POLITECNICO DI MILANO
FACOLTÀ DI INGEGNERIA EDILE/ARCHITETTURA
CORSO DI LAUREA IN INGEGNERIA DEI SISTEMI EDILIZI

APPLICATION OF THE FACTOR METHOD TO THE PREDICTION OF THE SERVICE LIFE OF CERAMIC EXTERNAL WALL CLADDINGS

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ACADEMIC YEAR 2011/2012

TABLE OF CONTENTS

TABLE OF FIGURES

TABLE OF TABLES

TITLE

Application of the factor method to the prediction of the service life of ceramic external wall claddings

ABSTRACT

This dissertation's objective is predicting the service life of the ceramic exterior wall claddings, using the factor method (ISO 15686). It is part of a line of research that concerns the study of the durability of building components. The interest of this study is the possibility of developing a tool to aid the planning of maintenance operations, so as to reduce costs and ensure a better performance of the cladding system.

The methodology adopted is based on field work data collection, concerning the state of conservation of the façades. The analysis of the latter, through the implementation of a degradation model, starts by defining the deterioration process of the cladding. This is followed by the application of the factor method. Reference Service Life and Estimated Service Life for directly adhered ceramic façades are evaluated. The factors affecting the durability of the component are individualized and quantified through several scenarios, with the aim of optimizing the set of the weighting coefficients.

The degradation model application has led to consistent results for most of the variables influencing the cladding's loss of performance. In particular, the basic importance of quality of execution and maintenance was demonstrated. Regarding the factor method, statistically significant outcomes were obtained with the ISO standard's values application, proving the reliability of the method. The overall encouraging results encourage the continuation and deepening of research in this field.

KEYWORDS

Service life, Durability, Ceramic external claddings, Factor method, Degradation models

1 INTRODUZIONE

Lo scopo di questa ricerca è la previsione della vita utile dei rivestimenti ceramici in facciata, utilizzando il metodo fattoriale. Il panorama in cui la tesi si inserisce è quindi quello dello studio della durabilità dei componenti edilizi. In questi ultimi anni si è riscontrata un'attenzione crescente a questo ambito. Le ragioni di questo interesse sono principalmente di carattere economico e ambientale (Hovde, 1998). Infatti, un'adeguata conoscenza inerente ai temi della vita utile e della durabilità permette un'appropriata pianificazione delle operazioni preventive di manutenzione, le quali consentono a loro volta di stimare il costo del ciclo di vita (Life Cycle Cost - LCC) e l'analisi del ciclo di vita (LCA).

È in questo settore che si inserisce il presente lavoro. Esso segue una linea di ricerca sviluppata da precedenti studi effettuati presso l'Insituto Superior Técnico di Lisbona. In particolare, gli studi di Sousa (2008) ed Emídio (2012) sono stati tenuti in considerazione durante lo svolgimento del lavoro. Il primo riguarda la previsione della vita utile dei rivestimenti ceramici in facciata, mediante l'utilizzo di modelli di degrado. Il secondo invece vede l'applicazione del metodo fattoriale ai rivestimenti in pietra. Per questo motivo, entrambi hanno costituito una base per il lavoro svolto.

Come accennato, il background concettuale della dissertazione è rappresentato dalla previsione della vita utile; quest'ultima è definita dalla norma UNI 11156, in linea con la ISO 15686, come *il periodo di tempo dopo l'installazione durante il quale l'elemento tecnico mantiene livelli prestazionali superiori o uguali ai limiti di accettazione, definiti in relazione al soddisfacimento delle funzioni richiestegli e alle esigenze espresse dall'utenza*. Come si evince da tale definizione, la vita utile è determinata in relazione a specifiche esigenze, tradotte in un livello minimo di prestazione richiesta. Tale concetto è strettamente legato a quello di durabilità del componente, intesa come *la capacità di svolgere le funzioni richieste durante un periodo di tempo specificato, sotto l'influenza degli agenti previsti in esercizio*.

Emerge quindi l'approccio prestazionale che caratterizza la presente ricerca, ovvero il bisogno di stabilire le esigenze prestazionali minime sopraccitate. In particolare, tali requisiti sono stati determinati sulla base di valutazioni tecniche, conseguenti al rilevamento delle condizioni di degrado del sistema di rivestimento in esame. Questo argomento sarà trattato nel capitolo 4, contestualmente alla valutazione della vita utile dei rivestimenti ispezionati.

1.1 Metodo fattoriale

Una breve trattazione dei metodi utilizzati per stimare la durabilità di un elemento tecnico chiude il discorso introduttivo. Secondo Daniotti (2006), vi sono tre tipi di metodo per determinare la vita utile, i quali si differenziano principalmente per il grado di complessità:

- Metodi stocastici (probabilistici) - Si basano sull'analisi statistica del contesto sollecitante (agenti) e del comportamento dei materiali, definendo la probabilità di cambiamento di stato dell'elemento in esame. Un esempio è rappresentato dal processo Markoviano;
- Metodi ingegneristici - Questi metodi sono utilizzati per identificare analiticamente la diminuzione delle prestazioni: la metodologia FMEA ne è un esempio;
- Metodi deterministici - Sono costituiti dallo studio dei fattori di degrado che interessano i materiali, dalla comprensione del loro meccanismo d'azione e dalla loro quantificazione attraverso le funzioni di degrado. Il metodo fattoriale rientra in questa categoria.

Questa dissertazione prende in considerazione proprio quest'ultima tipologia di stima. La formula che compone il metodo fattoriale è la seguente:

$$ESL = RSL \cdot A \cdot B \cdot C \cdot D \cdot E \cdot F \cdot G \qquad \text{Equazione 1.1}$$

Dove:

ESL Estimated service life (Vita Utile Stimata in condizioni di progetto);

RSL Reference service life (Vita Utile di Riferimento);

A Qualità del componente;

B Qualità di progettazione;

C Qualità di esecuzione;

D Ambiente interno;

E Ambiente esterno;

F Condizioni d'uso;

G Livello di manutenzione.

Riguardo ai termini che compaiono nell'Equazione 1.1, la Vita Utile di Riferimento e i fattori moltiplicativi rappresentano gli input che lo studio effettuato ha avuto il compito di determinare. Infatti, la metodologia consiste nel definire un valore di riferimento (RSL), il quale viene corretto mediante la moltiplicazione di una serie di fattori di ponderazione che considerano le specifiche condizioni del contesto in cui il componente è inserito.

2 CARATTERIZZAZIONE DEI RIVESTIMENTI CERAMICI IN FACCIATA

I rivestimenti oggetto di studio rientrano nella categoria delle facciate incollate. Secondo Goldberg (1998), tale termine si riferisce ad *una chiusura esterna rivestita con un materiale di rivestimento, il quale è* *direttamente incollato ad una struttura di supporto*. Come si desume da questa definizione, gli elementi che compongono il sistema di rivestimento ceramico in facciata sono diversi; più nel dettaglio, consistono in:

- Piastrelle ceramiche;
- Sottofondo (malta o adesivi);
- Giunti di dilatazione.

Lo studio effettuato ha approfondito la conoscenza di ciascuno dei componenti menzionati, soffermandosi in modo particolare sulla progettazione e sulla posa in opera del sistema.

2.1 Patologia dei rivestimenti ceramici

Una volta presentati gli aspetti tecnologici delle facciate in ceramica, le possibili patologie che caratterizzano il sistema di rivestimento in esame sono state definite e raggruppate secondo la loro natura e il componente interessato. La base di questa categorizzazione è rappresentata dallo studio di Sousa (2008): come menzionato, il presente lavoro si propone come il proseguimento di quest'ultimo. La classificazione dei meccanismi di degrado è mostrata nella Tabella 2.1.

Tabella 2.1 - Caratterizzazione delle patologie che interessano i rivestimenti ceramici in facciata

Anomalie	
Difetti di carattere estetico	Sporco superficiale Degrado superficiale (usura e graffi) Rottura dei bordi Fori superficiali Macchie di umidità Crescita biologica Variazione del colore originale Efflorescenze
Fessurazioni	Fessurazione della superficie Fessurazioni senza direzione marcata Fessurazioni con direzione marcata
Deterioramento dei giunti di dilatazione	Macchie o variazione del colore Deterioramento senza perdita di materiale Deterioramento con perdita di materiale
Perdita di adesione	Mancanza di adesione Sollevamento delle piastrelle Distacco

Successivamente sono state esaminate le principali cause del deterioramento. Tra quelle individuate, le più ricorrenti sono: invecchiamento naturale, scelta di materiali non adatti per l'uso e scarsa attenzione alla progettazione dei dettagli costruttivi (Silvestre, 2005). Si può già osservare come gli aspetti della progettazione e posa in opera rivestono un ruolo chiave per la durabilità di questo tipo di rivestimento.

2.2 Definizione dei livelli di degrado

A questo punto, si è proceduto con la classificazione dei meccanismi di degrado in base alla loro gravità. È stato quindi necessario definire una scala fisica e visiva che permetta di quantificare il livello di degrado del componente edilizio. Tale classificazione rappresenta la base per le analisi svolte successivamente. Sono stati pertanto individuati cinque livelli di degrado, dal livello 0 (nessun degrado visibile), al livello 4 (degrado generalizzato). Per quanto riguarda le anomalie sopraelencate, queste sono state valutate in base alla loro importanza e all'area della facciata che interessano. Il risultato di questa classificazione è mostrato nelle Tabelle 2.2, 2.3, 2.4 e 2.5.

Tabella 2.2 – Livelli di degrado: Difetti di carattere estetico (Sousa, 2008)

Livelli di degrado	Anomalie	% area interessata
Livello 0 - Nessun degrado visibile	-	-
Livello 1 - Buone condizioni	Sporco superficiale	-
	Degrado superficiale (usura e graffi) Rottura dei bordi Fori superficiali Macchie di umidità Variazione del colore originale	≤ 10%
Livello 2 - Degrado leggero	Degrado superficiale (usura e graffi) Rottura dei bordi Fori superficiali Macchie di umidità Variazione del colore originale	> 10% e ≤ 50%
	Efflorescenze Crescita biologica	≤ 30%
Livello 3 - Degrado moderato	Degrado superficiale (usura e graffi) Rottura dei bordi Fori superficiali Macchie di umidità Variazione del colore originale	> 50%
	Efflorescenze Crescita biologica	> 30%

Tabella 2.3 - Livelli di degrado: Fessurazioni (Sousa, 2008)

Livelli di degrado	Anomalie	% area interessata
Livello 0 - Nessun degrado visibile	-	-
Livello 1 - Buone condizioni	Fessurazione della superficie	-
	Fessurazioni con direzione marcata (< 0,2 mm)	-
Livello 2 - Degrado leggero	Fessurazioni senza direzione marcata	≤ 30%
	Fessurazioni con direzione marcata (> 0,2 mm)	-
Livello 3 - Degrado moderato	Fessurazioni senza direzione marcata	> 30% e ≤ 50%
	Fessurazioni con direzione marcata (> 1 mm)	-
Livello 4 - Degrado generalizzato	Fessurazioni senza direzione marcata	> 50%
	Fessurazioni con direzione marcata (> 5 mm)	-

Tabella 2.4 - Livelli di degrado: Deterioramento dei giunti di dilatazione (Sousa, 2008)

Livelli di degrado	Anomalie	% area interessata
Livello 0 - Nessun degrado visibile	-	-
Livello 1 - Buone condizioni	Macchie o variazione del colore	-
Livello 2 - Degrado leggero	Deterioramento senza perdita di materiale	≤ 30%
	Deterioramento con perdita di materiale	≤ 10%
Livello 3 - Degrado moderato	Deterioramento senza perdita di materiale	> 30% e ≤ 50%
	Deterioramento con perdita di materiale	> 10% e ≤ 30%
Livello 4 - Degrado generalizzato	Deterioramento senza perdita di materiale	> 50%
	Deterioramento con perdita di materiale	> 30%

Tabella 2.5 – Livelli di degrado: Perdita di adesione (Sousa, 2008)

Livelli di degrado	Anomalie	% area interessata
Livello 1 - Buone condizioni	Nessun degrado visibile	-
Livello 2 - Degrado leggero	Mancanza di adesione Sollevamento delle piastrelle	≤ 20%
Livello 3 - Degrado moderato	Mancanza di adesione Sollevamento delle piastrelle	> 20%
	Distacco	≤ 10%
Livello 4 - Degrado generalizzato	Distacco	> 10%

3 LAVORO SUL CAMPO

Il lavoro sul campo è costituito da due fasi: la prima riguarda gli studi preliminari alle ispezioni, la seconda consiste nel lavoro in loco vero e proprio. Come accennato, lo presente studio segue la linea di ricerca del lavoro realizzato da Sousa (2008) sullo stesso argomento. Per questo motivo gli esiti della ricerca effettuata dall'autrice sono stati analizzati.

Sousa (2008) aveva raggiunto risultati solo in parte soddisfacenti: lo studio aveva infatti prodotto un output poco significativo dal punto di vista statistico. Un'indagine svolta con l'ausilio di ispezioni visive ha individuato la causa di tale risultato. Il motivo è stato identificato in alcuni elementi del campione raccolto dall'autrice, caratterizzati da esecuzione inadeguata o errori di progettazione. Questo li rende non statisticamente modellabili, in quanto non soggetti ad un "normale" processo di deterioramento. Tali rivestimenti sono stati rimossi dal campione.

A questo punto, una caratterizzazione delle facciate ispezionate da Sousa (2008) è stata effettuata; lacune e carenze sono state evidenziate, in modo tale da definire i dati necessari all'ottenimento di un campione più completo e uniforme. Gli aspetti considerati corrispondono alle variabili che influenzano la durabilità dei rivestimenti; tale elenco è stato stilato considerando i coefficienti moltiplicativi del metodo fattoriale, in funzione della successiva applicazione di tale metodo. Il numero minimo di facciate da ispezionare è stato calcolato pari a 115 rivestimenti (Tabella 3.1), definito in base alle fasce di età ed alle caratteristiche sopraccitate. L'età è stata conteggiata a partire dalla data di entrata in servizio del'edificio, o, nel caso in cui il rivestimento sia stato rinnovato, dalla data della ristrutturazione più recente.

Tabella 3.1 - Rivestimenti da ispezionare

Età	Distanza dal mare	Substrato	Orientazione della facciata	Azione di vento e pioggia	Esposizione all'umidità	Superficie	Colore	Dimensione	Totale
0 to 9	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**	10
10 to 19	**20**	15	**20**	**20**	15	15	15	**20**	20
20 to 29	**10**	5	5	**10**	**10**	**10**	**10**	**10**	10
30 to 39	**15**	10	**15**	**15**	10	10	**15**	10	15
40 to 49	**10**	5	**10**	**10**	**10**	5	**10**	**10**	10
50 to 59	**30**	20	20	**30**	20	20	25	20	30
60 to 69	**20**	15	**20**	10	10	15	15	**20**	20
									115

L'ultimo passo preliminare allo svolgimento delle ispezioni è consistito nella redazione di una checklist che permettesse di valutare lo stato di conservazione della facciata. La base per la stesura di tale modulo è la classificazione dei meccanismi di degrado effettuata nel capitolo precedente: le patologie presenti sono state annotate, insieme alla percentuale dell'area di facciata interessata e alle sue caratteristiche.

A questo punto, le ispezioni in loco sono state effettuate, per un ammontare finale di 120 elementi. I rivestimenti ispezionati sono stati aggiunti al campione di Sousa (2008), ottenendo un campione totale di 195 facciate. Le analisi statistiche riguardanti i risultati del lavoro sul campo concludono questa sezione; in generale, tale indagine ha mostrato come lo scopo prefissato di colmare le lacune presenti nel campione dell'autrice è stato realizzato per la maggior parte delle variabili. Il campione ottenuto è quindi in grado di fornire una solida base per gli studi successivi sulla previsione della vita utile.

4 EVOLUZIONE DEL DEGRADO

4.1 Modello di degrado

Una volta concluso il lavoro sul campo, la fase seguente della ricerca ha visto l'applicazione di un modello di degrado. Per modello di degrado si intende una funzione matematica in grado di associare l'informazione qualitativa ottenuta con le ispezioni in loco ad un indice quantitativo, che sia in grado di descrivere lo stato di degrado del componente considerato. Il metodo adottato per tale valutazione è stato ideato da Gaspar (2009), contestualmente allo studio relativo alla durabilità dei componenti edilizi. I dati necessari per l'applicazione del modello di calcolo sono rappresentati dalla classificazione dei meccanismi di degrado effettuata nel capitolo 2 e dalle informazioni relative ai rivestimenti raccolte durante le ispezioni;

l'output è invece un valore che quantifica il deterioramento complessivo del rivestimento, denominato severità del degrado ($S_{w,rp}$). Più è alta la percentuale di $S_{w,rp}$, peggiore è la condizione in cui versa la facciata.

Prima dell'applicazione è stato necessario definire dei coefficienti di ponderazione per ogni causa di degrado (Tabella 4.1). Tale ponderazione stabilisce una gerarchia tra le varie anomalie, partendo dal presupposto che non tutte le patologie sono ugualmente rilevanti. In questo modo, la formula applicata, oltre a considerare l'area affetta da un determinato meccanismo di degrado, prende in esame anche l'importanza relativa dello stesso, permettendo una valutazione più affidabile e realistica. L'equazione 4.1 riporta il modello di Gaspar (2009):

$$S_{w,rp} = \frac{\sum(A_n \cdot k_n \cdot k_{a,n})}{A \cdot \sum(k_{max})} \qquad \text{Equazione 4.1}$$

Dove:

$S_{w,rp}$ - severità del degrado, espressa in percentuale;

A_n - area del rivestimento ceramico affetta da una patologia n, in metri quadrati;

k_n - livello di degrado della patologia n, con $k_n \in \{1, 2, 3, 4\}$;

$k_{a,n}$ - importanza relativa delle anomalie riscontrate, vedere Tabella 4.1;

A - area del rivestimento ceramico, in metri quadrati;

k_{max} - somma dei coefficienti k_n pari al maggior livello di degrado possibile; è uguale a 15 (3 + 4 + 4 + 4 → anomalie estetiche + fessurazioni + deterioramento dei giunti + perdita di aderenza).

Tabella 4.1 - Importanza relativa delle anomalie riscontrate

Difetti di carattere estetico	$K_{a,n}$	Fessurazioni	$K_{a,n}$	Deterioramento dei giunti di dilatazione	$K_{a,n}$	Perdita di adesione	$K_{a,n}$
Sporco superficiale	0.25	Fessurazione della superficie	0.25	Macchie o variazione del colore	0.25	Mancanza di adesione	1.50
Degrado superficiale (usura e graffi)	0.60	Fessurazioni senza direzione marcata	1.00	Deterioramento senza perdita di materiale	1.00	Sollevamento delle piastrelle	1.50
Rottura dei bordi	0.60	Fessurazioni senza direzione marcata	1.00	Deterioramento con perdita di materiale	1.50	Distacco	2.00
Fori superficiali	0.60						
Macchie di umidità	0.60						
Crescita biologica	1.00						
Variazione del colore originale	0.60						
Efflorescenze	1.00						

4.2 Evoluzione del degrado dei rivestimenti ceramici in facciata

L'utilizzo della formula sopraccitata permette di tracciare un grafico che illustri l'evoluzione del deterioramento dei rivestimenti nel tempo (Figura 4.1). I punti del grafico rappresentano gli elementi del campione in esame: per ognuno di essi è stata calcolata la severità del degrado, utilizzando i dati raccolti sul campo. Il valore di $S_{w,rp}$ ottenuto è stato poi relazionato all'età della facciata. La curva di degrado in Figura 4.1 rappresenta la linea di regressione media dei valori; come si può osservare, tale curva delinea in modo molto chiaro la perdita di performance del componente col passare del tempo. Tale grafico si dimostra statisticamente significativo, fatto testimoniato dal valore medio-alto del coefficiente di determinazione (R^2), il quale indica la correttezza del modello statistico utilizzato.

