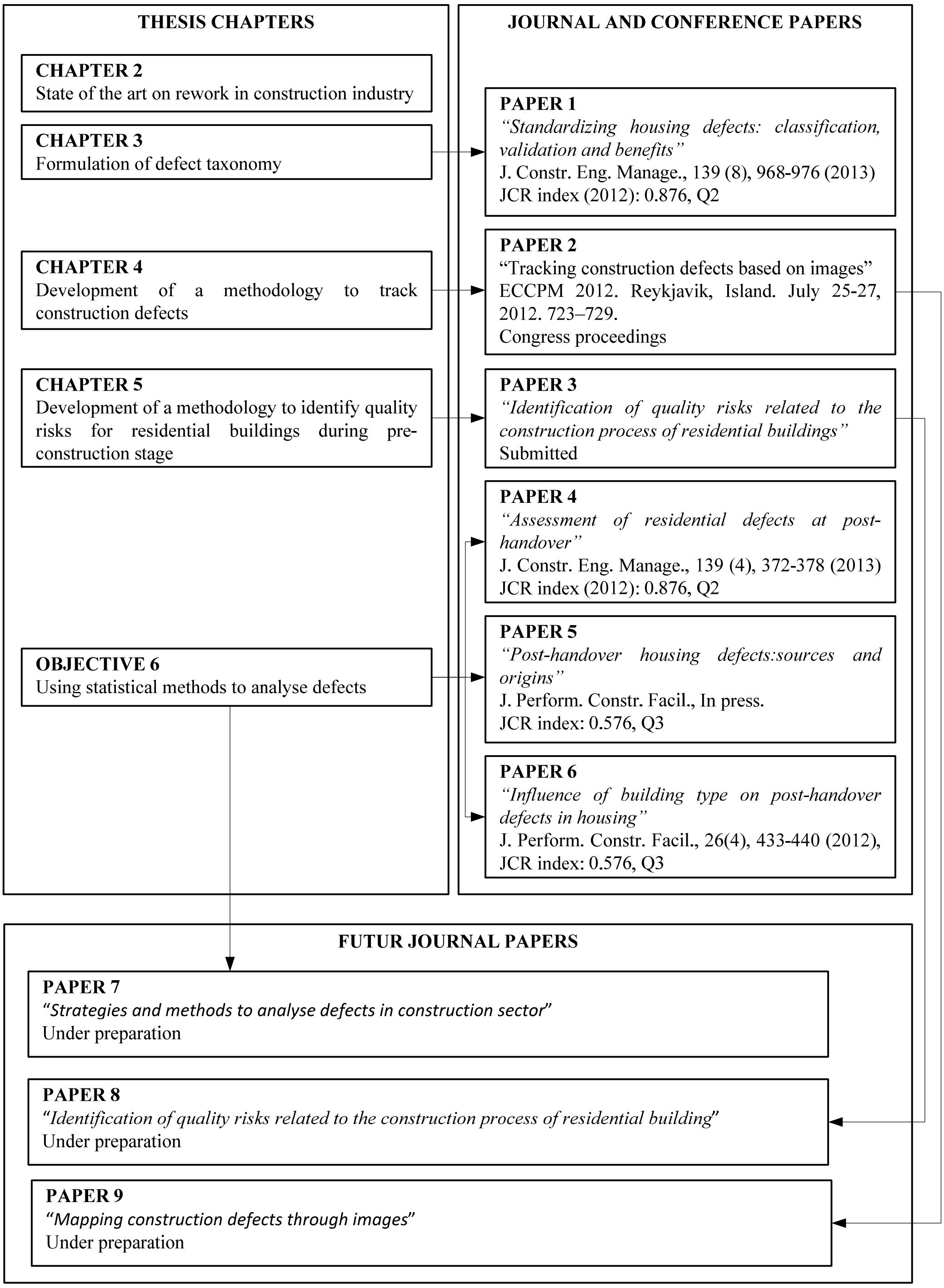

Figure 17. Publication outline

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Appendix A

A. Standardised vocabulary to classify construction defects

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A.1 Defects' classification system for construction industry