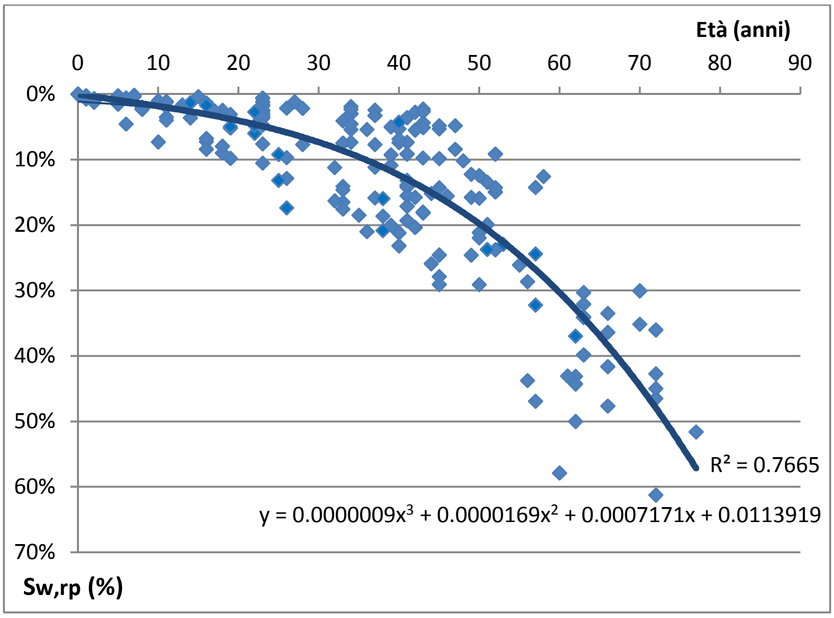

Figura 4.1 - Evoluzione del degrado dei rivestimenti ceramici in facciata

Il passo successivo è consistito nell'estrapolare il valore della vita utile dal grafico ottenuto. Per fare ciò, si è ricorsi alla classificazione dei livelli di degrado effettuata nel capitolo 2: i livelli precedentemente definiti sono stati correlati ai valori di severità del degrado calcolati con il modello di Gaspar (2009). La Tabella 4.2 riporta tale suddivisione. Come si può vedere, ad ogni grado di deterioramento corrisponde un range di valori di severità del degrado.

A questo punto, è stato stabilito lo stato limite di vita utile per i rivestimenti esterni in ceramica. Secondo le corrispondenze proposte nella Tabella 4.2 e i requisiti minimi da soddisfare, il livello 3 è stato fissato come fine della vita utile. Questa scelta è stata fatta per dare continuità agli studi precedentemente svolti da Sousa (2008), Silva (2009), Emídio (2012) e Ximenes (2012) riguardanti la determinazione della vita utile di vari componenti edilizi. Tale soglia corrisponde al momento in cui lo stato di degrado passa da essere considerato leggero ad essere moderato, ovvero quando il rivestimento presenta gravi difetti localizzati o lievi anomalie generalizzate. In riferimento alla Tabella 4.2, il limite stabilito per la vita utile corrisponde ad un valore di severità del degrado pari al 20%. Tornando al grafico in Figura 4.1, si può notare come la curva di degrado, in corrispondenza di $S_{w,rp}$ = 20%, individua una media pari a 50 anni. Tale valore rappresenta quindi la vita utile prevista per i rivestimenti esterni in ceramica.

Tabella 4.2 - Corrispondenza tra gli indicatori del degrado

Livelli di degrado	Stato di conservazione del rivestimento	Sw,rp
Livello 0	Nessun degrado visibile	Sw,rp ≤ 1%
Livello 1	Buone condizioni	1% < Sw,rp ≤ 6%
Livello 2	Degrado leggero	6% < Sw,rp ≤ 20%
Livello 3	Degrado moderato	20% < Sw,rp ≤ 50%
Livello 4	Degrado generalizzato	Sw,rp ≥ 50%

Il risultato ottenuto con l'applicazione del modello di degrado adottato è stato poi analizzato in base alle variabili che caratterizzano le proprietà dei rivestimenti e i vari agenti di degrado (Tabella 3.1). Risultati statisticamente significativi sono stati ottenuti per la maggior parte dei fattori considerati. Alcuni esempi sono riportati nelle Figure 4.2, 4.3, 4.4 e 4.5. Come si può osservare, le curve medie relative ad ogni variabile delineano nettamente il deterioramento del rivestimenti nei vari casi. Per la maggior parte di essi, l'affidabilità dei risultati è corroborata dai valori apprezzabili dell'indicatore statistico R^2.

Si presti maggiore attenzione alla Figura 4.5, ritenuta particolarmente significativa. Da tale grafico emerge chiaramente come un'esecuzione incorretta od una scarsa attenzione ai dettagli costruttivi comporta una sensibile riduzione della vita utile prevista. Si è dimostrato quindi come i rivestimenti caratterizzati da una progettazione inadeguata, o addirittura assente, mostrano un aspettativa di vita dimezzata: 24 anni anziché 50. Si ricorda comunque che le facciate che presentano una'esecuzione carente sono state escluse dal campione. Interessante è anche il grafico riguardante il livello di manutenzione: una lettura di tale output suggerisce che le facciate sottoposte ad una regolare manutenzione non solo durano più a lungo, ma il loro degrado sembra essere "azzerato" per i primi 20 anni; in altre parole, prima che entrino in azione meccanismi di degrado più seri che intaccano parti vitali del sistema di rivestimento, il componente si presenta come nuovo.

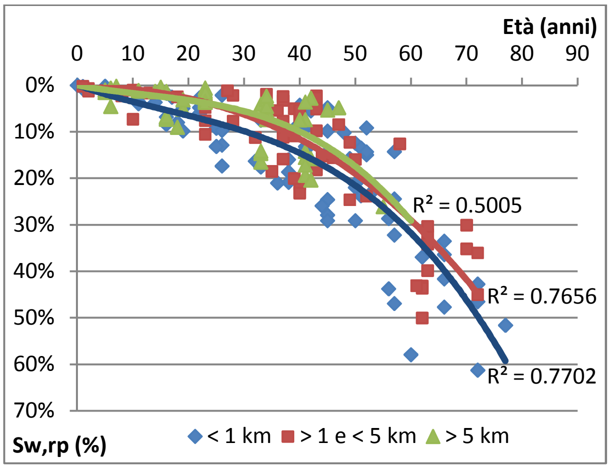

Figura 4.2 - Evoluzione del degrdao in base alla distanza dal mare

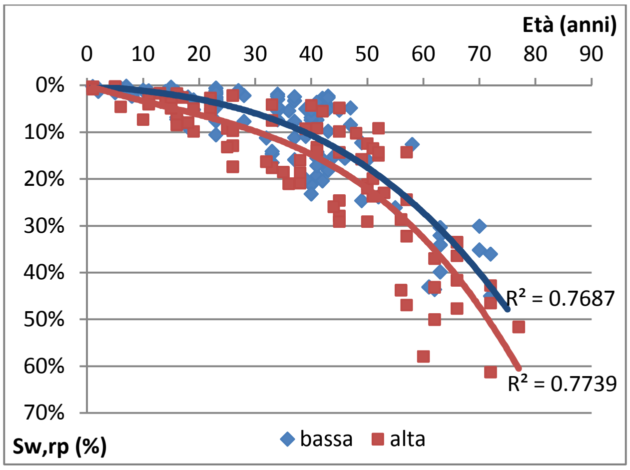

Figura 4.3 - Evoluzione del degrdao in base all'esposizione all'umidità

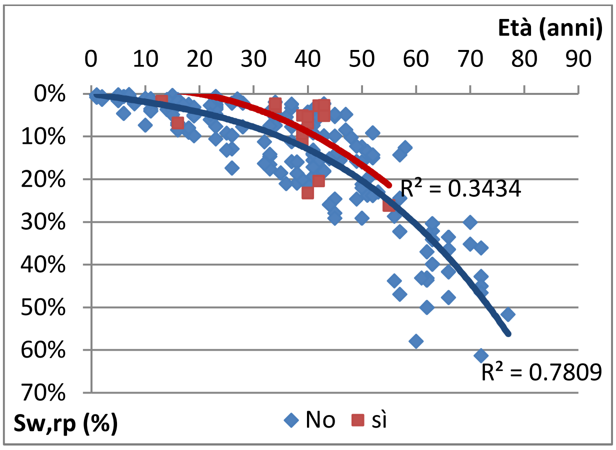

Figura 4.4 - Evoluzione del degrdao in base al livello di mantunezione

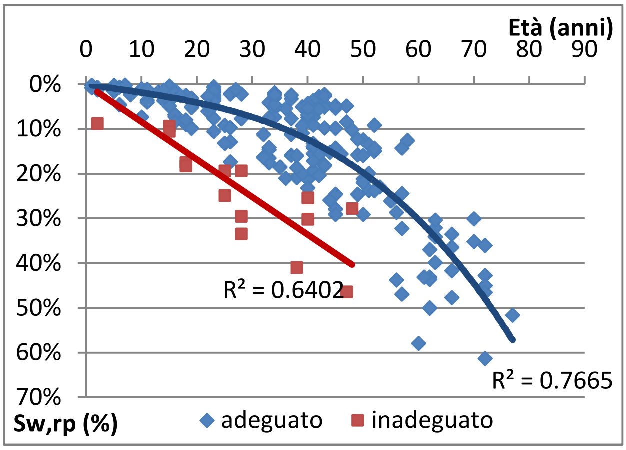

Figura 4.5 - Evoluzione del degrdao in base al livello di esecuzione

5 APPLICAZIONE DEL METODO FATTORIALE

L'applicazione del metodo fattoriale agli elementi del campione è svolta in due fasi, corrispondenti ai termini che compongono l'equazione 1.1: dapprima è stata calcolata la Vita Utile di Riferimento, successivamente si è proceduto con l'attribuzione dei coefficienti moltiplicativi, per poi giungere alla valutazione finale della Vita Utile Stimata in condizioni di progetto.

5.1 Vita Utile di Riferimento

Per valutare la Vita Utile di Riferimento, sono stati effettuate alcune operazioni preliminari. La RSL svolge un ruolo fondamentale nell'applicazione del metodo. Per questo motivo, è stata calcolata come la media di tre valori, in modo tale da ottenere un dato che fosse il più affidabile possibile. Per prima cosa, la vita utile è stata valutata per ogni rivestimento che compone il campione. Pe fare ciò, è stata utilizzata la metodologia proposta da Gaspar (2002): si tratta del metodo di conversione al valore delle ordinate, esplicitato nell'Equazione 5.1. Fondamentalmente, questo consiste nell'identificazione di un fattore k che metta in relazione le coordinate dei punti del grafico.

$$f' = k \cdot (f) = k \cdot a \cdot x^3 + k \cdot b \cdot x^2 + k \cdot c \cdot x \qquad \text{Equazione 5.1}$$

Dove:

f Funzione della curva media di degrado (Figura 4.1);

f' Funzione della curva di degrado in ogni punto del grafico;

k Fattore di relazione. In particolare, k = $S_{w,rp}$ A/$S_{w,rp}$ M; in riferimento alla Figura 4.1, $S_{w,rp}$ A = severità di degrado di un punto A qualsiasi e $S_{w,rp}$ M = severità di degrado della curva media, in corrispondenza della stessa età del punto A;

a, b, c Costanti dell'equazione della curva di degrado.

La funzione sopraccitata ha permesso di calcolare un valore di vita utile per ogni punto del grafico. I risultati sono stati utilizzati per tracciare un altro grafico, mostrato in Figura 5.1. In questo caso viene rappresentata la distribuzione nel tempo dei valori di vita utile dei rivestimenti. La linea di regressione rappresenta il valore medio, pari a 53 anni. La variazione minima tra i due valori (50 e 53 anni) avvalora i risultati ottenuti finora. Come per lo studio precedente, anche questo grafico è stato analizzato in base a tutte la variabili che influenzano il deterioramento dei rivestimenti (Tabella 3.1). I risultati ottenuti comprovano quelli precedenti. A titolo esemplificativo è riportata l'analisi relativa alla distanza dal mare degli edifici (Figura 5.2). Si può notare come esso confermi la netta differenza riscontrata in Figura 4.2.

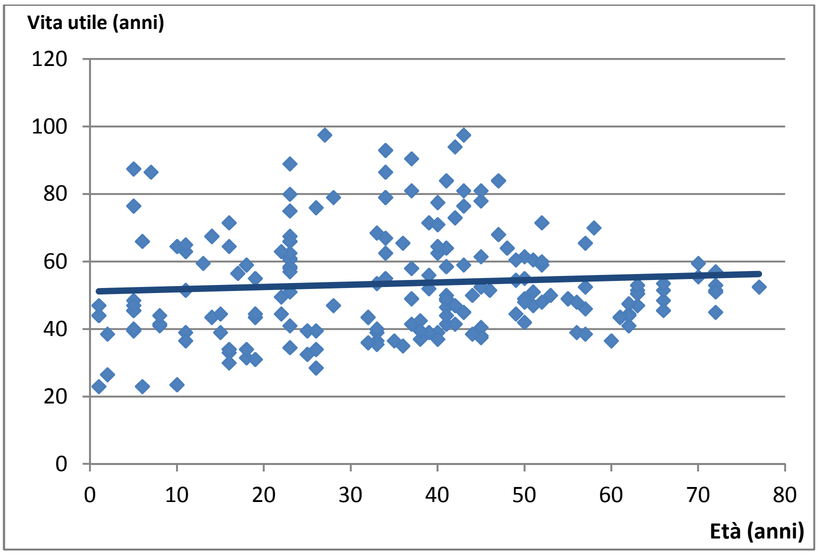

Figura 5.1 - Dsitribuzione nel tempo della vita utile prevista

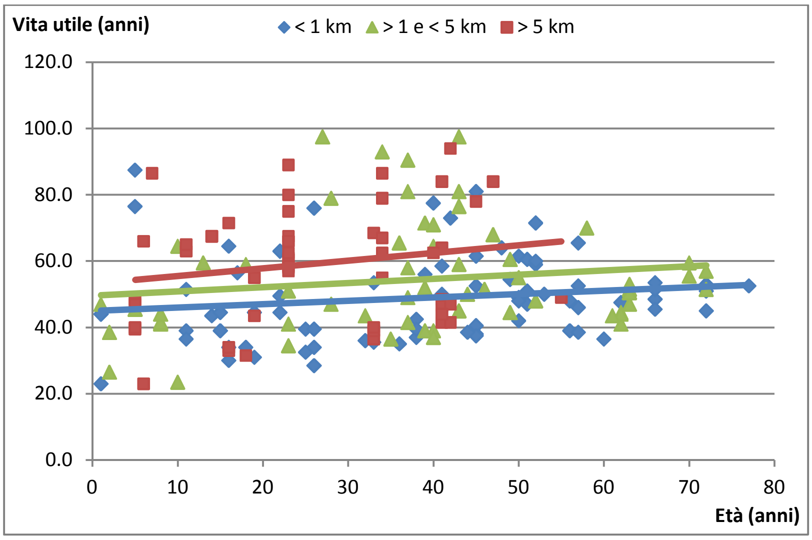

Figura 5.2 - Dsitribuzione nel tempo della vita utile prevista relativamente alla distanza dal mare

Viene ora preso in considerazione il metodo fattoriale, con lo scopo di calcolare la RSL. Le variabili considerate finora per le analisi riguardanti i modelli di degrado sono state classificate in base ai fattori moltiplicativi facenti parte del metodo (Equazione 1.1). Ognuno di essi comprende più variabili, le quali a loro volta si compongono di sub-fattori, che descrivono le varie caratteristiche esaminate (Tabella 5.1). Non sono state considerati i fattori relativi all'ambiente interno e alle condizioni d'uso; il primo in quanto non influenza il degrado della facciata esterna, il secondo perché alquanto difficile da determinare con esattezza mediante ispezioni visive.

Tabella 5.1 - Dsitribuzione nel tempo della vita utile prevista relativamente alla distanza dal mare

A - Qualità del componente		E - Ambiente esterno	
A1 - superficie	Invitriata Non invitriata	E1 - orientazione della facciata	Nord Est Sud Ovest
A2 - colore	Chiaro Scuro Bianco	E2 - azione del vento e della pioggia	Lieve Media Severa
A3 - dimensione della piastrella	L < 20 L ≥ 20	E3 - distanza dal mare	< 1 km > 1 e < 5 km > 5 km
B - Qualità di progettazione		E4 - esposizione all'umidità	Alta Bassa
B1 - substrato	Muratura Calcestruzzo	F - Condizioni d'uso	
B2 - giunti periferici	Sì No	G - Livello di manutenzione	
B3 - protezioni periferiche	Sì No	G1 - manutenzione regolare	Sì No
C - Qualità di esecuzione		G2 - facilità di ispezione	Normale Sfavorevole
C1 - livello di esecuzione	Adeguato Inadeguato		
D - Ambiente interno			

Successivamente, ad ognuna delle variabili elencate nella Tabella 5.1 è stato assegnato un coefficiente moltiplicativo, al fine di pesare la loro influenza sulla perdita di prestazione dei rivestimenti. I valori attribuiti sono 0.8, 0.9, 1, 1.1 e 1.2, a seconda della minore o maggiore severità: tanto più il sub-fattore indica una condizione favorevole, tanto più è alto il valore conferito. Il punto di riferimento per l'assegnazione di tali coefficienti sono i grafici ottenuti in precedenza. Per esempio, in riferimento alle Figure 4.4 e 5.2, i coefficienti sono stati 0.8, 1 e 1.1, rispettivamente per gli edifici vicini, a media distanza e lontani dal mare. La moltiplicazione dei valori attribuiti ad ogni variabile individuerà il coefficiente moltiplicativo dei fattori che compongono l'Equazione 1.1.

Una volta che i sub-fattori sono stai ponderati, il metodo fattoriale e stato inversamente applicato (Equazione 5.2):

$$ESL = RSL \cdot A \cdot B \cdot C \cdot D \cdot E \cdot F \cdot G \quad \rightarrow \quad RSL = \frac{ESL}{A \cdot B \cdot C \cdot D \cdot E \cdot F \cdot G} \quad \rightarrow \quad RSL = \frac{ESL}{0.8^x \cdot 0.9^y \cdot 1.1^z \cdot 1.2^k}$$

Dove: Equazione 5.2

ESL 50 anni;

x numero di occorrenze di 0.8;

y numero di occorrenze di 0.9;

z numero di occorrenze di 1.1;

k numero di occorrenze di 1.2.

Lo scopo dell'operazione era determinare un valore di Vita Utile di Riferimento per ogni elemento del campione. A questo punto il valore finale della RSL è stato calcolato, come accennato, tramite la media di tre valori:

- 50 anni - Vita utile media ottenuta con il metodo grafico di Gaspar (2009) di Figura 4.1;
- 51 anni - Media dei valori di RSL calcolati con l'Equazione 5.2, considerando solo gli elementi caratterizzati da tutti i sub-fattori uguali a 1 (condizione standard);
- 53 anni - Media dei valori di RSL calcolati con l'Equazione 5.2, considerando solo gli elementi caratterizzati da una deviazione standard del rapporto ESL/RSL < 3%.

La Vita Utile di Riferimento per i rivestimenti ceramici in facciata è stata fissata a 51 anni. Come si può osservare, anche in questo caso la coerenza e l'affidabilità dei risultati sono confermate dalla scarsa differenza tra i valori ottenuti.

5.2 Fattori moltiplicativi

Il secondo ed ultimo passo effettuato preliminarmente all'applicazione del metodo fattoriale è rappresentato dallo studio di sei scenari, il cui scopo è migliorare l'accuratezza dei coefficienti precedentemente assegnati ai sub-fattori. Ogni scenario è il risultato di una diversa iterazione ed è caratterizzato da una diversa serie di coefficienti. I criteri che hanno portato all'attribuzione dei valori sono riportati nella tabella 5.2.

Quindi, il metodo fattoriale è stato applicato sei volte agli elementi facenti parte del campione, una per ogni scenario studiato, utilizzando un diverso set di fattori moltiplicativi. In questo modo, la Vita Utile Stimata in condizioni di progetto è stata valutata per ogni rivestimento. Successivamente, sono state eseguite analisi statistiche dei valori di ESL ottenuti, attraverso il calcolo di diversi indicatori statistici.

In generale, lo scopo principale era verificare quale fosse l'iterazione di coefficienti che massimizzasse la percentuale di valori FM/GM intorno a 1.00. Con FM/GM si intende il rapporto tra la Vita Utile Stimata ottenuta attraverso il Metodo Fattoriale e il valore risultante del Metodo Grafico (modello di Gaspar (2009)). Più il rapporto è vicino a 1.00, più vicino è il risultato alla realtà; in altre parole, un valore FM/GM prossimo all'unità indica che la vita utile calcolata con il metodo fattoriale è pressoché la medesima di quella riscontrata sul campo, e valutata attraverso l'Equazione 5.1. La percentuale in questione è indicata nell'ultima riga della Tabella 5.3.

Tabella 5.2 - Criteri di attribuzione dei coefficienti per ogni scenario

Scenario 1	Questo scenario assume come riferimento la vita utile media ottenuta con lo studio di Figura 5.1 (53 anni). È stata poi attribuita una variazione di 0.05 da 1.00 per ogni anno di differenza tra la vita utile di ciascun sub-fattore e la media. Un esempio: i rivestimenti caratterizzati da una superficie non invetriata presentano una previsione di vita utile media pari a 50 anni. Il coeffciente assegnato a tale variabile sarà quindi 0.85 (1.00 - 3*0.05)
Scenario 2	Il meccanismo di attribuzione è il medesimo dello scenario precedente, ma in questo caso la vita utile media considerata è quella di Figura 4.1 (50 anni).
Scenario 3	Un coefficiente pari a 1.00 è stato attribuito a tutti i sub-fattori, con l'intento di studiare una condizione neutra
Scenario 4	I valori assegnati sono quelli suggeriti dalla norma ISO 15686: 0.80, 1 e 1.20; il riferimento per il conferimento sono i grafici delle Figure 4.1 e 5.1; tali valori non sono stati tuttavia vincolanti, ma solo indicativi
Scenario 5	I valori assegnati sono 0.90, 1 e 1.10; come per il caso precedente, i coefficienti sono attribuiti orientativamente secondo i risultati degli scenari 1 e 2
Scenario 6	L'ultimo scenario consiste in un iterazione manuale ottimizzata. I valori conferiti presentano tre decimali e sono stati scelti in base a tutti gli studi precedenti e ai relativi risultati

Si può notare come gli scenari 1 e 2 hanno ottenuto i risultati peggiori in termini di percentuale; il motivo è che alcuni sub-fattori presentano una notevole differenza tra la vita utile prevista e il valore medio. Questo comporta l'attribuzione di coefficienti di ponderazione eccessivamente alti o bassi, i quali conducono a valori irrealistici di ESL. Infatti, lo scenario 3 mostra una percentuale maggiore, a conferma del fatto che il set ottimale dei coefficienti dovrebbe essere più vicino alle condizioni standard (1.00). Gli scenari 4, 5 e 6 hanno dato risultati decisamente migliori, come testimoniato dagli indicatori statistici. Il particolare, la percentuale più alta riguarda l'iterazione ottimizzata (Tabella 5.4). Tuttavia, anche lo scenario che figura i valori suggeriti dallo standard ISO ha raggiunto risultati ragguardevoli.

Tabella 5.3 - analisi statistica dei risultati dell'applicazione del metodo fattoriale

Scenario		**1**	**2**	**3**	**4**	**5**	**6**
Media FM/GM (< 1.05)		0.737	0.747	1.039	0.978	1.033	**1.003**
Deviazione standard FM/GM		0.524	0.315	0.313	**0.287**	0.289	0.291
Ampiezza dei risultati	FM (anni) (< GM)	148.13	69.14	0.00	56.78	37.89	58.32
	GM (anni)	74.50	93.00	74.50	74.50	74.50	74.50
Valori estremi ottenuti con FM	Max. (< 106 anni)	156.22	83.65	51.00	88.08	74.70	89.70
	Min. (> 13.25 anni)	8.09	14.51	51.00	31.30	36.81	31.38
FM/GM ≥ 0.85 (> 50%)		33.33%	33.85%	66.67%	64.10%	**69.23%**	**69.23%**
FM/GM ≥ 1.50 (< 10%)		8.21%	**1.54%**	5.13%	5.64%	7.18%	5.64%
0.85 ≤ FM/GM ≤ 1.15		14.87%	22.05%	36.41%	45.64%	41.54%	**47.69%**

Tabella 5.4 - Valori assegnati nello scenario 6

Fattori	Sub-fattori	Coefficienti
A1 - superficie	Invitriata	**1.050**
	Non invitriata	**0.850**
A2 - colore	Chiaro	**1.000**
	Scuro	**1.000**
	Bianco	**1.025**
A3 - dimensione della piastrella	L < 20	**1.000**
	L ≥ 20	**0.800**
B1 - substrato	Muratura	**1.000**
	Calcestruzzo	**1.000**
B2 - giunti periferici	Sì	**1.025**
	No	**1.000**
B3 - protezioni periferiche	Sì	**1.000**
	No	**1.000**
C1 - livello di esecuzione	Adeguato	**1.000**
	Inadeguato	**0.500**
E1 - orientazione della facciata	Nord	**0.950**
	Est	**1.000**
	Sud	**1.050**
	Ovest	**1.050**
E2 - azione del vento e della pioggia	Lieve	**1.125**
	Media	**1.000**
	Severa	**0.975**
E3 - distanza dal mare	< 1 km	**0.925**
	> 1 e < 5 km	**0.950**
	> 5 km	**1.050**
E4 - esposizione all'umidità	Alta	**0.900**
	Bassa	**1.050**
G1 - manutenzione regolare	Sì	**1.350**
	No	**1.000**
G2 - facilità di ispezione	Normale	**1.000**
	Sfavorevole	**0.950**

6 CONCLUSIONI

Complessivamente, i risultati della ricerca svolta sono stati soddisfacenti. Inizialmente, il lavoro sul campo ha prodotto un consistente numero di rivestimenti; tali ispezioni hanno permesso di migliorare il campione di Sousa (2008). Sulla base dei questi dati è stato poi applicato il modello di degrado sviluppato da Gaspar (2009). La vita utile prevista per i rivestimenti ceramici è stata quantificata pari a 50 anni. Le analisi successive riguardanti le variabili di degrado hanno prodotto esiti apprezzabili: come illustrato in precedenza, particolarmente significativo è lo studio che interessa i rivestimenti caratterizzati da un esecuzione inadeguata, che erano stati esclusi dal campione. Questi mostrano un'aspettativa di vita di 24 anni, esattamente la metà di un rivestimento ben progettato e posato.

Per quanto riguarda il metodo fattoriale, gli output si sono dimostrati statisticamente significativi, incoraggiando ulteriori ricerche nel campo della previsione della vita utile con l'utilizzo di questa metodologia. Infatti, il secondo moglior risultato, in termini di percentuale di valori di ESL prossimi alla realtà, è rappresentato proprio dallo scenario che vede l'attribuzione dei coeffcienti previsti dalla norma

ISO. Tale esito è indice dell'affidabilità del metodo fattoriale, il quale, nonstante i limiti intrinsechi, ha dimostrato di essere uno strumento efficace e di semplice impiego.

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1 INTRODUCTION

1.1 Preliminary considerations

Ceramic tiles have been used for centuries as a decorative and functional cladding for the exterior façades of buildings. Their development can be traced to 4000 B.C. in Egypt. However, it was not until the 13th century that ceramic tiling for exterior walls was established in the Middle East. All prominent buildings during that period had ceramic tile clad exterior walls. Then, in the 16thcentury, the influence of Islamic architecture gradually spread to Spain, Portugal and Italy: ceramic tile was used extensively as an external cladding in public buildings. Portuguese azulejos bear testimony to this historical period (Goldberg, 1998).

Ceramic tiles have been used primarily in building façades until when the bulk of production began to be intended to floors and interior walls. From that moment, the use of ceramic tiles in modern building façades has been mostly limited to an isolated decorative element. This was due to the inconsistent performance of past installations, caused by the great reliance of this component on a proper installation and a careful choice of materials.

Only recently, with the current awareness about the importance of these aspects, did the use of ceramic tiles as an external cladding system begun to increase again, with the enhancement of installation techniques and the development of new applications (Figure 1.1). An example is represented by ventilated façades, which have been widely used in the last years.

Figure 1.1 - Examples of ceramic external wall claddings: traditional and new façades

1.2 Target of the dissertation

The main goal of this dissertation consists on evaluating the service life of ceramic external claddings, through the factor method. Therefore, the background of the study is service life prediction for buildings and their components. The general aim of that research is worth being briefly discussed. In fact, the recent interest on the durability of buildings and materials is increasing. According to Hovde (1998), the reasons behind that attention are mainly economic and environmental; the evaluation of these aspects is fulfilled with the Life Cycle Cost and analysis and the Life Cycle Assessment (Hendriks et al., 2004). Service life prediction falls within these categories: in fact, it allows planning the duration of a building component, and accordingly the maintenance operations and the costs related.

Therefore, the main scope of the service life evaluation of buildings materials and components is to define their durability after installation, which ensures a more realistic planning (Marteinsson, 2005). More precisely, the assessment of service life is proposed as a work tool for designers.

In this respect, Frohnsdorff and Martin (1996) have debated the present difficulty for designers in collecting the needed information from scattered sources, which are of uncertain quality. Here lies the importance of developing an approach to life prediction, which is based on standardized and reliable knowledge. This idea is sketched in Figure 1.2. Radial arrows represent the flows of knowledge, being drawn on to support decision in the indicated stage of the building cycle. The inward arrows concern the occupancy and renovation phases, whereas the outward ones feature all processes, but in particular the steps of planning and programming. In fact, it is exactly at these moments that the knowledge acquired through research on components' durability demonstrates its practical usefulness.

Therefore, the reason of the importance of service life prediction is as follows: when applying environmental Life Cycle Assessment (LCA), Life Cycle Costing (LCC) analysis, or maintenance planning to buildings and their components, a central piece of information required is exactly a reasonable assumption of the service life of such material, product or component (Sjöström et al., 2005).

1.3 Conceptual underpinnings of the study

At international level, the prediction of the service life is dealt by the CIB/RILEM technical committee, which developed an ISO standard on service life planning (ISO 15686). Service life is defined by the ISO as *the period of time, after construction, during which the building and its elements are expected to perform within specified parameters*. In this definition, the performance approach that characterizes the service life prediction clearly emerges: that is, the identification of a performance threshold that defines the minimum acceptable requirements (Daniotti, 2006). Indeed, service life prediction may be described as a performance based planning processes, which establishes the rationale for each project and for its specific conditions (Hovde and Moser, 2004; Sjöström et al., 2005).

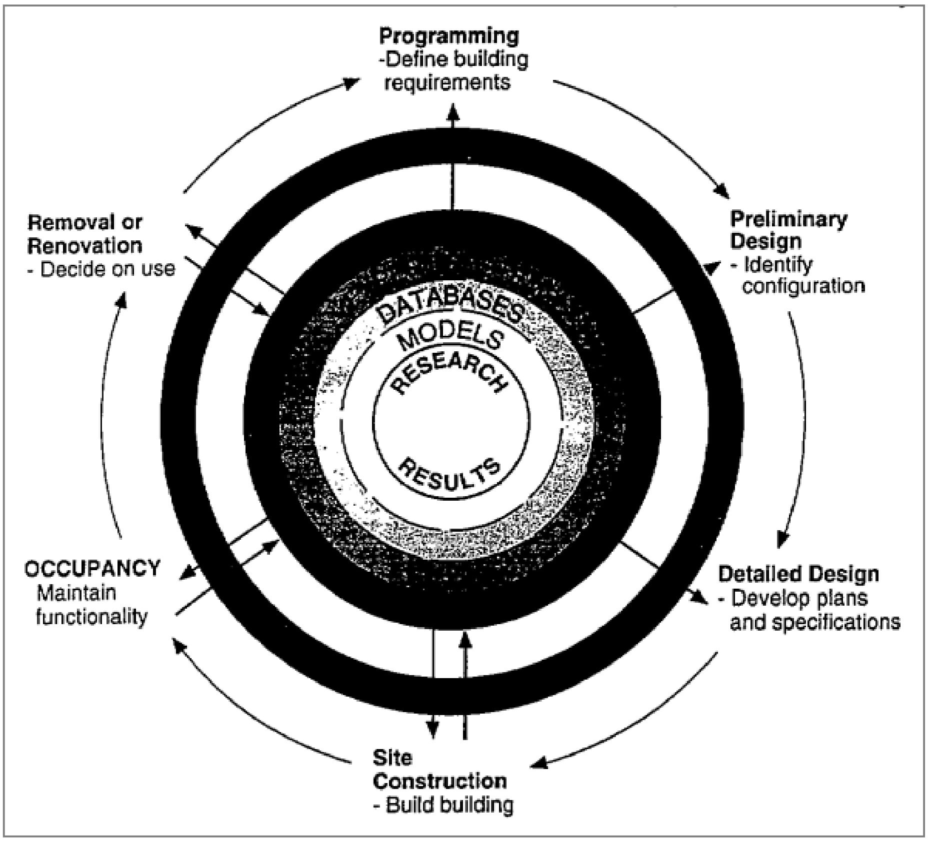


Figure 1.2 - Integrated knowledge of performance of building materials and components (Frohnsdorff and Martin, 1996)

Concerning the ISO 15686 standard, this also defines obsolescence, as the *loss of the ability of an element in meeting the changing performance requirements; it may be functional, technological or economic*. Gaspar (2002) related this categorization with the service life definition. The author developed three different criteria to evaluate the building loss of usefulness, corresponding to as many parameters:

- Functional or visual criteria → Functional service life (serviceability) - Time period during which a construction allows its use without the need of substantial changes;
- Physical/technical criteria → Physical service life (durability) - Period of time in which a building maintains the initial physical and technical performance;
- Economic criteria → Economic service life - Period of time during which a construction maintains an annual cost/benefit ratio lower than the alternatives.

The approach applied in the current dissertation takes into account the second criterion. As seen in chapter 4, the minimum requisites that determine the service life of ceramic claddings will be set according to physical and technological parameters.

1.3.1 End of service life

The next step of the review is the examination of the performance requirements, in order to define the end of service life. In fact, the prediction of service life entails the setting of a limit for the component's lifetime, which can vary according to the threshold established.

This leads to the need to define another important concept: durability. This is *the capability of a building or its parts to perform its required function over a specified period of time under the influence of the agents anticipated in service* (ISO 15686-1). Such agents result in degradation, which is the modification over time of the component properties, as a result of various causes.

The concepts of durability and service life end are graphically expressed in Figure 1.3. Such schematic degradation path for building components has been developed by Moser (1999), which dealt with the enhancement of the practical evaluation of service life. As seen in further chapters, this graph, featuring time in abscissa and loss of performance in ordinate, perfectly represents the ideas above mentioned. The end of the service life is the value given by the intersection between the curve and the limit defined.

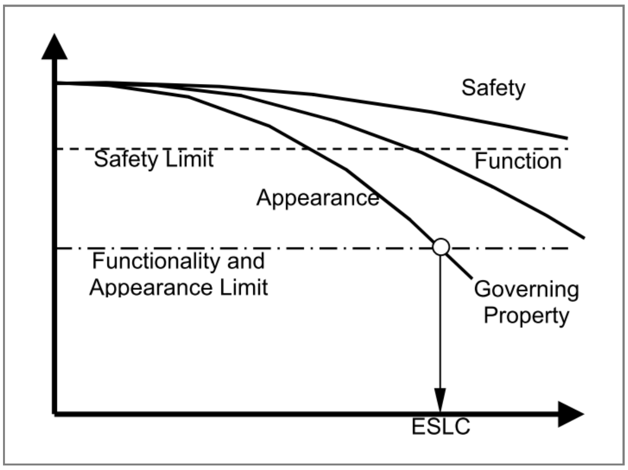


Figure 1.3 - Schematic degradation (Moser, 1999)

As depicted, Moser (1999) considers three parameters to set the required threshold: appearance, function and safety, in increasing order of severity. This is the same basic concept considered by Gaspar (2002) and it can be related to the three criteria that determine the minimum requisites:

- End of functional service life - Functionality no longer meets the requirements, or changes in style or fashion involve new requirements regarding appearance, or material choice;
- End of physical service life - Some critical material properties no longer meet the technical requirements;

- End of economic service life - It is no longer economic to maintain the existing component, and the replacement with a new one, of similar type, represents a better choice.

In the current dissertation, the end of the service life will be set further, in the context of the degradation evolution analysis, based on the pathological condition of the inspected claddings. In fact, as mentioned, the parameter adopted to evaluate the component performance concerns physical and technical service life, i.e. durability.

1.3.2 Service life estimation methods

Once defined the service life as a concept, a short review on the methodologies that allow its evaluation has been made. According to Daniotti (2008), there are the three main families of methods, which identify a sort of reliable hierarchy. They are:

- Probabilistic methods - They can be defined as stochastic processes, which are based on probabilistic matrix calculations through which one can define the probability of state change of the element under study; Markov chain model is an example. These methods are the most reliable, but also the most complex, as they require fairly sophisticated inputs in the form of probabilities (Re Cecconi, 2002);
- Engineering methods - These methods are used to analytically identify the decrease of performance, enabling a better control of the degradation phenomena that are object of study (Daniotti, 2003). These methods are at an intermediate level between the other two methods. An example is represented by the FMEA method;
- Deterministic methods - They consist of the study of degradation factors affecting the materials, in the understanding of their mechanism of action, and finally, in their quantification through degradation functions (Gaspar, 2002). Such methodologies are characterized by their easy applicability; an example is the factor method.

1.3.3 Factor method

As the methodology adopted for the current dissertation, the factor method application has been examined. Defined within the ISO 15686-1, it estimates the service life of building component by multiplying their reference service life by several factors, whose value depends on the type of building component under investigation (Re Cecconi, 2005). In detail:

$$ESL = RSL \cdot A \cdot B \cdot C \cdot D \cdot E \cdot F \cdot G \qquad \text{Equation 1.1}$$

Where:

ESL Estimated service life;

RSL Reference service life;

A Factor related to the quality of the materials;

B Factor related to the design level;

C Factor related to the execution level;

D Factor related to the interior environmental conditions;

E Factor related to the exterior environmental conditions;

F Factor related to the in-use conditions;

G Factor related to the level of maintenance.

Regarding the inputs of the method, these consist of RSL and multiplying coefficients; for this, the main task of the service life prediction using the factor method consists of determining reliable values for such terms.

In particular, reference service life is defined as *the period in years that the component or assembly can normally be expected to last* (ISO 15686-1). According to Hovde (1998), there are various procedures to deduce such value: experience and knowledge of actual circumstances, testing, or statistics. In the current work, RSL will be deducted by statistical data obtained from a substantial amount of onsite inspections.

Instead, concerning the multiplying factors, they mirror the effects that influence the service life of a building component. For this reason, each of them takes into account several variables, named sub-factors, which define the cladding condition. Such sub-factors are individuated for each category, based on the features and the agents that characterize the degradation of the component under analysis. A schematic representation of the process that leads to the sub-factors definition is shown in Figure 1.4.

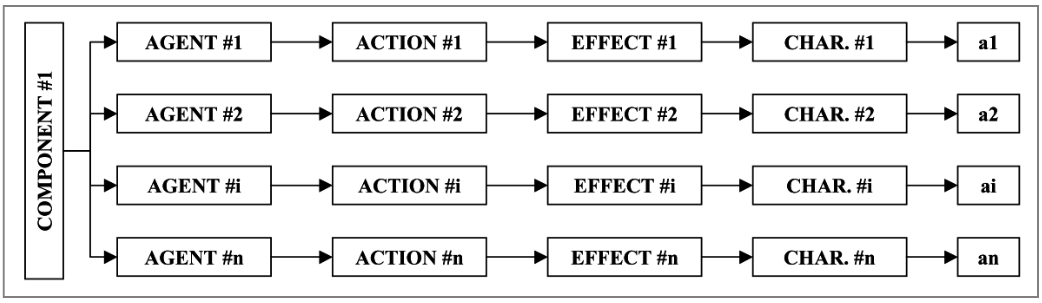


Figure 1.4 - The way leading from agents to sub-factors (Re Cecconi and Iacono, 2005)

In this work, the variables concerning ceramic external façades will be defined in chapter 5, in the context of the factor method application on the collected sample.