Table 37. Defects' classification for housing in Spain

Category 1	Category 2	Definition	Example
Affected functionality	Disabled	MEI that must be replaced because its functionality is completely affected.	Air conditioning motor does not work
	Bad operation	MEI that must be repaired but not necessary replaced because its functionality is partially affected.	Door scrapes on floor
Inappropriate installation	-	MEI not well positioned, or does not satisfy project specifications or does not have the characteristics it should have to.	Slab's bars in wrong layer
Biological action and change	-	All defects caused by living beings as moulds.	Mould in walls, or the attack of woodworm
Broken / Deteriorated	-	MEI physically and forcibly separated into pieces or split, as well as deteriorated elements because of its use and also the physical interaction with the environment, among many others.	Window glass broken
Chemical action and change	-	Includes all defects produced by the interaction between chemicals elements and compounds that make up materials used in and around buildings; and the constant action of people, processes and environment.	Corrosion of metals or the carbonation of concrete
Detachment	-	MEI that are not fixed in their position.	Detached tiles after their collocation
Soiled	General	Includes all defects related to dirtiness, either caused by the dirty of the construction process or provoked by the use of workers on-site, etc.	Dust in all building, residues of packaging
	Stain	Stains appeared on surfaces that cannot be cleaned, or elements that became stained due to the nature of the activities which are being carried out such as painting	Painting stains, Fuel stains
Flatness and levelness	-	Surfaces significantly irregular and/or with excessive sloping.	Slabs or walls too inclined
Misaligned	-	MEI that are imperfectly or badly aligned. The difference between flatness and levelness, and misaligned categories is that the first one refers to a surface, and the second one is referred to a line.	Pillars not aligned, or walls made by masonry do not follow a line
Missing	Item	MEI that are not collocated (Omissions)	Lack of a doorknob
	Work	Works that are not completed/done, although in the project or in the specifications are supposed to be collocated or completed/done.	The second layer of paint when painting a wall
Stability / Movement	Collapse	Extremely damaged structure that threatens to ruin, or a collapsed structure; for example.	Slab collapse
	Landslip	Land movement.	Settling of the ground
	Cracking	Cracks in construction elements.	Cracks in concrete elements
	Excessive deflection	Excessive deformation of a structure before its use.	Excessive deflection in slab
	Excessive structural vibration	Excessive movement of a structure before its use when a dynamic load is applied.	Excessive vibration in slabs

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Category 1	**Category 2**	**Definition**	**Example**
Surface appearance	Bumps	Protuberance on a level surface	Bumps in plaster board joins
	Dips	Opposite effect to a bump.	Honeycombs in concrete elements
	Uneven	Surface not even or uniform as e.g. in shape or texture, an uneven color, uneven ground, uneven margins, wood with an uneven grain.	Walls with uneven color
	Hit/Scratches	The result of a collision or abrasion.	Impact in the mailbox
	Efflorescence	Surface with a powdery deposit caused by the evaporation of water when have certain level of dissolved salts.	Efflorescence in external walls
Water problems	Excess moisture	Wetness caused by moisture, including rising damp, penetration damp and condensation.	Moisture stain
	Entrapped water	Water that do not drain.	Floods and puddles
	Water ingress	Defects related to water which seeps through walls, slabs, roofs, etc.	Flood in the parking
Tolerance errors	-	Defects associated to dimension or distance. This term is related to the thickness of construction elements, the distance between them and defects concerning positioning them.	Laying out pillars, the thickness of pavements
Others	-	Includes all defects that cannot be classified in the previous categories.	