In conclusion, some considerations concerning the factor method's reliability need to be made. In the last years, there has been a lively discussion amongst experts about the methodology. One of the most frequent remarks against the factor method is the question of how trustworthy the method is (Marteinsson, 2003). For this, strengths and weaknesses of the methodology have been highlighted (Hovde, 1998).

Advantages:

- It allows recognising the effect of combined deteriorating factors;
- It allows flexibility, as the model can be developed along simple or complex lines;
- At date, it represents the only standardized method to obtain ESL from experimental data;
- It features an intrinsic simplicity.

Disadvantages:

- Subjectivity of the method;
- Limitations in its applicability (e.g. it is important to establish a general value, and not to incorporate specific and local experiences or conditions);
- Precise mathematical impact of the adjustments may imply a greater level of confidence in the judgement than the data available would warrant;
- Unless fairly definite limitations on the number of factors are adopted, the process could become very long and complex.

As one can see, the deficiencies of its application are as many as the advantages. In spite of this, the fact that it represents the only method to estimate service life from actual data that was adopted in standards and widely used proves its marked practicality.

1.4 Methodology of the research

As stated, the object of this dissertation is the evaluation of the service life of ceramic claddings. Regarding the methodology adopted to reach the set goal, it consisted in the following steps:

- Literature review - At first, a broad research was carried out. The subjects deepened concern service life prediction, ceramic cladding system's technology and pathology, external façades' inspection methods, degradation models and factor method applications. In the context of the information gathering, the primary source of this dissertation has been identified: in fact, the latter is the continuation of the studies carried out by Sousa (2008) on the same building component. Therefore, the thesis *"Previsão da vida útil dos revestimentos cerâmicos aderentes em fachada"* was the basis of the current work;
- Preliminary work - In this phase, the dissertation of Sousa (2008) has been analysed and characterized, with the aim of identifying the information needed to obtain a more complete and uniform

sample. With this purpose, a minimum number of inspections were set. Throughout this survey, the variables that affect the ceramic claddings' durability were identified and classified according to their severity. This allowed preparing an inspection sheet used during the field work;

- Field work - With the aid of the inspection checklists, a consistent amount of *in situ* visual inspections were carried out. The sample collected was added to the one of Sousa (2008), forming a final sample, which was the basis for the analysis further performed;
- Service life prediction methods' application - This stage consisted on two parts. The first one concerns the application of the models developed by Gaspar (2009), which evaluated the degradation evolution of the elements of the sample. Subsequently, the factor method was applied to the sample. The RSL, ESL and weighting factors were determined for each cladding;
- Analysis and discussion of the results - This phase was developed in parallel to the studies carried out: degradation process' evaluation and factor method application. The outcomes of the service life prediction methods were examined and the most interesting data were highlighted. Finally, the findings of the research were analysed, together with suggestions for future developments.

1.5 Dissertation structure

The structure of the dissertation reflects the paths just listed: each chapter represents an essential step of the work performed. The dissertation is organised in six chapters, as follows.

Chapter 1 - This chapter introduces the work carried out; the dissertation's aim, background and organisation have been debated. Concerning the line of research of the study, it consists on service life prediction. Therefore, the concept of service life was developed and the performance approach that characterizes the work was explained. Finally, the factor method was properly analysed.

Chapter 2 - As the previous one, the purpose of chapter 2 is also to deal with the knowledge needed in the further work. This time, the topic addressed is ceramic claddings. Therefore, the materials that form the building component and the related anomalies have been examined and classified.

Chapter 3 - This chapter deals with the explanation of the work accomplished. First, an analysis of the results of Sousa (2008) was done; the aim was to spot lacunas and weak points of the sample at issue. After having characterised this sample, the data needed to obtain a uniform sample were defined. Afterwards, an inspection sheet was developed, based on the anomalies' classification and rating carried out in the previous chapter. At this point, the *in situ* inspections were described. The presentation and discussion of the outcomes of this survey close the section.

Chapter 4 - In this chapter, the degradation model of Gaspar (2009) has been applied to the sample collected. At first, the limit states of the service life of ceramic façades were set, relating qualitative information obtained through the field work with minimum performance requirements. Then, the application of the model aforementioned allowed defining the overall degradation curve for the sample. The crossing of these data resulted in an average service life value for ceramic claddings. These results were analysed and discussed, according to variables that influence the façades deterioration.

Chapter 5 - At the beginning of this chapter, further studies on the degradation evolution of the component and the variables affecting its durability were carried out, preliminarily to the factor method application. Afterwards, the Reference Service Life for ceramic external wall façades was determined. Then, the weighing coefficients of the method were set and optimized through six different iterations, which allowed calculating the Estimated Service Life of the sample's claddings. The results of each scenario were statistically analysed, in order to determine the most reliable factors' combination. The discussion of the outcomes ends the work performed.

Chapter 6 - Given the assumptions of the introduction and the results obtained, the conclusions concerning the current dissertation were drawn. In general, the rationality of the research's findings gives reliability to the service life prediction methods applied: degradation model and factor method. In fact, conclusions were encouraging, leading to suggest some future developments, with the aim of improving the research line followed.

2 CHARACTERIZATION OF CERAMIC EXTERNAL WALL CLADDINGS

2.1 Introduction

This dissertation deals with the prediction of the service life of ceramic external wall claddings. Therefore, after the analysis of the concept of service life, a general understanding of that building system is essential. The purpose of this chapter is to study ceramic façades, so as to provide a basis for further evaluation of the degradation. It consists of two parts:

- In the first one, the technology regarding ceramic claddings is examined. The most important properties and characteristics of ceramic façades are listed. In addition to this, a brief review on design strategies and installation techniques is made;
- The second section takes into account the anomalies that affect this type of cladding. The defects and their possible causes are investigated. Finally, anomalies are classified in five degradation levels.

2.2 Ceramic claddings' technology

According to Goldberg (1998), *"direct adhered façade" refers to an exterior wall that is clad on the exterior surface with a weather-resistant, non-combustible cladding material, which is directly adhered to a structural backing material with an adhesive*. Specifically, this dissertation takes into account ceramic external walls. As it emerges from the just quoted definition, such cladding system consists of various components; more in detail, these are: ceramic tiles, bedding materials and joints filling materials. In this paragraph, each of them is separately analysed.

2.2.1 Ceramic tiles

According to EN 14411, ceramic tiles are *slabs made from clays and/or other inorganic raw materials and generally used as coverings for floors and walls.* Such materials change depending on the tile type, and consist of silica, feldspar, quartz, alumina-silicate, kaolin, aluminium oxide and others. Ceramic tiles *are usually shaped by extruding (Method A) or dry-pressing (Method B) at room temperature, followed by drying and firing at temperatures sufficient to develop the required properties, but can be formed by other processes. Tiles can be glazed (GL) or unglazed (UGL) and are incombustible and unaffected by light*. This norm is based on ISO 10545 and defines the required characteristics of a tile in order to comply with the conformity evaluation.

Concerning the manufacturing processes taken into account, *extruded tiles are shaped in the plastic state in an extruder, being cut into tiles of predetermined dimension*. The following tiles belong to this group: extruded sandstone (AI), clinker (AII_a), terracotta (AII_b) and brick tiles (AIII). Instead, *dry-pressed tiles* *are formed from a finely milled body mixture and shaped by pressing*. Porcelain (group BI), single firing tiles (group BII) and azulejos (group BIII) are part of this category (Table 2.1).

This dissertation takes into account all the types of tiles just listed.

Table 2.1 - Classification of ceramic tiles with respect to water absorption and shaping (EN 14411)

Shaping	Group I $E \le 3$ %	Group II_a 3 % < $E \le 6$ %	Group II_b 6 % < $E \le 10$ %	Group III $E > 10$ %
A **Extruded**	Group AI_a $E \le 0{,}5$ % (see Annex M)	Group $AII_{a\text{-}1}$ [a] (see Annex B)	Group $AII_{b\text{-}1}$ [a] (see Annex D)	Group AIII (see Annex F)
	Group AI_b 0,5 % < $E \le 3$ % (see Annex A)	Group $AII_{a\text{-}2}$ [a] (see Annex C)	Group $AII_{b\text{-}2}$ [a] (see Annex E)	
B **Dry pressed**	Group BI_a $E \le 0{,}5$ % (see Annex G)	Group BII_a (see Annex J)	Group BII_b (see Annex K)	Group BIII [b] (see Annex L)
	Group BI_b 0,5 % < $E \le 3$ % (see Annex H)			

[a] Groups AII_a and AII_b are divided into two parts (Parts 1 and 2) with different product specifications.

[b] Group BIII covers glazed tiles only. There is a low quantity of dry-pressed unglazed tiles produced with water absorption greater than 10 % that is not covered by this product group.

On the other hand, Table 2.2 shows the tiles requirements concerning different applications: external wall requirements have been highlighted. In such table, all the features that characterize a ceramic tile are listed.

Among them, one of the most influential on the durability performance is water absorption: that is, the percentage of absorbed water by mass (EN ISO 10545-3). This property is directly influenced by the degree of vitrification of the ceramic tile (Silvestre, 2005). In fact, porosity decreases with the increase of the vitrification degree, and vice versa.

A low water absorption rate also hinders mechanical adhesion to substrate with traditional mortar (Medeiros and Sabattini, 1999); for this reason, vitrified tiles require additional adhesives. In addition to this, porosity also affects the dimensional variations due to moisture: the lower the absorption, the greater resistance to moisture expansion. But, while there are no special breaking strength provisions for ceramic tile intended for use as external cladding, moisture consistently influences the deterioration of the façade.

A clarification: surface type (glazed or not glazed) will be further taken into account during the definition of the factors that influence the claddings durability. Nevertheless, it should not be confused with the degree of vitrification. A vitrified tile is made by baking fine minerals that create a single mass, which is extremely hard and low porous (water absorption ≤ 0.5%). Instead, glazed tiles feature an impervious facial finish, fused into the body of the tile, which is non-vitreous. In other words, glazed tiles feature only a vitrified covering (EN 14411), being resistant to water at the surface, but susceptible at the edges.

Table 2.2 - Characteristics required for different applications (EN 14411)

Characteristics	Floors		Walls		Test
Dimensions and surface quality	Interior	Exterior	Interior	Exterior	Reference
Length and width	X	X	X	X	EN ISO 10545-2
Thickness	X	X	X	X	EN ISO 10545-2
Straightness of sides	X	X	X	X	EN ISO 10545-2
Rectangularity	X	X	X	X	EN ISO 10545-2
Surface flatness (curvature and warpage)	X	X	X	X	EN ISO 10545-2
Surface quality	X	X	X	X	EN ISO 10545-2
Physical properties	Interior	Exterior	Interior	Exterior	Reference
Water absorption	X	X	X	X	EN ISO 10545-3
Breaking strength	X	X	X	X	EN ISO 10545-4
Modulus of rupture	X	X	X	X	EN ISO 10545-4
Resistance to deep abrasion – unglazed tiles	X	X			EN ISO 10545-6
Resistance to surface abrasion – glazed tiles	X	X			EN ISO 10545-7
Linear thermal expansion [a]	X	X	X	X	EN ISO 10545-8
Resistance to thermal shock [a]	X	X	X	X	EN ISO 10545-9
Resistance to crazing – glazed tiles	X	X	X	X	EN ISO 10545-11
Frost resistance [b]		X		X	EN ISO 10545-12
Coefficient of friction	X	X			Declare test method used
Moisture expansion [a]	X	X	X	X	EN ISO 10545-10
Small colour differences [a]	X	X	X	X	EN ISO 10545-16
Impact resistance [a]	X	X			EN ISO 10545-5
Chemical properties	Interior	Exterior	Interior	Exterior	Reference
Resistance to staining					EN ISO 10545-14
— glazed tiles	X	X	X	X	EN ISO 10545-14
— unglazed tiles [a]	X	X	X	X	EN ISO 10545-14
Resistance to acids and alkalis of low concentration	X	X	X	X	EN ISO 10545-13
Resistance to acids and alkalis of high concentration [a]	X	X	X	X	EN ISO 10545-13
Resistance to household cleaning agents and swimming pool chemicals	X	X	X	X	EN ISO 10545-13
Lead and cadmium release – glazed tiles [a]	X	X	X	X	EN ISO 10545-15

[a] Test method available, but this standard does not specify values.

[b] For tiles intended to be used in situations where frost conditions apply.

Generally, according to Goldberg (1998) and referring to Table 3.2, the other main properties of ceramic tiles that affect the degradation process of external ceramic façades are:

- Thermal shock - In exterior applications there are constant cycles of thermal shock;
- Thermal expansion - It defines the compatibility with substrate and adhesive materials, and the design of movement joints;
- Chemical and stain resistance - For external cladding, it mainly concerns atmospheric pollution.

2.2.2 Bedding materials

Concerning ceramic cladding techniques, the most commonly used are: traditional methods and ventilated façade systems. In this dissertation, only the first ones will be taken into account: in such methods tiles are fixed to the building by an adhesive or cement mortar. Figure 2.1 shows a representative detail of the technique at issue. More in detail, these are:

- Thick bed mortar - This is a traditional and very old method of installation. It consists of lay the tiles over a 5/20 mm thick Portland cement mortar bed. The mortar bed is laid over the substrate and provides a smooth and stable base for installation of the tiles;
- Adhesives (hydraulic binder, organic binder and resin based adhesive) - In this case, tiles are adhered to the substrate with a 2/5 mm thick layer of adhesive. Thin layer mortar installations are only acceptable for use on uniform substrates, since the thinness of the adhesive prevents hiding imperfections. In spite of this, adhesion strength for this technique is greater than for the thick bed mortar method (Medeiros and Sabattini, 1999).

About the various bedding materials, a thorough categorization has been done by Silvestre (2005), based on APICER (2003). For more in-depth research regarding composition, recommended applications, general characteristics and benefits of each technique, one can refer to these sources.

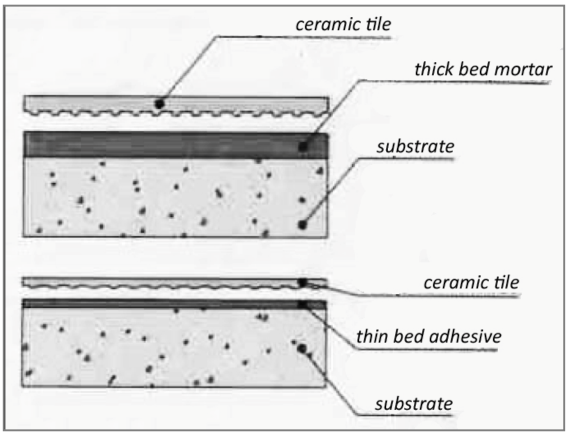


Figure 2.1 - Representative scheme of ceramic tiling

2.2.3 Joints

Movement joints consist of the free space between tiles; they are sealed with grout and allow the thermal expansion of the tiles themselves. In addition to the allowance for movement of the system, grouts prevent the seepage of water, dirt, dust. For these reasons, they turn out to be a component of fundamental importance in ceramic claddings. Concerning width, it can vary, depending on tiles type and composition. For external ceramic façades, a 6 mm joint may be used for extruded tiles, whereas a narrower joint of 4 mm may be used for dry pressed tiles (CSTB, 2000).

In addition to this, there are other three joints types that will be considered in this work. Each of them performs a specific function in the ceramic cladding system:

- Splitting joints - They avoid cracking or detachment of tiles due to hygrothermal expansion. They are commonly used in large façades, in which such expansions are greater, and are positioned at regular intervals. These joints develop in depth for the entire thickness of the bedding layer, whereas normal joints do not affect such layer, but only the outer one (tiles);

- Structural joints - These are unions that allow the relative movement of adjacent parts of a building. In correspondence to the latter, a structural joint is realised also in the cladding; its width has to be greater than the width of the joint below (Abreu, 2005);
- Peripheral joints - They are located at the corners of the façades, preventing the adjacent elements from restricting the expansion of the ceramic cladding.

2.2.4 Design and installation

The quality of design of a façade is one of the main guarantees for the cladding durability; this fact will be later confirmed by the results of the field work that has been carried out, contextually to the execution level analysis. Concerning this matter, several characteristics need to be taken into consideration for a proper cladding design. Among these are included: structure type, deformability of the substrate, environmental aspects and possibility of maintenance (CTBUH, 1995). Such characteristics affect the selection of the just seen components: tiles' type, sizing of joints and choice of bedding and filling materials.

Ceramic exterior walls design is a practice that has not come into common use yet; nevertheless, the aspects that a technician should define are many. For this, it has been chosen to list some details, concerning ceramic façades, which require particularly attention from the designer:

- Regarding the installation, the suitable time to lay the tiles would be when live loads have already been applied to the building. Since this is difficult to occur, horizontal splitting joints in correspondence to each floor should be provided; besides these, one should also design vertical splitting joints, so as to form approximately square areas (about 20 m^2) with the horizontal ones (Lucas and Abreu, 2003);
- In buildings featuring a ceramic façade that is more than 3 m high, it would be necessary to provide a protection for the possible tiles detachment and falling (Campante, 2001);
- In the case of structures built with different materials, the designer has to pay attention to the difference in expansion of the substrate, providing an adequate joints' width (Medeiros, 1999). Otherwise, edge crushing, cracking, or joints deterioration may originate;
- Façade crowning is an element that needs careful design: in fact, this zone is particularly susceptible to rain and moisture action (Goldberg, 1998);
- In the case of large façades, the designer should provide anchoring points for maintenance purposes.

Instead, considering the installation of a ceramic cladding, it consists of five stages (Silvestre, 2005):

- Substrate preparation;
- Application of the bedding material;
- Laying of tiles;
- Filling of joints;
- Final cleaning.

In this dissertation, this aspect is only succinctly mentioned; nevertheless, one should remember the extreme importance of each step for an adequate laying. In fact, tiling system is totally dependent on provision of a sound substrate, use of suitable adhesive and grout, and a correct installation technique.

2.3 Ceramic claddings pathology

2.3.1 Anomalies classification

Pathology is the study and diagnosis of anomalies. A survey on the ceramic façades' most common defects is needed to provide a basis for the *in situ* inspections and the further analysis on the degradation evolution. The classification adopted in this dissertation is based on the works of Silvestre (2005), Silvestre and de Brito (2008) and Sousa (2008). In particular, the latter has divided the anomalies affecting ceramic claddings in four categories, each of them including several defects:

- Aesthetic defects;
- Cracking;
- Joints deterioration;
- Adhesion failure.

This classification has been entirely kept, so that this study is consistent with the work of Sousa (2008); in fact, as mentioned, it represents the starting point for the current dissertation. The only difference in the anomalies enumeration concerns *graffiti*: these have not been considered, since they are not related to a gradual and modelling-prone degradation process. Generally, the author performed extensive researches about claddings failures, coming to a complete categorization, which takes into account the possible anomalies affecting the various elements that make a ceramic façade.

On the other hand, Silvestre (2005) analysed and classified the defects according to the component affected. In fact, the same anomaly can concern different parts of the cladding, being in this way less, or more severe. E.g., cracking can affect only the outer layer (tiles), or the entire cladding system (tiles, bedding layer and, more seldom, the substrate).

In addition to this, the author examined the causes of the anomalies that affect ceramic claddings.

Summing up this review, Silvestre (2005) developed a matrix of correlation between anomalies and related causes. This tool is characterized for its simplicity, but also for a remarkable practicality and completeness.

At this point, the works mentioned above have been adapted for the current one: the outcomes of this study are shown in Tables 2.3, 2.4, 2.5 and 2.6. These tables refer to the four defects' categories mentioned above. For each anomaly an explanatory description has been provided; then, based on the matrix of Silvestre (2005), the possible causes connected have been listed. As noticed, many anomalies have, as a common cause, a deficient care in designing and installing the cladding, confirming the importance of those aspects.

Table 2.3 - Description of aesthetic anomalies and related causes

Anomalies		Description	Possible causes	Examples
Aesthetic defects	Superficial dirt	Dust accumulation	Lack of maintenance/Dust retention for tiles surface texture/Pollution	
	Degradation	Areas showing scratching or abrasions or missing tiles glaze	Natural aging/Incorrect cleaning/Choice of materials not suitable for use/Shocks	
	Edge crushing	Edge crushing	Differential movements substrate-cladding, resulting in tiles compression / Inadequate joints	
	Small spots on the surface	Expansion of particles of calcium oxide by hydration, resulting on small spots on the surface	Deficient care in detailing the cladding/Choice of materials not suitable for use/Natural aging	
	Humidity stains	Humidity stains	Rising damp from the ground/Deficient care in detailing the cladding	
	Biological growth	Appearance of mould, fungi or vegetation	Presence of water or moisture that provides the biological colonization/Reduced solar exposure/Lack of maintenance	

Table 2.3 (continuation) - Description of aesthetic anomalies and related causes

Anomalies		Description	Possible causes	Examples
Aesthetic defects	Change in brightness and/or colour	Localized change in the initial color of the tiles	Biological action/Natural aging	
Aesthetic defects	Efflorescences	Presence of salts in tiles, bedding material or substrate that, as a result of humidification, are transported to the surface and therein crystallize	Moisture/Incorrect chioce of materials	

Table 2.4 - Description of cracking and related causes

Anomalies		Description	Possible causes	Examples
Cracking	Glazing cracking	Cracks only affect the glazed surface; they intertwine in the form of a lacework	Different thermal expansion coefficient of the glazed surface from the body of the tile/Thermal shocks/Contraction of bedding materials transmitted to tiles surface	
Cracking	Cracking without predominant direction	Cracking without predominant direction	Deficient care in detailing the cladding/Thermal and moisture expansion	
Cracking	Cracking with marked direction	Cracking with marked direction	Deficient care in detailing the cladding/Substrate movements	

2.3.2 Degradation levels definition

As stated in the introduction, the analysis carried out so far is fundamental to the further assessment of the service life of exterior ceramic façades. This aspect is directly related to the degradation process: for this reason, in order to globally define the deterioration of a ceramic façade, the anomalies presented in the previous paragraph need to be rated.

Table 2.5 - Description of joints anomalies and related causes

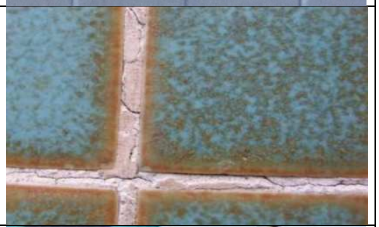
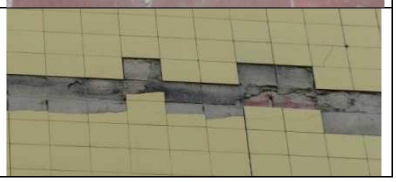
Anomalies		Description	Possible causes	Examples
Joint deterioration	Staining or change in colour	Joints colour change due to dirt	Lack of maintenance/Natural aging/Pollution	
	Deterioration without loss of material in joints	Shrinkage of grount, or cyclical expansions due to thermo-hygrometric variations, causing joints cracking; biological growth	Incorrect choice of materials/Incorrect joints sizing/Moisture/Natural aging/Inadequate execution/Presence of water or moisture that promotes biological colonization	
	Deterioration with loss of material in joints	Grount detaching	Incorrect choice of materials/Incorrect joints sizing/Moisture/Natural aging/Inadequate execution/Evolution of the phenomena giving rise to the anomalies previously described	

Table 2.6 - Description of adhesion defects and related causes

Anomalies		Description	Possible causes	Examples
Adhesion failure	Adhesive failure	Loss of adhesion between tiles and bedding layer	Incorrect choice of materials/Laying on dirty or not regular substrate/Inadequate laying of tiles/Substrate movements/Natural aging/Thermal and moisture expansions	
	Arching	Tiles' arching	Inadequate laying/Substrate movements/Thermal and moisture expansions/Incorrect joints sizing	
	Detachment	Tiles detachment and falling	Incorrect choice of materials/Laying on dirty or not regular substrate/Inadequate laying of tiles/Substrate movements/Natural aging/Thermal and moisture expansions	

The basis of this rating scale is the fact that not all anomalies have the same consequences for the cladding system service life: some of them affect the façade decay more than others. E.g. aesthetic anomalies usually do not contribute to the loss of performance of cladding, but only involve a visual degradation; it is clear that such anomalies do not feature the same severity as cracks or detachment. It is therefore necessary to define a physical and visual scale that allows quantifying the level of degradation of the building component.

With this purpose, Gaspar (2002) and Gaspar and de Brito (2005) had developed a criterion to quantify the façade deterioration; the latter has been classified in five levels, from level 0 (no visible degradation) to level 4 (generalized degradation). Each level corresponds to a features' set used as a benchmark for the field work inspections (Marteinsson et al. 1999). Within each category, a rating scale for the various defects has been defined, based on the percentage of affected area. In this way, cladding conditions are defined during the field work through a visual assessment, which evaluates the affected areas, leading to the definition of a degradation level. Concerning this dissertation, the scheme adopted is based on the work of Sousa (2008), for the coherence reasons mentioned above. The author developed a rating to define the degradation of ceramic external cladding, according to the works of Gaspar (2002) and Gaspar and de Brito (2005). This classification is shown in Tables 2.7, 2.8, 2.9 and 2.10.

Table 2.7 – Levels of degradation: aesthetic defects (Sousa, 2008)

Degradation levels	Anomalies	% affected area
Level 0 - No visible degradation	-	-
Level 1 - Good condition	Superficial dirt	-
	Degradation (scratches) Edge crushing Small spots on the surface Humidity stains Change in brightness and/or color	≤ 10%
Level 2 - Slight degradation	Degradation (scratches) Edge crushing Small spots on the surface Humidity stains Change in brightness and/or color	> 10% and ≤ 50%
	Efflorescences Biological growth	≤ 30%
Level 3 - Moderate degradation	Degradation (scratches) Edge crushing Small spots on the surface Humidity stains Change in brightness and/or color	> 50%
	Efflorescences Biological growth	> 30%

Table 2.8 - Levels of degradation: cracking (Sousa, 2008)

Degradation levels	Anomalies	% affected area
Level 0 - No visible degradation	-	-
Level 1 - Good condition	Glazing cracking	-
	Cracking with marked direction (< 0,2 mm)	-
Level 2 - Slight degradation	Cracking without predominant direction	≤ 30%
	Cracking with marked direction (> 0,2 mm)	-
Level 3 - Moderate degradation	Cracking without predominant direction	> 30% and ≤ 50%
	Cracking with marked direction (> 1 mm)	-
Level 4 - Generalized degradation	Cracking without predominant direction	> 50%
	Cracking with marked direction (> 5 mm)	-
Notes: Cracks with infiltration - Increase in a level of degradation Crack < 0.2 mm - Detectable at a distance greater than 5 m only with the use of binoculars Crack > 0.2 mm - Detectable at a distance greater than 5 m, without the use of binoculars. Crack > 1 mm - Detectable from a distance of more than 5 m and less than 10 m, without the use of binoculars Crack > 5 mm - Detectable from a distance of more than 10 m, without the use of binoculars.		

Table 2.9 - Levels of degradation: joints deterioration (Sousa, 2008)

Degradation levels	Anomalies	% affected area
Level 0 - No visible degradation	-	-
Level 1 - Good condition	Staining or change in color	-
Level 2 - Slight degradation	Without loss of material in joints	≤ 30%
	With loss of material in joints	≤ 10%
Level 3 - Moderate degradation	Without loss of material in joints	> 30% and ≤ 50%
	With loss of material in joints	> 10% and ≤ 30%
Level 4 - Generalized degradation	Without loss of material in joints	> 50%
	With loss of material in joints	> 30%
Notes: Deterioration with infiltration - Increase in a level of degradation		

Table 2.10 – Levels of degradation: adhesion failure (Sousa, 2008)

Degradation levels	Anomalies	% affected area
Level 1 - Good condition	No visible degradation	-
Level 2 - Slight degradation	Adhesive failure Arching	≤ 20%
Level 3 - Moderate degradation	Adhesive failure Arching	> 20%
	Detachment	≤ 10%
Level 4 - Generalized degradation	Detachment	> 10%

2.4 Conclusion

This chapter has dealt with the analysis of external ceramic façades' technology and pathology. As mentioned, a proper knowledge of the matter at issue is needed. In fact, the information collected will be further used as a theoretical and practical basis for the *in situ* inspections and the degradation evaluation, leading to the service life estimation.

More in detail, the ceramic cladding system has been defined, and its components have been analysed. Attention has also been paid to design and installation, which turn out to be fundamental aspects to avoid the occurrence of early failures. Finally, the defects affecting this building component have been listed, contextually to their classification according to the levels of degradation.

In this chapter, a complete state of art of ceramic claddings has not been actually realized. In fact, the main aim was only to define a knowledge basis that is functional for the dissertation development. For a deeper research on the topics covered, one may refer to the many cited works, which have represented the foundation of the current review.

3 FIELD WORK

3.1 Introduction

In this chapter, the field work carried out is described. It consists on *in situ* façades visual inspections, with the purpose of gathering data on the anomalies that affect the ceramic claddings. These data will integrate the collected sample of Sousa (2008), leading to a more complete and reliable result.

This chapter is divided into three parts, the first two of which are preliminary to the actual work *in situ*:

- In the first one the results of Sousa's work have been analyzed. This close study has led to the exclusion of some façades of the sample of Sousa (2008);
- In the second step the sample selected by Sousa (2008) has been analyzed, trying to determine its absences and to characterize it. Then, an analysis on the number and type of claddings needed has been done, in order to have a sample as complete as possible;
- The last part concerns the field work and its results.

3.2 Target of the field work

The main goal of this stage is to identify and take note of the defects of the ceramic external wall claddings. The collected information is needed to evaluate the overall degradation level of the buildings, according to the methodology developed by Gaspar (2009). Furthermore the data have been used as a basis for the quantification of the main factors affecting the façades service life. These studies will be discussed and deepened in the following chapters, along with the evaluation of degradation and the application of the factor method.

3.3 Analysis of the results of Sousa (2008)

As the starting point for the present dissertation, the results of the work of Sousa (2008) have been studied. In order to do that, some topics that will be further tackled need to be anticipated. For a more detailed description refer to chapter 4.

3.3.1 Severity of the degradation

As stated previously, the information gathered through the field work allows the calculation of the façade's degradation evolution. The overall degradation level of a building is a qualitative level or a quantitative index which shows the overall performance of that building (Gaspar and de Brito, 2008).

Figure 3.1 shows the final outcome of the Sousa's (2008) analysis in terms of overall degradation curve. This is a regression of the values corresponding to the degradation level of the inspected ceramic claddings, distributed according to the age of each cladding. The overall degradation level (ordinate) is calculated through the numerical indicator severity ($S_{w,rp}$), which is an index determined by a ratio between the weighted degraded area and a reference area.

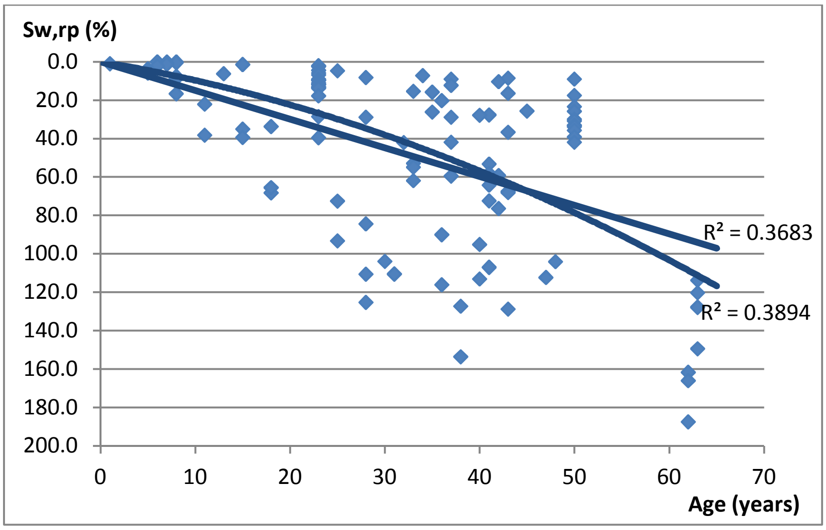


Figure 3.1 - Degradation curve of the inspected sample of Sousa (2008)

The first conclusion that emerged is that the degradation evaluation in Sousa (2008) is calculated with a formula that has been replaced with another in more recent studies (Gaspar, 2009; Silva, 2009; Emídio, 2012). Sousa's (2008) formula is:

$$S_w = \frac{\sum(A_n \cdot k_n \cdot k_{a,n})}{A \cdot k} \qquad \text{Equation 3.1}$$

Where:

S - severity of the degradation of the normalized façade, expressed in percentage;

A_n - area of façade affected by defect n, in square meters;

k_n - condition level for defect n, with n Є {1, 2, 3, 4};

$k_{a,n}$ - relative importance of the defects detected; if no specification exists, $k_{a,n}$ = 1;

k - constant, equivalent to the value of the worst condition level;

A - exposed cladded area of façade, in square meters.

The degradation severity determined in this way can reach a maximum theoretical value of 300%. This happen if the façade presents all the anomalies with the worst degradation level. In Sousa (2008) the higher severity value is 187.5%.

In order for the severity to be more easily understood, Gaspar (2009) developed a formula which results a range of values between 0% and 100%. The new ratio is between the weighted affected area of the cladding and the maximum degradation extension:

$$S_{w,rp} = \frac{\sum(A_n \cdot k_n \cdot k_{a,n})}{A \cdot \sum(k_{max})} \qquad \text{Equation 3.2}$$

Where:

S - severity of the degradation of the normalized façade, expressed in percentage;

A_n - area of façade affected by defect n, in square meters;

k_n - condition level for defect n, with n ∈ {1, 2, 3, 4};

$k_{a,n}$ - relative importance of the defects detected; if no specification exists, $k_{a,n}$ =1;

k - constant, equivalent to the value of the worst condition level;

A - exposed cladded area of façade, in square meters;

k_{max} - sum of the weighting coefficients equals to the highest level of degradation of A area cladding; it has the value of 15 (3 + 4 + 4 + 4 - aesthetic defects, cracking defects, joint deterioration defects, detachment defects).

The highest severity index after the updating of the calculation of Sousa (2008) has a value of 50%. These severity values are easy to understand and can be related to the other studies carried out in this subject. Figure 3.2 shows the degradation curve that will be considered from this point onwards.

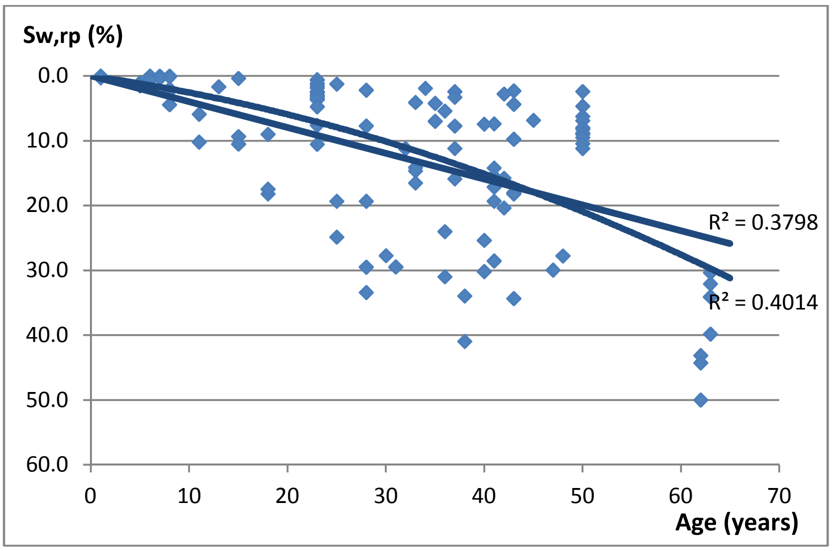


Figure 3.2 - Degradation curve of the inspected sample of Sousa with the Gaspar's (2009) formula

3.3.2 Cases excluded

Once the Sousa (2008) data was updated, it can be analyzed in term of the degradation curve. The correlation coefficient R^2 between the values is very low. The reason is that the points in the graphs are too scattered to be statistically relevant. It means that the analysis done by Sousa (2008) is unable to typify the degradation evolution for ceramic tiles.

In the conclusions reached at the end of the work, Sousa (2008) tries to give an explanation to this result; it was concluded that ceramic claddings, according to Shohet and Laufeer (1996), are more susceptible to the changes of all the parameters that characterize this type of cladding. Table 3.1 shows how the sensitivity of ceramic tiles to a variety of parameters is on average higher than in other cladding materials.

Table 3.1 - Susceptibility of five categories of claddings to technological, use and maintenance aspects (Shohet and Laufeer, 1996)

Parameter	Cementitious stucco	Synthetic finish stucco	Ceramic tiles	Stone (wet fixing)	Stone (dry fixing)
Interdependence with other building activities	Moderate to high	Moderate to high	High	Very high	Low
Sensitivity to quality of materials	High	Moderate	Very high	High	High
Sensitivity to quality of implementation	High	Moderate to high	Very high	High	Very high
Sensitivity to quality of workmanship	Moderate to high	Moderate to high	Very high	Very high	Very high
Sensitivity to precision of building skeleton	Moderate	Moderate	Very high	Low to moderate	Moderate to high
Maintainability	Very high	Excellent	Moderate	Moderate	Variable

This leads to a major difficulty of a correct detection of the anomalies and their causes, but justifies only partially the outcome of the work in question. Therefore, it has been decided to verify the reliability of the degradation values of Sousa (2008) by inspecting some façades.

Looking at the degradation curve graph three groups of values particularly scattered have been identified, showing a severity level that is not reasonable compared with age. They can be seen in Figure 3.3. The first cluster, in the low part of the graph, includes values considered too high. The second one, in the upper right, groups 12 points corresponding to as many façades of the same group of buildings. These are 8 identical blocks located in Avenida do Brasil and built in the same year. The last one includes values corresponding to façades which degradation severity was assessed to be zero.

At this point, 31 façades had been inspected. All the buildings taken into account are located in Lisbon. The methodology used during the visual inspections is the same as the one used by Sousa (2008); this is due to ensure consistency with the previous studies. The inspection technique is described in paragraph 3.5.1, in the context of the discussion of the work performed for the new sample.

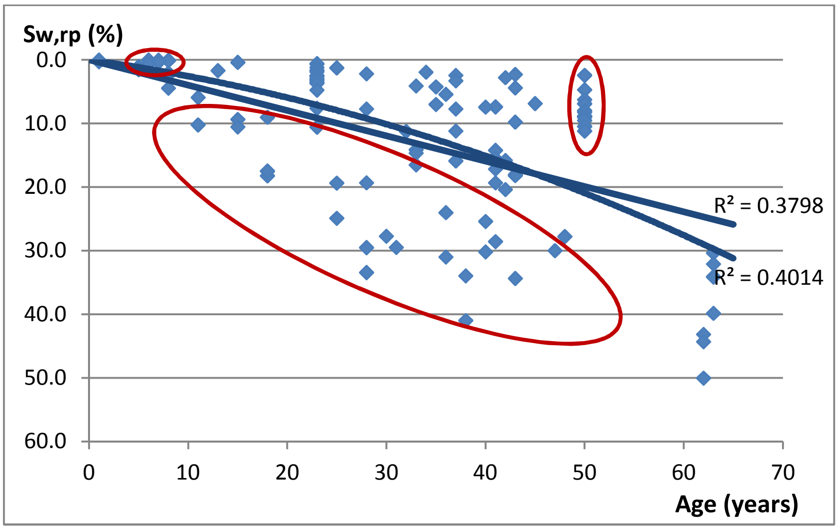


Figure 3.3 - Highlight of the degradation curve's scattered values

As anticipated, the inspections carried out have led to the exclusion of some façades from the sample of Sousa (2008). For each of them a rational explanation is provided. The analysis of the façades has been divided into three parts, concerning different situations that occurred in the study.