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A.2 Construction processes

Materials, equipment and waste management

Waste classification

Transportation, unloading and internal movements of materials, equipments and waste

On-site facilities

Demolitions, earthworks and earth management

Site preparation and earthworks

Foundations, retaining walls and evacuation elements

Removal of garden elements

Basements and underpinning excavations

Excavations and review of ditches and wells

Earth filling and compacting

Filling of ditches and wells

Gravel spreading

Compacting embankment

Shoring up

Soil and inert waste loading and transportation

Soil and inert waste transportation

Soil and inert waste loading

Bailing out and reductions on groundwater level

Bailing out

Reductions on groundwater level

Earth management

Soil supplying

Soil transportation to official management centres

Foundations

Formwork, reinforcing and concreting

Ditches and wells

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Retaining walls

Braces and butt pillars

Slab foundations

Piles and micropiles

Micropiles execution

Piles drilling and concreting

Reinforcing piles

Precast piles

Pile caps

Pile-caps concreting, reinforcing and formwork

Screen walls

Screen walls drilling and concreting

Screen walls reinforcing

Structures

Timber structures

Pillars, beams, joists, trusses, purlins, wood boards and floorboards

Laminated timber structures

Pillars, beams, joists, trusses and purlins

Steel structures

Pillars, anchoring elements, beams, joists, lintels, braces, trusses and purlins

Concrete structures

Formwork, reinforcing and shuttering of pillars, walls, beams, lintels and straps

Formwork, reinforcing and shuttering of structural floors with precast resistant elements, unidirectional and bidirectional reinforced concrete slabs

Masonry structures

Concrete block and ceramic brick walls

Concrete block and ceramic brick lintels

Concrete block and ceramic brick straps

Ceramic brick pillars

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Ceramic brick arches

Ceramic brick vaults

Stone masonry structures

Stone masonry walls

Expanded clay brick masonry structures

Lightweight expanded clay brick walls

Expanded clay brick lintels

Precast resistant elements for slabs and other structural elements

Steel small beams and small vaults

Reinforced concrete joists and small vaults

Prestressed concrete small beams and small vaults

Prestressed concrete foists and vaults

Galvanized steel plates for composite slabs

Reinforced concrete slabs

Alveolar prestressed concrete slabs

Ribbed reinforced concrete slabs

Ribbed prestressed concrete slabs

Precast reinforced concrete pillars

Precast reinforced concrete main beams

Triangular prestressed precast concrete main beams

Triangular reinforced precast concrete main beams

Precast reinforced concrete staircases

Precast reinforced concrete terraces

Roofs

Flat roofs

Tile roofs

Ceramic tiles

Mortar tiles

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Slate tiles

Roof windows

Sheet roofs

Fibrocement sheets

Reinforced polyester sheets

Steel sheets with slope less than 30%

Metal sheet roofs

Zinc sheets

Copper sheets

Steel sheets with slope less than 30%

Steel sheets with slope more than 30%

Deck

Roof lights

Partitions and closures

Masonry walls, partition walls and thick partition walls

Ceramic brick walls and partition walls

Mortar block walls

Expanded clay mortar block walls

Cellular concrete block walls

Molded glass walls

Plaster partition walls

Sheet closures

Fibrocement sheets

Reinforced polyester sheets

Steel sheets

Aluminium panels for facades

Precast, lightened or ribbed reinforced concrete slabs

Metal sheets

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Metal frames for plasterboard walls

Dividing screens

Fixed steel frames

Fixed anodised aluminium frames

Fixed lacquered aluminium frames

Curtain wall elements

Aluminium frames for curtain walls

Waterproofing and insulation

Unprotected bituminous sheet membranes

Unprotected bituminous adherent sheet membranes

Unprotected bituminous non-adherent sheet membranes

Bituminous sheet membranes with mineral autoprotection

Bituminous adhered sheet membranes with mineral autoprotection

Bituminous semi-adhered sheet membranes with mineral autoprotection

Bituminous sheet membranes with metal autoprotection

Bituminous adhered sheet membranes with metal autoprotection

Bituminous semi-adhered sheet membranes with metal autoprotection

Unprotected PVC sheet membranes

Unprotected PVC adhered sheet membranes

Unprotected PVC non-adhered sheet membranes

Autoprotected PVC sheet membranes

Autoprotected PVC adhered sheet membranes

Autoprotected PVC non-adhered sheet membranes

Autoprotected PVC fixed sheet membranes

Elastomeric sheet membranes

Elastomeric adhered sheet membranes

Elastomeric semi-adhered sheet membranes

Elastomeric non-adhered sheet membranes

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Elastomeric fixed sheet membranes