Cases of anomalous situations

In this section, the cases in which the anomalous value of degradation severity is believed to be caused by errors in the design or in the execution are analyzed. The nomenclature of the buildings is the one used by Sousa (2008) and refers to that sample.

- Ed56 - Largo do Leão, 12

After an inspection *in situ* it has been ascertained that the high severity of the degradation is due to the efflorescence, which is widespread all over the wall cladding (Figure 3.4). This is probably the result of a seriously wrong (or missing) design of the bedding mortar materials; the salts efflorescence affects most of the façade surface. As a consequence of the bad design, this case cannot be statistically modelled; in fact, it corresponds to an abnormal situation and it would not make sense to include it into the sample.

- Ed58 - Av. do Infante Santo, 72

In this case of the evaluation of the degradation is obviously far from reality because of a big markedly orientated crack that runs through the whole height of the wall (Figure 3.5). It affects not only the cladding, but also the structure and it causes serious infiltration and efflorescence. This situation is clearly caused by a problem of foundations settlement and it is not related to the normal degradation evolution of the ceramic cladding.

Figure 3.4 - Façade excluded; on the right a detail of the efflorescence affecting the cladding

Figure 3.5 - Cracking in the building in Avenida do Infante Santo.

On the left the whole crack can be seen; the centre and right pictures show details thereof

- Ed16a - Rua Prof. Francisco Gentil, 18-26

This façade is affected by many cracks, both markedly oriented and without predominant direction. After a close analysis it has been acknowledged that the reason for the defect is a structure settlement, caused by a too large span. In fact, the worst cracks are located in correspondence with the tension zones of the structure, at the bottom of the building (Figure 3.6). As a consequence of a structural problem, this façade cannot be included in the sample that is object of the study.

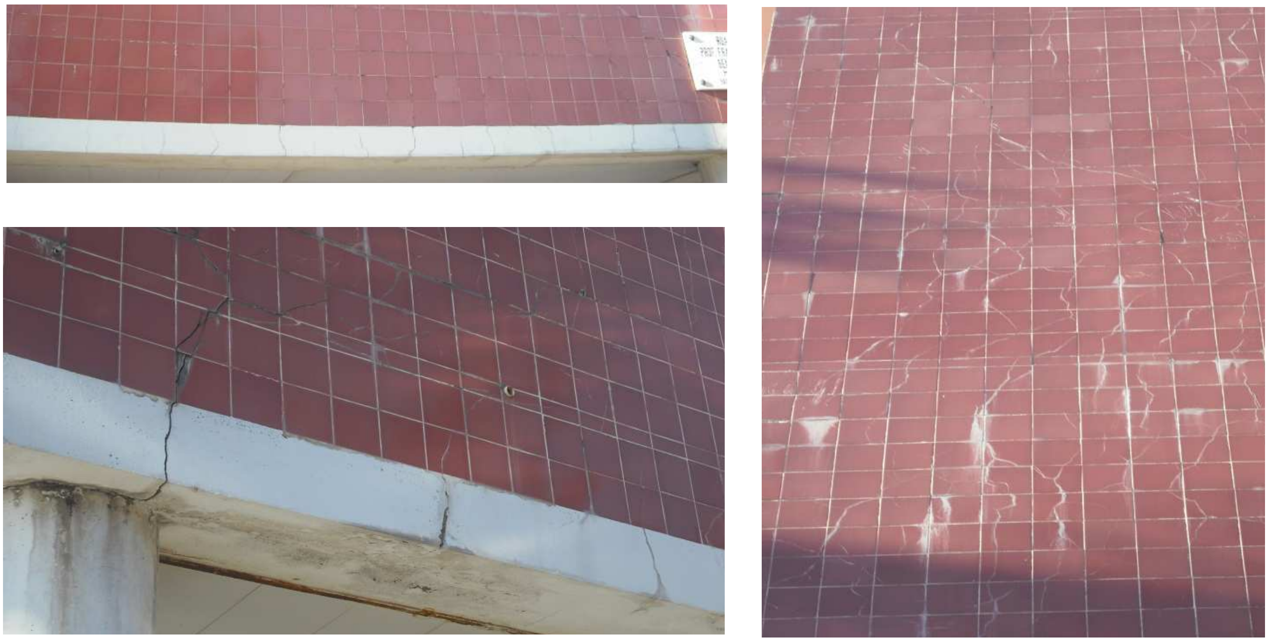


Figure 3.6 - Cladding showing cracks due to structure settlement; notice how the cracks originate in the lower part of the façade (photos on the left) and then progress upwards (picture on the right)

- Ed16b - Rua Prof. Francisco Gentil, 18-26

The façade is part of the previously analyzed building; but in this case the abnormal degradation value (very high if compared with the façade age) is probably the result of a grossly deficient execution. The cladding features joints deterioration, lack of flatness and localized detachment. Figure 3.7 shows how the mortar has not been properly pressed, causing swelling and detachment.

This situation cannot be considered as a result of a normal degradation evolution process and it has been excluded from the sample of Sousa (2008). In fact, it does not make sense to insert anomalous values (outliers) in a statistical model.

Figure 3.7 - Detachment detail of the excluded façade

- Ed16c - Rua Prof. Francisco Gentil, 18-26

This cladding is located at the bottom of the previous building. Here the joints are deteriorated and present infiltrations. These defects, together with widespread scratches, increase the degradation severity to a high level. During the inspection it has been noticed how the people usually leave the garbage in front of this façade: the height at which the scratches are located corresponds perfectly to the bin size (Figure 3.8). The continuous impacts to which the façade is subjected are not a normal use condition and cannot be statistically modelled. For this reason the façade has been removed from the sample.

- Ed17c / Ed17d - Rua José Escada (building K1)

These are two façades of the same block of flats (orientation South and East). In the evaluation of degradation of Sousa (2008) a widespread joint deterioration came out, raising much the degradation level. After the *in situ* inspection, was determined that the claddings don't present any defects but a severe lack of flatness, as seen in Figure 3.9. So, what had been considered as joints degradation is actually really poor execution and it’s not related to a “normal” deterioration evolution. For this reason it has been decided to remove the façades from the collected sample.

Figure 3.8 - Evidence of the anomalous state of deterioration of the excluded building

Cases of impossibility of re-inspection

Differently from the previous situations, it has been decided to remove the following façades from the sample because of the impossibility to checking the reliability of the information collected by Sousa (2008). All these cases show a high degradation level in spite of a young age.

In the first three cases (Figures 3.10 - 3.11 - 3.12) the façades have been recently renewed and the ceramic claddings have been replaced by rendered or stone claddings.

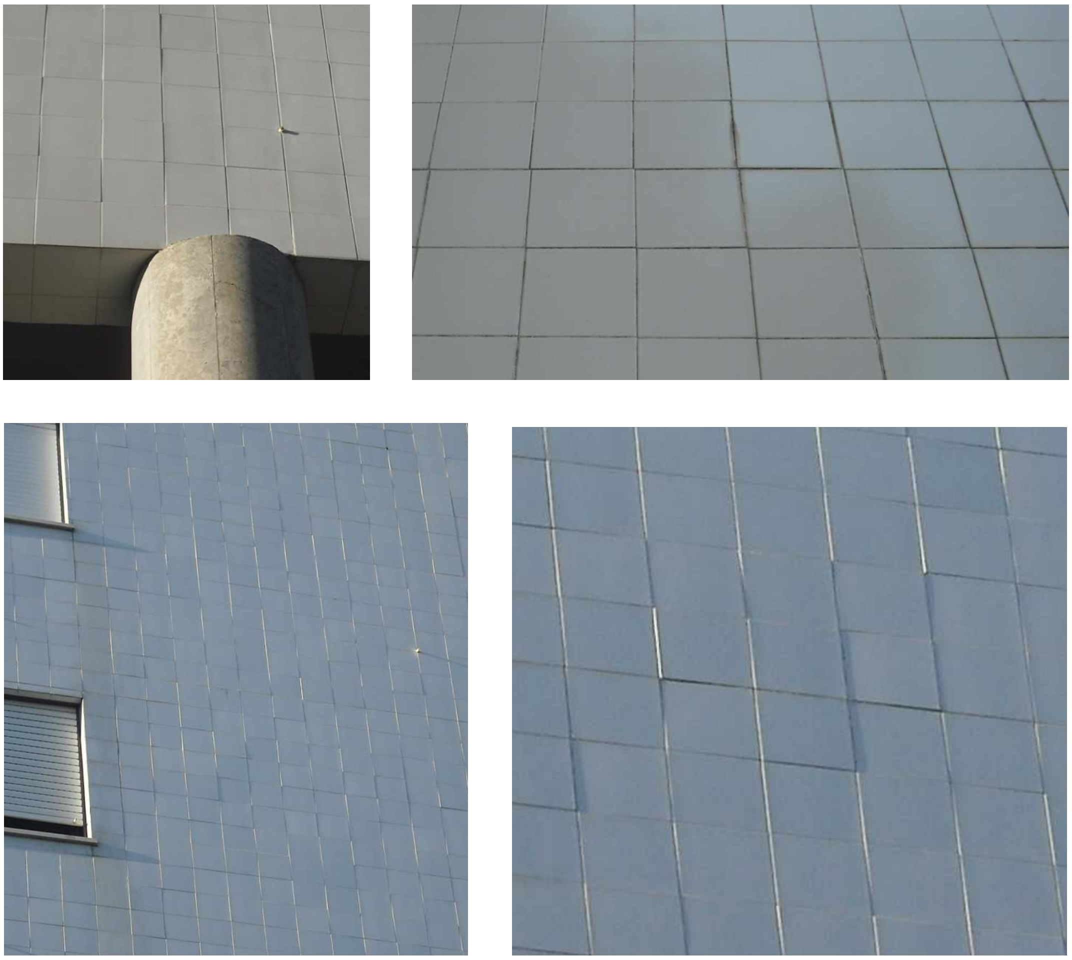


Figure 3.9 - Lack of flatness of the cladding in the building located in Rua José Escada.
The first two pictures refer to the East façade. The pictures below refer to the South façade

- Ed57 - Rua Sousa Martins, 24

Figure 3.10 - Façade recently renovated

- Ed23 - Rua Ilha do Pico, 28

Figure 3.11 - Façade recently renovated

- Ed15 / Ed16 - Rua Cidade da Horta, 41

Figure 3.12 - Façade recently renovated

- Ed6 - Alameda Linhas de Torres, 50

Although a close search was conducted, it was not possible to find this building. The address numbers skip from 46 to 60 in adjacent constructions. Talks with the people that live and work in the area revealed that the building has probably been demolished in the meantime.

- Ed53 / Ed54 / Ed55 / Ed56 / Ed57 / Ed58 / Ed59 / Ed60 / Ed61 / Ed62 / Ed63 / Ed64 - Avenida do Brasil, blocos 19, 20, 22

These are eight identical blocks of flats built in 1958 (Figure 3.14). 12 façades had been analyzed by Sousa (2008), i.e. four orientations of three buildings. All of them feature a low value of degradation severity if related to the age (50 years). An inspection has been carried out, but it was not possible to identify which blocks are the ones considered by Sousa (2008). This is due to the fact that in the sample of Sousa (2008) they are named as Block 19, Block 20 and Block 22, despite being three buildings out of eight. After a search in the *Arquivo Municipal de Lisboa* it has been observed that the building are named as *Lote* 1, 2, 3, 4, 5, 6, 7 and 8, which is logical. Furthermore, the address numbers run from 112 to 132. Since it was not possible to contact Sousa, it was not possible as well to understand what the author refers to as “Block 19, 20 and 22”. For this reason, the façades have been removed from the sample.

Figure 3.13 - On the left, a picture of the area. Numbers skip from 46 (gasoline pump) to 60, the building on the left. On the right, a picture from Google Maps: the circled area shows ruins

Figure 3.14 - Block of flats in Avenida do Brasil

Cases of incorrect evaluation

Concerning the following cases, the evaluation did not find any anomalous situation but a mismatch between the evaluation of Sousa (2008) and reality. The first two cases would be removed. Instead, the other inspections have led to modify the values of Sousa (2008) in order to get a more reasonable evaluation of the overall degradation level. These cases have been kept into the sample.

- Ed02f / Ed02g - Mercado da Encarnação Norte

This is no ceramic cladding, but a solid bricks wall (Figure 3.15). it has been taken out from the sample.

Figure 3.15 - Bricks façade of the Encarnação Norte market

- Ed46a / Ed46b / Ed29 / Ed31 / Ed34 / Ed47

In these cases, the façades had been assessed to have a severity value equal to zero. That means being in perfect condition, as just built. These façades are 1, 6, 7 or 8 years old. Faced with the impossibility of having no defects at all after some years of life, three of them have been re-inspected. They are now part of the new sample. Clearly, none of them has been found to be in perfect condition: the new evaluation has led to low values of degradation, which are thought to be reliable and to adequately represent the reality. The rest of the façades concerned have been removed from the sample.

- Ed08e - Mercado S. Domingo de Benfica

The high value of the degradation severity was due to a widespread change of shine and colour (90% of the façade area), cracking and joint deterioration.

An inspection proved that these are hand painted matt tiles. For this, the opaque effect is an artistic choice and it is not due to degradation (Figure 3.16). In addition to this, the cracking and the joint deterioration had been overvalued; visual inspection proved that the percentage area affected by those anomalies is significantly less than in Sousa's (2008) assessment. The method used for the evaluations is the one described in Gaspar (2009), already used by Silva (2009) and Emídio (2012). It consists of visual inspection, application of image processing, computer aided design and spreadsheet. It is described more thoroughly in section 3.5.1.

The current evaluation changed the value of the degradation severity from 28.5% to 5.3%, which seems more reasonable and closer to reality.

- Ed13 - Rua Cidade da Horta nº 51-59

An overall slightly worse situation has been found compared to the analysis of Sousa (2008), evidence that the previous evaluation was basically correct. But the high degradation level in Sousa (2008) was mostly due to a 100% joint deterioration (fungus cause). A closer inspection showed that this anomaly affects no more than the 25% of the façade. This reduces the degradation severity value from 29.5% to 18.5%. The next pictures (Figure 3.17) show that a portion of the façade is affected by fungus (on the left) and another is not (on the right).

Figure 3.16 - Portion of the façade of the building in S. Domingo de Benfica; one can see the hand painted tiles

Figure 3.17 - Details of the façade showing joints deterioration

- Ed24 - Rua Ilha do Pico nº 28

As for the previous cases, two of the anomalies affecting the façade had been overvalued. These are scratches and joint deterioration with loss of material; they are shown in Figure 3.18, respectively on the right and on the left side. The methodology used to estimate the surface area is the same (visual inspection, photography and computer aid). The current value of severity is 21.2%, instead of 31% (Sousa, 2008).

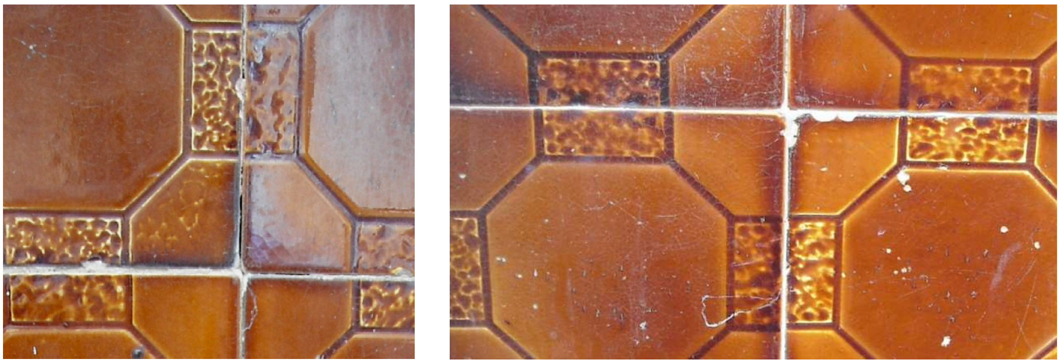


Figure 3.18 - Examples of the deteriorated cladding

- Ed47a / Ed47b - Pavilhão de Portugal

These are two façades of the Pavilhão de Portugal, built in 1998 for Expo 98. They have been inspected twice, at first by Silvestre (2005) and afterwards by Sousa (2008). It has been chosen to analyze them again because of the wide-apart values of the two evaluations. After the assessment, all the values have been replaced by the ones of the new inspection.

Regarding the detected anomalies, the north façade was considered to have the 90% of the surface affected by the change in brightness; after the current inspection was found that this is not change in the tiles colour, but superficial dirt. More than this, the cracking in the façade had been definitely overvalued by Sousa (2008). The final value of the degradation severity (3.8%) is more similar to the Silvestre (2005) one (4.4%); the percentage of Sousa (2008) was 10.2%.

The same goes for the opposite façade. An accurate inspection led to a value of the severity that replaces the previous ones in the sample. In this case the 2005 degradation evaluation is considered to be lightly undervalued, whereas the analysis of Sousa (2008) is more reliable. The severity values regarding this façade are: 0.1% (2005), 5.9% (2008) and 4.9% (2012).

Figure 3.19 - The opposite façades of the Pavilhão de Portugal, located in Santa Maria dos Olivais

3.3.3 Final outcome and up to date degradation curve

The paragraph above has rationally described the steps that have led to the exclusion of some façades from the Sousa's (2008) sample. In Figure 3.20 (overall degradation curve) all the points corresponding to the claddings that have been taken into account are highlighted.

The 40 elements that would be removed from the sample are yellow. All the points considered not properly accurate and marked in Figure 3.3 correspond to the anomalous cases listed before. Among these, there are some points that are located in the upper part of the graph. This is because some façades inspected by Sousa (2008) had been previously analyzed by Silvestre (2005) and were kept in the 2008 sample. For this reason there are 8 façades that correspond to two values each in the graph: one for 2005 and one for 2008. So, the exclusion of these façades led to the removal of 16 points, four of which are those at the top of the graph.

On the contrary, the seven red points represent the evaluations that have been corrected, based on the new inspections. These ones have been replaced according to the new degradation severity values. These points have also been translated in relation to the current age. It must be noted that the four points, which are 7 and 10 years old, correspond to only two façades, analyzed before in 2005 and after in 2008: these have been replaced with two values only.

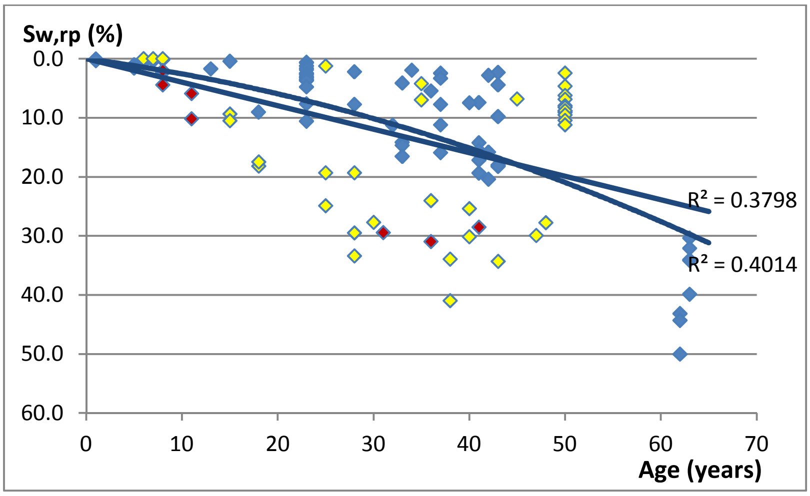


Figure 3.20 - Degradation curve: highlighting of inspected façades

Figure 3.21 is the result of the just performed analysis. Three aspects have been noticed by analysing the graph:

- The regression line fits the data much better than the outcome of Sousa (2008); this is testified by the fact that R-squared increase from 0.4014 to 0.8197;

- A linear regression is no more suitable to describe the relationship between the values. The large difference between the two coefficients of determination has led to take into account only the 3rd-order polynomial trend line;
- There is a wide gap between the 45 and 62 years old façades. Considering the importance of the curve down slope, this gap must be filled with new inspections.