Polyethylene and polyolefin sheet membranes

Polyethylene and polyolefin fixed sheet membranes

Polyethylene and polyolefin non-adhered sheet membranes

Waterproofing with amorphous products

Elastomeric pastes

Acrylic polymers

Waterproofing with panels and drainage sheets

Drained polyethylene relief sheets

Watertight barriers

Bituminous

Synthetic

Metal

Thermal, acoustic and sound-absorbing insulations

Amorphous

Polystyrene boards

Polyurethane boards

Glass wool boards

Cork boards

Cellular glass boards

Polyethylene sheets, boards and slabs

Rock wool boards

Expanded perlite boards

Expanded polystyrene boards ready for supporting continuous amorphous coatings

Felts and polyester panels

Sandwich panels

Fire-resistant insulations

Perlite mortars

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Intumescent fire-resistant paints

Silicate boards

Silicate false ceiling boards

Coatings

Parging and plastering

Parging

Plastering

Tilling

Natural ceramic tilling

Refractory ceramic tilling

Glazed tilling

Brilliant glazed ceramic tilling

Matt glazed ceramic tilling

Glazed ceramic tilling

Unglazed stoneware tilling

Glazed stoneware tilling

Porcelain stoneware tilling

Pressed glazed stoneware tilling

Ceramic veneering

Cement mortar veneering

Veneering

Artificial stone veneering

Stoneware stone veneering

Limestone stone veneering

Granite stone veneering

Laminated plasterboard veneering

Fiberboard veneering

Synthetic board veneering

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- Fibrocement board veneering
- Aluminium panel veneering

False ceilings

- Plasterboard false ceilings
- Mineral or vegetal fiberboard false ceilings
- Laminated plasterboard false ceilings
- Wooden board false ceilings
- Metal slats or board false ceilings
- PVC slat false ceilings

Decorative coatings

- Wood decorative coatings
- Cork decorative coatings
- Synthetic decorative coatings
- Stainless steel board decorative coatings
- Aluminium board decorative coatings

Stuccoworks, sgraffitos and painted elements

- Stuccoworks, sgraffitos and single layer coatings
- Structures, faces and closure elements painting
- Pipes and heating and protection elements painting

Varnished elements

- Structures, faces and closure elements varnishing
- Heating and protection elements varnishing

Pavements

Subbases

- Subbases
- Aggregate subbases
- Expanded clay subbases

Bases and screeds

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Concrete or lightweight concrete bases

Lightened concrete bases

Screeds

Inside technical pavements

Natural stone pavements, skirting and steps

Stoneware pavements, skirting and steps

Limestone pavements, skirting and steps

Granitic pavements, skirting and steps

Artificial stone pavements, skirting and steps

Smooth terrazzo pavements, skirting and steps

Relief terrazzo pavements, skirting and steps

Acid wash terrazzo pavements, skirting and steps

Terrazzo upon supports pavements, skirting and steps

Continuous terrazzo pavements, skirting and steps

Ceramic and stoneware tile pavements, skirting and steps

Natural ceramic tile pavements, skirting and steps

Unglazed stoneware tile pavements, skirting and steps

Glazed stoneware tile pavements, skirting and steps

Porcelain stoneware tile pavements, skirting and steps

Pressed and glazed stoneware tile pavements, skirting and steps

Ceramic cobblestones pavements, skirting and steps

Concrete pavements

Finishes without additives

Finishes with additives

Light

Cork slabs pavements

Synthetic pavements skirting boards

PVC synthetic pavements and skirting boards

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Rubber

Wood pavements, skirting and steps

Adhered parquet pavements, skirting boards and steps

Nailed parquet pavements, skirting boards and steps

Wood finishes floating parquet pavements, skirting boards and steps

Synthetic finishes floating parquet pavements, skirting boards and steps

Textile pavements

Wool fitted carpets

Synthetic fitted carpets

Metallic board and lattice pavements, skirting boards and steps

Special elements for pavements

Pavements, tapering and polishing

Painting and varnishing of pavements

Door and window closures

Wood door and window closures

Oak for varnishing

African teak for varnishing

Southern pine for varnishing

Scots pine for painting

Laminated steel door and window closures

Laminated steel doors

Aluminium door and window closures

PVC door and window closures

Glass door and window closures

Commercial, industrial and common use doors

Swinging, rolling, pivoted, fast or sectional doors

Fire doors

Acoustic doors

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Blinds

Wood blinds

Steel blinds

Aluminium blinds

PVC blinds

Textile blinds

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A.4 Sources of defects

Table 38. Sources of defects

Source	Definition	Example
Design sources	Defects caused by poor decisions in design.	Bad specification of materials, layouts, and bad integration between different materials and systems
Workmanship sources	Defects caused by poor work practices on site.	Poor mixing of materials, poor handling of materials, poor planning from the contractor that results in poor completed quality, failure provide proper joints, gaps or materials to avoid defects.
Material sources	Defects caused by inferior material quality derived from suppliers' poor practices. Materials can only be expected to perform to their required standards; however, if they are exposed to excessive force, they will not be considered poor in terms of quality. When this happens, the source can be directed toward design or workmanship.	Doors gets to the construction site without doorknob
Maintenance sources	Defects caused either by materials or systems that are not maintained properly, or maintenance that is irregular or nonexistent at the occupancy stage.	Corrosion of metals due to the maintenance tasks is not done, air conditioning motor does not work due to the filter is blocked.
Lack of protection sources	Defects caused by failure to provide proper preservation of parts of the building already finished while other activities are being carried out.	Painting stains, fuel stains

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A.5 Origin of defects

Table 39. Origin of defects

Source	Definition	Example
Change	Directed action altering the currently established requirements.	Changes may encompass design, fabrication, or construction, and materially affect the approved requirements, the basis of design, the existing scope of the contract plans and specifications, or operating capability of the facility
Error	Any item or activity in a system that is performed incorrectly resulting in a deviation e.g., design error, fabrication error, construction error, etc. An error requires an evaluation to determine what corrective action is necessary.	Pillars not aligned, or walls made by masonry do not follow a line
Omission	Any part of a system, including design, construction and fabrication that have been left out resulting in a deviation. An omission requires an appraisal to determine what corrective action is necessary.	Lack of a doorknob, the second layer of paint when painting a wall
Damage	Physical harm impairing the value, usefulness, or normal function of something.	Impact in the mailbox

∴

A.6 Construction elements

Construction elements

Fixture and fittings

Doors and windows

Plumbing and sanitary system (P&B)

General

Mechanical and electrical system (M&E)

Furniture

Exterior works

Internal wall

Door

Ceiling

Floor

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A.7 Construction areas

Area

Balcony

Bathroom

Kitchen

Exterior

Garage

General

Bedroom

Hall/corridor

Lounge

Terrace

Common areas

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Appendix B

B. Surveys and Questionnaires

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B.1 Taxonomy defects' validation

B.1.1 Section 1: Epistemological adequacy

- Epistemological clarity

1. Do all concepts in the classification system clear and unequivocal meaning? Please rank your answer on a scale from 1 to 6.

- Epistemological intuitiveness

2. Does the classification system provide a vocabulary that matches the intuition of the experts in the domain? Please rank your answer on a scale from 1 to 6.