From this point on, the sample that will be used for the next characterization and that will be the basis for further work is shown in Figure 3.22.

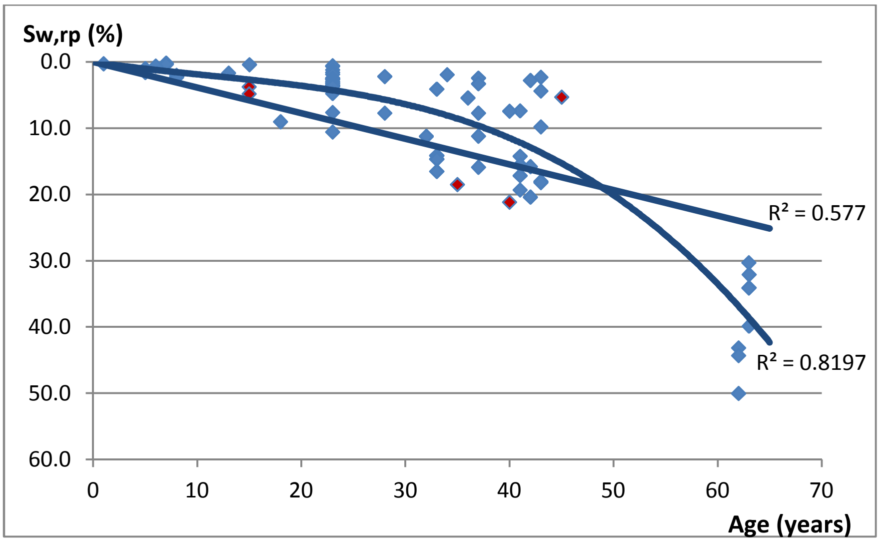


Figure 3.21 - Degradation curve after the façades removal

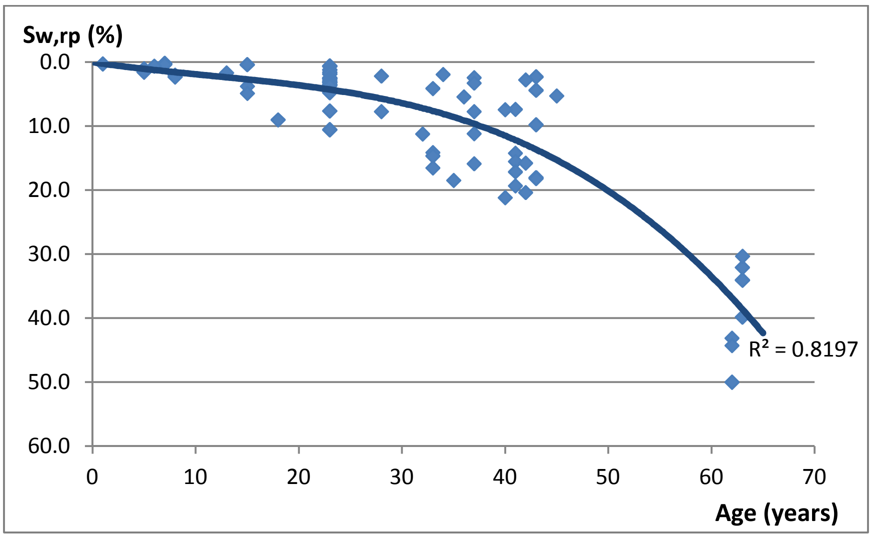


Figure 3.22 - Final degradation curve based on Sousa (2008) data

3.4 Characterization of the work of Sousa (2008) and definition of the necessary sample

The sample of Sousa (2008) consists of 117 façade claddings. As mentioned, this is the union of the work carried on by the author and some façades taken from the sample of Silvestre (2005). The analysis described in Paragraph 3.3 has led to the exclusion of 40 façades and the value updating of 7 of these (these have been replaced with 5, as already explained). The final result is a 75 façades sample.

At this point, a characterization of the sample has been carried out. This is followed by the definition of the information to be gathered during the new inspections, in order to obtain a final sample as complete and uniform as possible. The tables in the next paragraphs calculate the minimum number of claddings that need to be collected. It should be noticed that the intended amount of façades is approximate. In the choice of the buildings it would be necessary to combine all the different factors and requested features.

3.4.1 Characterization of the claddings

The external claddings will be analyzed according to three different aspects that define their state of degradation: age of the façade, the environment that influences the façade performance and features of the cladding itself.

Characterization of the claddings age

Figure 3.23 shows the distribution by number of the façades, according to their age. As adopted in the previous works (Sousa, 2008; Silva, 2009; Emídio, 2012), age is counted from the date of the entrance into service of the façade, or, in case this has been renovated, the date of the most recent refurbishment. Age has been divided in seven ranges, from 0 up to 70 years old. In fact, it is considered useless to consider buildings too old, which feature a generalized degradation level, far beyond the acceptable level of service ability.

The total absence of 50 to 59 years old claddings stands out, as well as the deficiency of façades dated between 10 and 19 years old and over 60 years old. The sample of the current work will remedy this deficiency. In fact, the age is considered the most important factor to be taken into account, since it is essential to define the degradation regression curve. For this reason, it was chosen to be used it as the basis for the next tables, in which the needed number of façades is defined. In each of these tables the age has been crossed with the information about each variable.

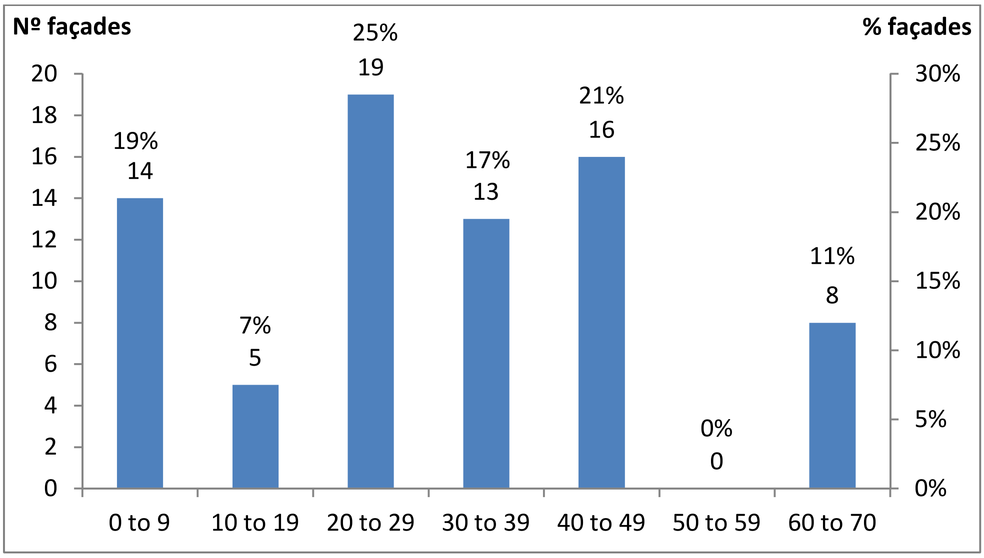


Figure 3.23 - Age distribution of the 75 façades of the sample of Sousa (2008)

Characterization of the claddings location

In matter of location, four factors influence the claddings degradation evolution: distance from the sea, façade orientation, intensity of wind and rain action, and humidity level.

Regarding the first one, the sea affects the durability of the materials because of the presence of salts in the air and stronger winds. All the buildings included in the sample are located in Lisbon; here the proximity to the mouth of the river Tagus makes the water salty and the air as well. In the sample of Sousa (2008) the number of claddings located next to the river bank is low: only 4 of 75 (Figure 3.24).

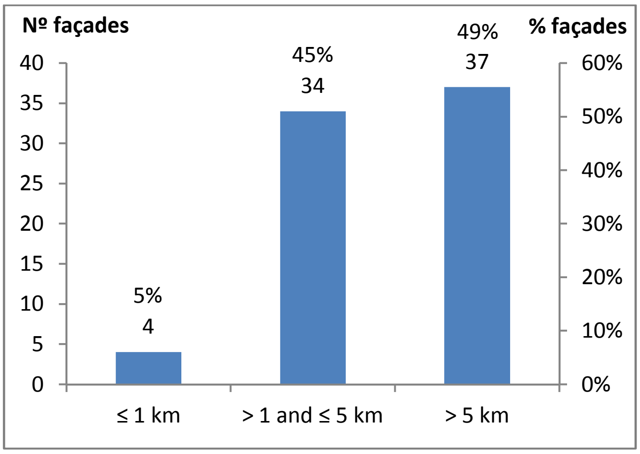


Figure 3.24 - Number of façades according the distance from the sea

For this, any conclusion concerning the degradation evolution for the buildings that are close to the sea is impossible, as can be seen in Figure 3.25. The suggested number of façades to be inspected, referring to the distance from the sea, is shown in Table 3.2. The difference between the numbers of cases estimated for the variable "≤ 1 km" and the others is noticeable. As mentioned before, the information regarding age and location are crossed: the sums calculated for each range are highlighter in green, and the total number of the sample's claddings is coloured in orange.

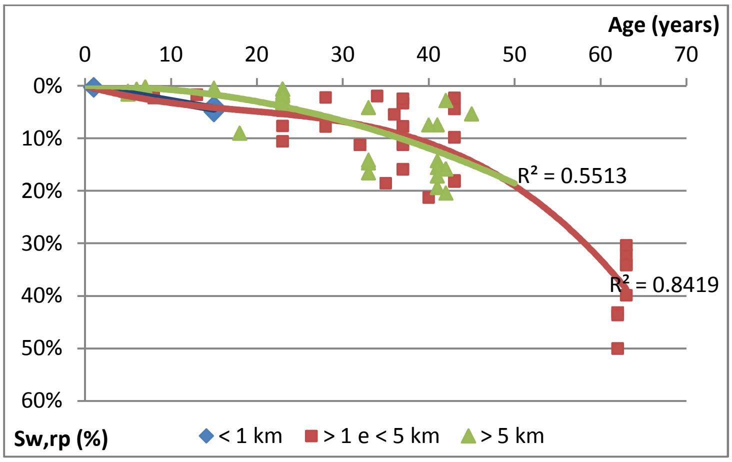


Figure 3.25 - Overall degradation curve according to distance from the sea

Table 3.2 - Minimum number of façades needed according to distance from the sea

Age	Sousa (2008)				Current work (target)				Sum
	≤ 1 km	> 1 and ≤ 5 km	> 5 km	Total	≤ 1 km	> 1 and ≤ 5 km	> 5 km	Total	
0 to 9	2	5	7	14	5	5	0	10	24
10 to 19	2	1	2	5	5	10	5	20	25
20 to 29	0	5	14	19	10	0	0	10	29
30 to 39	0	10	4	14	10	0	5	15	29
40 to 49	0	5	10	15	10	0	0	10	25
50 to 59	0	0	0	0	10	10	10	30	30
60 to 70	0	8	0	8	10	0	10	20	28
	4	34	37	75	60	25	30	115	190
				Sum	64	59	67		

Considering now the façades orientation, Figure 3.26 illustrates how the majority of the selected façades feature the main orientations (north, east, south and west), while the intermediate directions have very few elements. For this reason, in order to reduce the number of variables, it has been chosen to not consider them in the following studies, but to focus the attention only on the main directions.

Looking instead at the overall degradation graph (Figure 3.27), it does not allow any reliable conclusion. Despite the high value of R-squared, there is no rational explanation to the fact that the west orientation curve is much worse than the others. Further, the north direction has quite scattered points, which yield a low R-squared value. Furthermore, the absence of over 42 years old claddings makes the tracing of a trend line impossible. In further inspections these aspects will be taken into account, especially regarding the north orientation.

Table 3.3 illustrates the minimum number of required claddings. To be noticed are the age ranges (10 to 19, 50 to 59 and 60 to 70 years old) which feature lack of façades in the Sousa (2008) sample; in these cases at least 5 claddings should be inspected for every orientation, with the aim of filling the gaps.

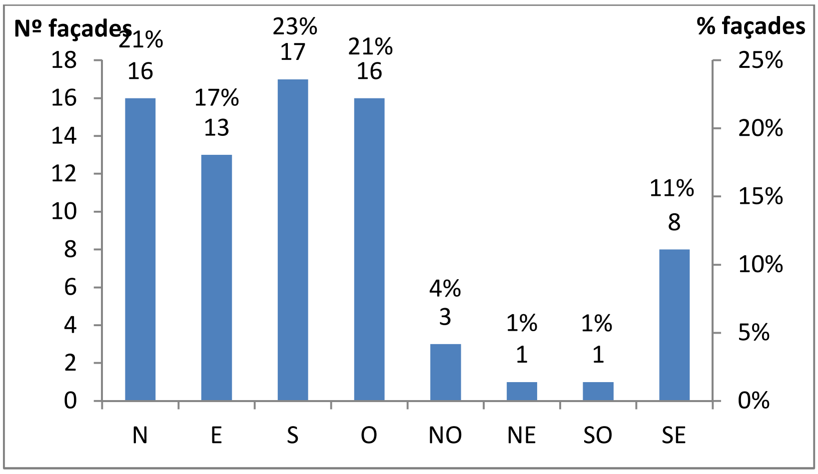


Figure 3.26 - Number of façades according to facades orientation

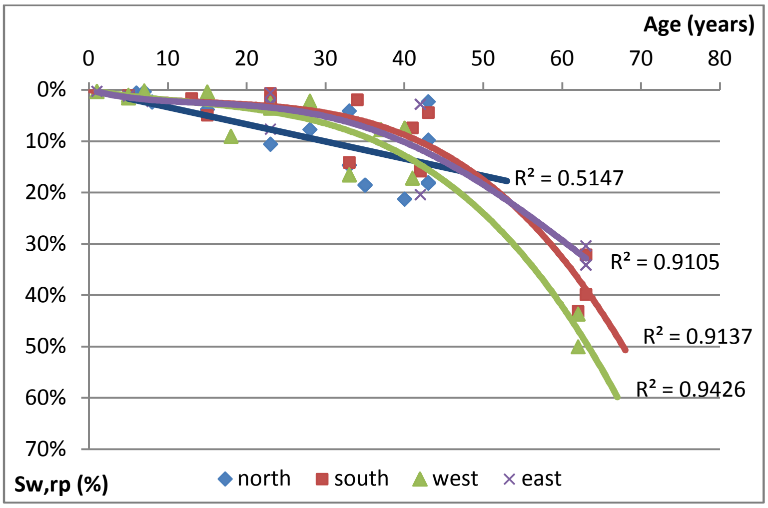


Figure 3.27 - Overall degradation curve according to facades orientation

Table 3.3 - Minimum number of façades needed according to facades orientation

Age	Sousa (2008)					Current work (target)					Sum
	N	E	S	W	Total	N	E	S	W	Total	
0 to 9	4	3	2	4	13	0	5	5	0	10	23
10 to 19	1	0	2	2	5	5	5	5	5	20	25
20 to 29	3	4	5	4	16	5	0	0	0	5	21
30 to 39	3	1	2	2	8	0	5	5	5	15	23
40 to 49	5	2	3	2	12	0	5	0	5	10	22
50 to 59	0	0	0	0	0	5	5	5	5	20	20
60 to 70	0	3	3	2	8	5	5	5	5	20	28
	16	13	17	16	62	20	30	25	25	100	162
					Sum	36	43	42	41		

The third factor, depending on the building location, is the wind and rain action. Figure 3.28 illustrates the statistics regarding this feature. Also in this case, one alternative has been poorly studied: the severe action of wind and rain, with only 4 claddings out of 75. This could be related to the lack of elements located next to the river, where the wind action is stronger.

Consequently, it is impossible to draw a trend line for the buildings located in zones where the atmospheric agents are more extreme (Figure 3.29). These considerations lead to the need to estimate a number of required façades that focus on eliminating this deficiency (Table 3.4).

Exposure to humidity is the last cause of degradation of the façades depending on the location. As for distance from sea and wind/rain action, the discrepancy between the number of claddings exposed to favourable and unfavourable conditions is wide (Figure 3.30). Once again, it may be related to the lack of elements located in the proximity of the river, where the environmental conditions are harsher.

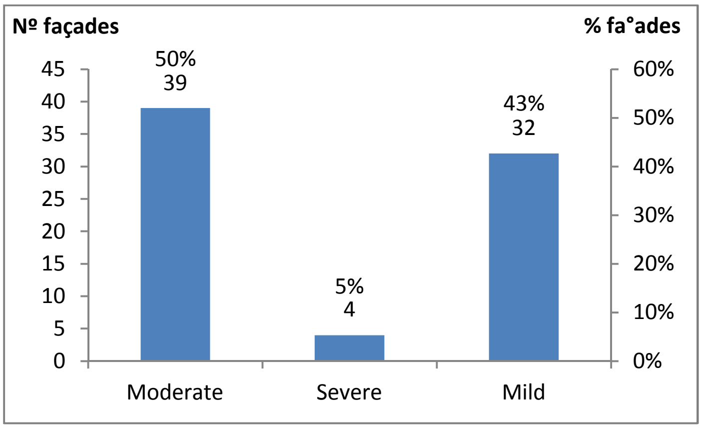


Figure 3.28 - Number of façades according to wind/rain action

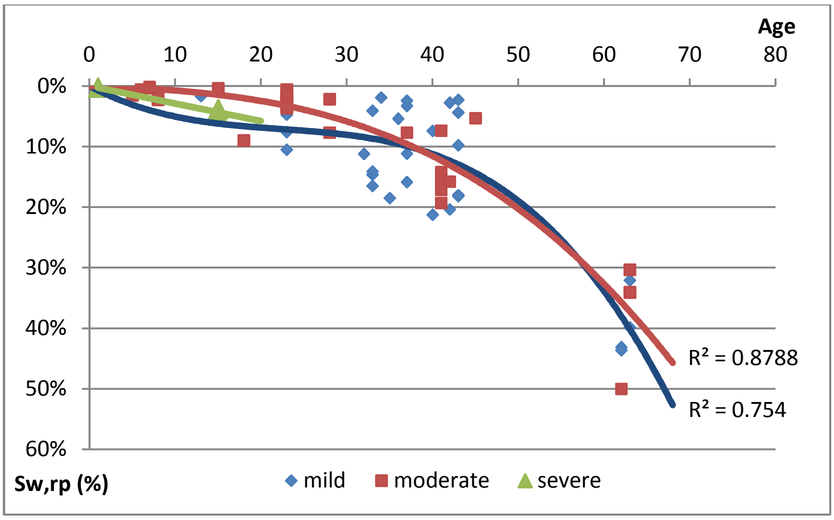


Figure 3.29 - Overall degradation curve according to wind/rain action

Table 3.4 - Minimum number of façades needed according to wind/rain action

Age	Sousa (2008)				Current work (target)				Sum
	Moderate	Severe	Mild	Total	Moderate	Severe	Mild	Total	
0 to 9	9	2	3	14	0	5	5	10	24
10 to 19	2	2	1	5	5	10	5	20	25
20 to 29	16	0	3	19	0	10	0	10	29
30 to 39	1	0	12	13	5	10	0	15	28
40 to 49	7	0	9	16	0	10	0	10	26
50 to 59	0	0	0	0	10	10	10	30	30
60 to 70	4	0	4	8	0	10	0	10	18
	39	4	32	75	20	65	20	105	180
				Sum	59	69	52		

On the other hand, the overall degradation curve gives good results (Figure 3.31). In spite of the low number of façades featuring "high humidity level", the regression curves are markedly defined. As it will be seen further, this factor is one the most significant for the degradation evolution, allowing a clear and reliable outcome.