- Epistemological relevance

3. Are all the concepts in the taxonomy relevant for the domain? Please rank your answer on a scale from 1 to 6.

- Epistemological completeness

4. Does the classification system cover all relevant concepts that may be relevant for any task, method and subdomain? Please rank your answer on a scale from 1 to 6.

B.1.2 Section 2: Reusability

- Task-and method reusability

5. Is the classification system dependent on certain (types of) construction tasks and methods? Please rank your answer on a scale from 1 to 6.

- Domain reusability

6. Is the taxonomy dependent on certain (types of) subdomains? Please rank your answer on a scale from 1 to 6.

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B.1.3 Section 3: Experimental verification

- Classifying defects.

7. The photos shown in the Table 3 are defects from real cases. Classify these defects in the taxonomy, and then rank your answer on a scale from 1 to 6 for each defect. For this verification, the defect classification is related to the visualised defect, not its root.

8. How easy was it to classify them? Please rank your answer on a scale from 1 to 6.

Defect	Classification	Score
 (Condensation problem)		
		
		

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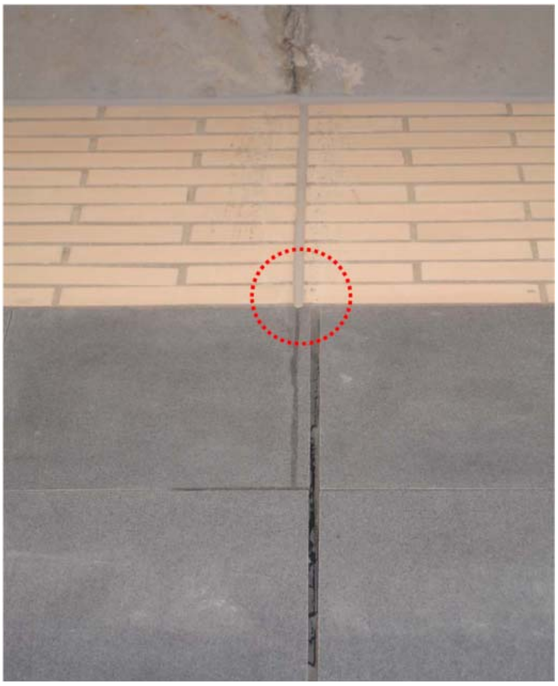
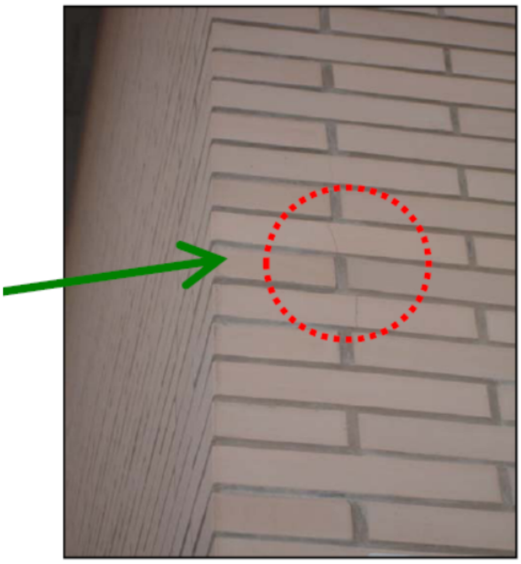
Defect	Classification	Score
		
		
		
		

Defect	Classification	Score
		
		
		

Defect	Classification	Score
		
		
		

Defect	Classification	Score
		
		
		

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Defect	Classification	Score
 (During Handover phase)		
		
		
		

Defect	Classification	Score
 (woodworm)		

B.1.4 Section 4: Open question

9. Do you have any suggestion to improve the taxonomy?

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B.2 Processes currently used in the construction industry to track defects

B.2.1 Section A. Respondent's details

- Date:
- Company:
- Activity

  □ Client

  □ Designer

  □ Contractor

  □ Project Manager

  □ Other. Indicate:

- Role:
- Nº of employees:
- Turnover:

B.2.2 Section B. Non-conformities management survey

1. Has the company ISO 9001 certification?

   □ Yes □ No

2. Does the company manage non-conformities and incidences (in terms of defects)?

   □ Yes □ No

3. How does the company capture these non-conformities on site?

   □ The site manager writes down (paper based) the non-conformities without using pre-established formats.

   □ The site manager writes down (paper based) the non-conformities using pre-established formats.

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□ The site manager collects non-conformities using a mobile device (Iphone, Blackberry, etc.) on site.

□ Others. Indicate:

4. How does the company transfer these non-conformities?

□ The manager downloads manually this information.

□ The information is transferred automatically to an application or database.

5. How does the company registers and manages these non-conformities?

□ This information is collected in an Excel/Word.

□ This information is collected in a local database.

□ This information is collected in a centralized database or a web application.

□ Others. Indicate:

6. Does the company have standard forms to collect non-conformities?

□ Yes □ No

7. What parameters does the company use to track non-conformities?

□ Type of defect

□ Description of the defects

□ Photo

□ Notes on the photo

□ Drawings and sketches

□ Video

□ Recorded voice

□ Element

□ Zone

□ Construction process affected

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□ Cause

□ Origin

□ Responsible

□ Affectation

□ Responsible

□ Cost

□ Opening Date

□ Closing Date

□ Others. Indicate:

8. Does the company have standard vocabulary to track non-conformities (For example: types of defects, causes, elements, causes of defects, etc.)?

□ Yes. Indicate which parameters:

□ No

9. Describe the procedure that your company uses to manage non-conformities.

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B.3 Questionnaire about Mobuild testing

B.3.1 Respondants' details

- Name:
- Surname:
- Company:

1. Please select mobile devices with which you were familiar before the experiment:

□ Mobile phone

□ Smartphone

□ Tablet

□ Digital camera

□ GPS

□ Others (which)

2. Do you have a smart phone with touch screen?

□ Yes □ No

3. Do you have a smart phone with touch screen?

□ Yes □ No

a. If yes, please specify the model

4. What is your initial training?

□ Architect

□ Interior Designer

□ Engineer (Building)

□ Other (please specify)

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5. Have you ever practiced site visits?

□ Yes □ No

a. If yes, please specify their frequency:

□ Daily

□ Weekly

□ Monthly

□ Occasionally

6. When was your last visit to the site?

B.3.2 Application utility

	<<Strongly disagree				Strongly agree>>
	1	2	3	4	5
1. Does the system help you developing your day-to-day work?					
2. Does Mobuild improve the quality of your work?					
3. Does the system facilitate your work?					
4. Does the system reduce the time to develop your work?					

5. Does the system include all the functionalities to capture all on site data?					
If <3, can you list the missing features below:					

6. Does the system include all the functionalities to manage all the data in the smartphone?					
If <3, can you list the missing features below:					

7. Does the system include all the functionalities to transfer the captured data to the web service?					
If <3, can you list the missing features below:					

8. Does the system include all the functionalities to manage the transferred data to the web service?					
If <3, can you list the missing features below:					

∴

Open questions:

- How long did it take to capture a situation/defect using Mobuild v0.2?
- How long does it normally take (in your current practice) to consult on site information in the office?
- Is your company ready to use this system for their day-to-day work?
- Which are the main barriers for implementing this system in your organization?

B.3.3 Application usability

<<Strongly disagree Strongly agree>>

	1	2	3	4	5
1. I think we will use the system frequently?					
2. This system is too complex					
3. This system is simple					
4. I would need to contact the technical service to use the system					
5. The different functionalities of the system are very well integrated					
6. There are many inconsistencies in the system					
7. Everybody can learn how to use the system					
8. The system is convincing for its use					
9. I felt confident using the system					

You can, if you wish, send us your comments or suggestions below:

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