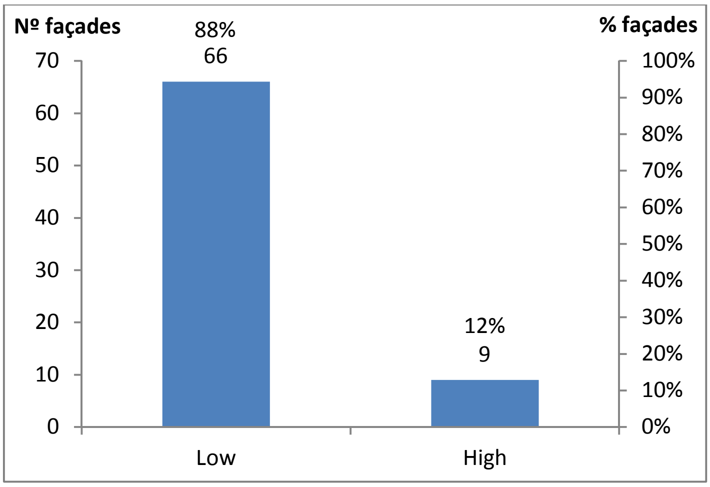


Figure 3.30 - Number of façades according to humidity exposure

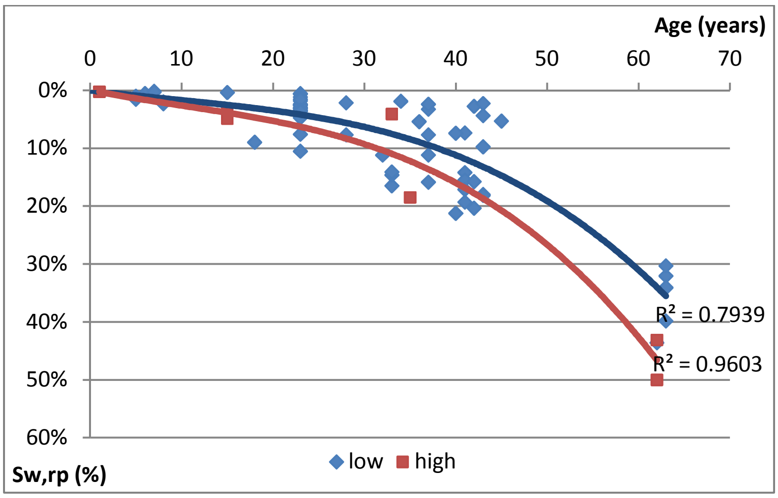


Figure 3.31 - Overall degradation curve according to humidity exposure

Although the degradation severity trend lines give a substantial outcome, it has been chosen to focus the next inspections on the claddings that are located in zones where the humidity level is thought to be more severe. Table 3.5 show the discrepancy between the facades' minimum required numbers concerning the two variables.

Table 3.5 - Minimum number of façades needed according to humidity exposure

Age	Sousa (2008)			Current work (target)			Sum
	High	Low	Total	High	Low	Total	
0 to 9	2	12	14	10	0	10	24
10 to 19	3	2	5	5	10	15	20
20 to 29	0	19	19	10	0	10	29
30 to 39	2	12	14	10	0	10	24
40 to 49	0	15	15	10	0	10	25
50 to 59	0	0	0	10	10	20	20
60 to 69	2	6	8	5	5	10	18
	9	66	75	60	25	85	160
			Sum	69	91		

Characterization of the claddings type

In this section the factors regarding the claddings and their characteristics will be analyzed. These are some of the features that are going to be taken into account in the further chapters and that are the basis for the factor method application: tiles surface, colour and size, and cladding substrate.

Regarding the surface of the ceramic tiles, in the sample of Sousa (2008) the number of claddings featuring a glazed surface is much higher than the not glazed ones (Figure 3.32). Therefore, the regression line corresponding to the not glazed surface is quite inconclusive (Figure 3.33). In Table 3.6, 55 the not glazed claddings to be inspected have been estimated, against 30 glazed ones.

The fact that the lack of the not glazed tiles reflects the real percentage among all the ceramic external wall claddings should be underlined. As it will be seen further, it is difficult to reach these figures, because the majority of the façades is actually constituted by glazed tiles.

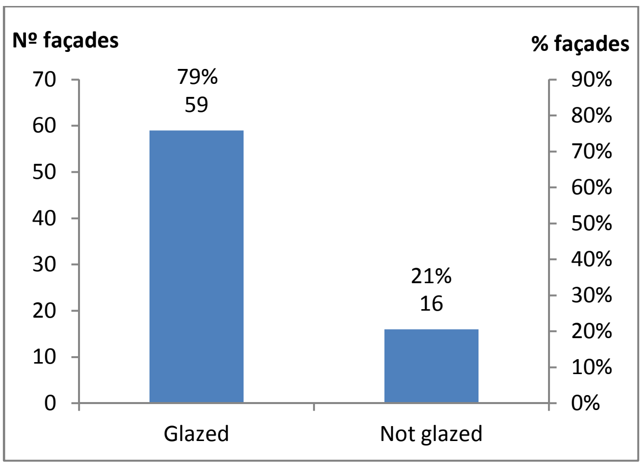


Figure 3.32 - Number of façades according to tiles surface

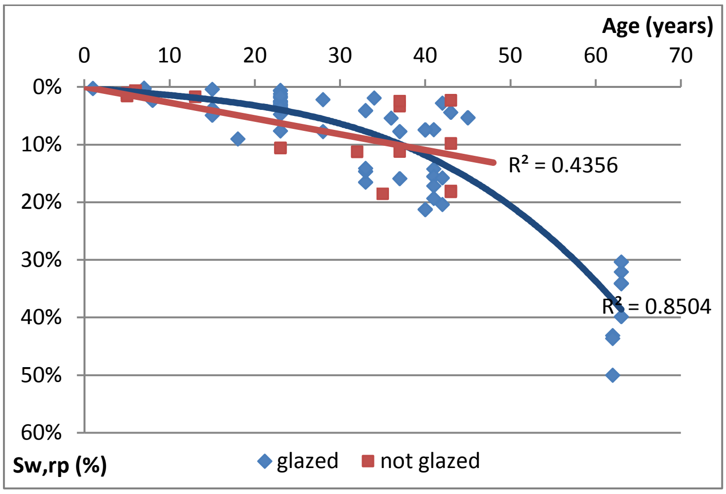


Figure 3.33 - Overall degradation curve according to tiles surface

Table 3.6 - Minimum number of façades needed according to tiles surface

Age	Sousa (2008)			Current work (target)			Sum
	Glazed	Not glazed	Total	Glazed	Not glazed	Total	
0 to 9	9	5	14	5	5	10	24
10 to 19	4	1	5	5	10	15	20
20 to 29	18	1	19	0	10	10	29
30 to 39	9	5	14	5	5	10	24
40 to 49	11	4	15	0	5	5	20
50 to 59	0	0	0	10	10	20	20
60 to 69	8	0	8	5	10	15	23
	59	16	75	30	55	85	160
			Sum	89	71		

Considering now the colour of the ceramic tiles, it has been classed in three groups: dark coloured, light coloured and white. This is done to simplify the analysis and to reduce the number of variables to be taken into account. Figure 3.34 shows how the number of dark coloured tiles is predominant, since it is more than the double of the other two groups.

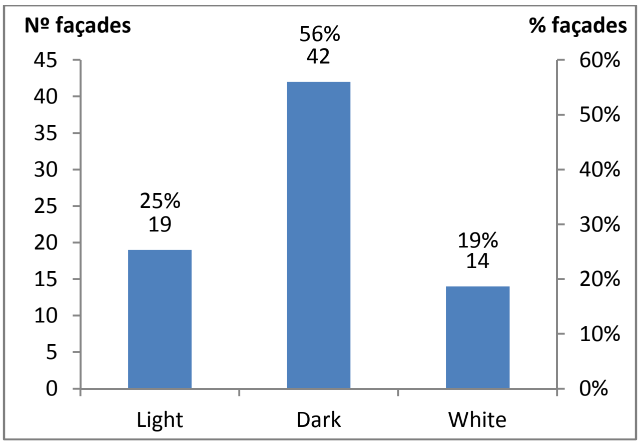


Figure 3.34 - Number of façades according to tiles colour

Figure 3.35 displays how the trend line of the light coloured claddings feature a high R-squared value (0.8654), which is better than the dark colour's one (0.6005). In spite of this, the general outcome is rather inconclusive. The estimated minimum number of the light coloured façades, to be collected for the new sample, is higher than the others (Table 3.7).

A separate discussion must be done for the colour white: all the white claddings of the sample are taken from a given block of flats, located in the same district and built in the same year (1985). This makes it impossible to define any regression line for this variable. With the current work, it will be tried to improve the reliability of the results. However, just like for the surface type, it will also be seen there is actually a shortage of white claddings.

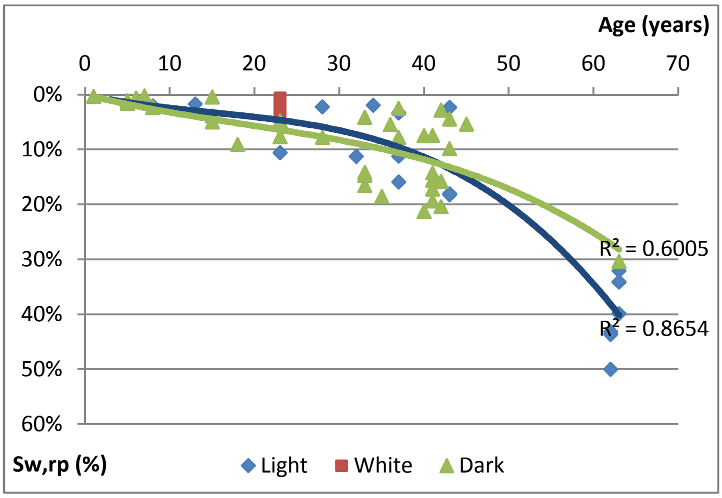


Figure 3.35 - Overall degradation curve referring to tiles colour

Table 3.7 - Minimum number of façades needed according to tiles colour

Age	Sousa (2008)				Necessary claddings (target)				Sum
	Light	White	Dark	Total	Light	White	Dark	Total	
0 to 9	1	0	13	14	5	5	0	10	24
10 to 19	1	0	4	5	5	5	5	15	20
20 to 29	2	14	3	19	5	0	5	10	29
30 to 39	5	0	8	13	5	5	5	15	28
40 to 49	3	0	13	16	5	5	0	10	26
50 to 59	0	0	0	0	10	5	10	25	25
60 to 69	7	0	1	8	5	5	5	15	23
	19	14	42	75	40	30	30	100	175
				Sum	59	44	72		

About the tiles size, based on the Sousa (2008) work, this has been divided in two groups: tiles with at least one of the two sides longer than 20 cm have been separated from the others. The situation is quite similar to those just listed. That is, the amount of external walls featuring small tiles is much higher than the other (75% to 25%), due to the actual proportion between them in the reality (Figure 3.36).

The trend line concerning the tiles with the sides shorter than 20 cm shows better results, in terms of shape. It is clear that the line of the large tile is steeper (Figure 3.37), meaning a faster degradation: in fact, this will be confirmed by the results of the further field work. Table 3.8 calculates the minimum required number of façades, concerning tiles size.

The last feature regarding the claddings characterization is the type of substrate: masonry or concrete. In this case as well, a deficit of one of the two variables can be noticed: masonry buildings make up only 31% of the total (Figure 3.38). Nevertheless, as happened before with the high humidity exposure and the light colour, the regression line shows a high R-squared value (0.8214), as evidence of the reliability of the sample (Figure 3.39) concerning this factor. Anyway, with the current work it will be tried to reach the targets of the two substrate types. The number of claddings to be inspected is calculated in Table 3.9.

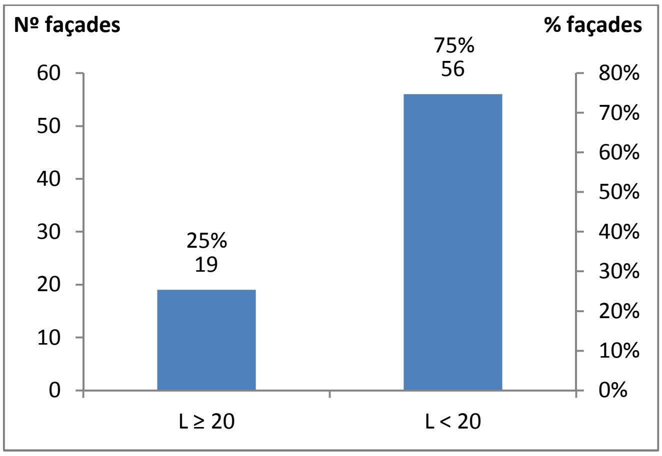


Figure 3.36 - Number of façades according to tiles size

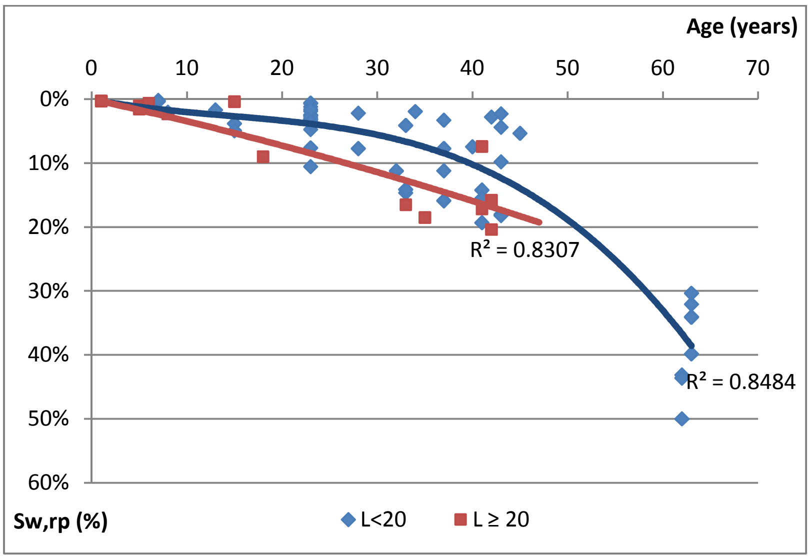


Figure 3.37 - Overall degradation curve according to tiles size

Table 3.8 - Minimum number of façades needed according to tiles size

Age	Sousa (2008)			Current work (target)			Sum
	L ≥ 20	L < 20	Total	L ≥ 20	L < 20	Total	
0 to 9	11	3	14	0	10	10	24
10 to 19	2	3	5	10	10	20	25
20 to 29	0	19	19	10	0	10	29
30 to 39	2	12	14	10	0	10	24
40 to 49	4	11	15	10	0	10	25
50 to 59	0	0	0	10	10	20	20
60 to 69	0	8	8	10	10	20	28
	19	56	75	60	40	100	175
			Sum	79	96		

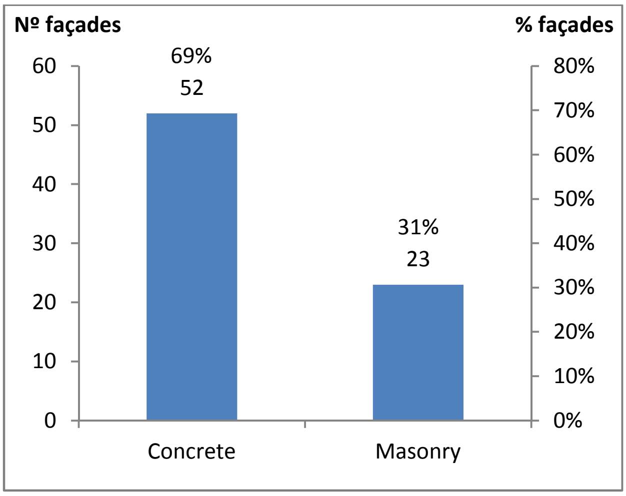


Figure 3.38 - Number of façades according to claddings substrate

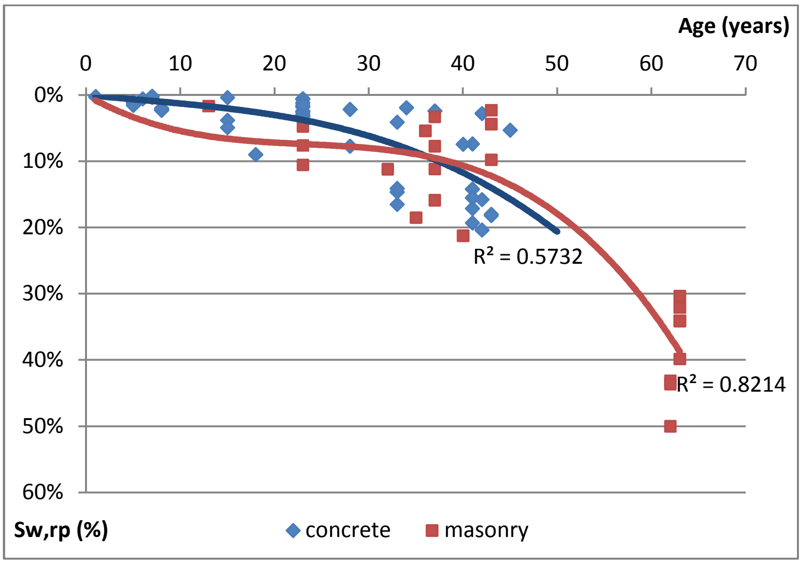


Figure 3.39 - Overall degradation curve according to claddings substrate

Table 3.9 - Minimum number of façades needed according to claddings substrate

Age	Sousa (2008)			Current work (target)			Sum
	Concrete	Masonry	Total	Concrete	Masonry	Total	
0 to 9	14	0	14	0	10	10	24
10 to 19	4	1	5	5	10	15	20
20 to 29	16	3	19	0	5	5	24
30 to 39	6	8	14	5	5	10	24
40 to 49	12	3	15	0	5	5	20
50 to 59	0	0	0	10	10	20	20
60 to 69	0	8	8	10	5	15	23
	52	23	75	30	50	80	155
			Sum	82	73		

3.4.2 Sample to be gathered

In the previous section, the sample of Sousa (2008) has been characterized, which is the basis for the current work and will be part of the final sample. The minimum number of façades, which should be inspected in order to fill the gaps of the previous work, has also been defined. All the tables regarding the various factors affecting the durability have been collected in Table 3.11. The minimum number of required inspection is found to be 115.

The values that are decisive in determining the total inspections number are highlighted in bold. One can observe how the most crucial ones are among those that have more than two sub-factors: distance from the sea and wind/rain action. In fact, the higher the number of variables, the higher is the number of inspections needed to compensate for the lacks.

Table 3.10 - Minimum number of façades needed: summary

Age	Sea distance	Substrate	Orientation	Wind/rain action	Humidity exposition	Surface	Colour	Dimension	Total
0 to 9	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**	10
10 to 19	**20**	15	**20**	**20**	15	15	15	**20**	20
20 to 29	**10**	5	5	**10**	**10**	**10**	**10**	**10**	10
30 to 39	**15**	10	**15**	**15**	10	10	**15**	10	15
40 to 49	**10**	5	**10**	**10**	**10**	5	**10**	**10**	10
50 to 59	**30**	20	20	**30**	20	20	25	20	30
60 to 69	**20**	15	**20**	10	10	15	15	**20**	20
									115

3.4.3 Characterization of the detected anomalies

To conclude the analysis of the results of Sousa (2008), the anomalies identified during the *in situ* inspections have been studied. The classification of the anomalies affecting the ceramic external claddings, as done by the author, has been presented in paragraph 2.3.1. Concerning the outcomes of the work of Sousa (2008) in terms of detected defects, these are illustrated in Figure 3.40 and Figure 3.41.

The two most common anomalies are the aesthetic defects and the joint deterioration: both make up around 30% of the noticed defects (Figure 3.40). These are followed by cracking; the less widespread anomaly is adhesion failure (11%). From this graph mainly emerges how the joints represent a brittle part of the ceramic wall cladding, and a component that needs particular attention.

Figure 3.41 goes into more detail. It shows how six anomalies are more common than the others, which feature a percentage value between 10% and 20%. It also shows how the three most frequent defects are also the less severe of each category: 79% of the ceramic façades feature staining or change in joints colour. This is followed by the superficial dirt (affecting 63% of the cladding of the sample) and glaze cracking (43%). Instead, the other widespread anomalies are more serious than those just listed; i.e. cracks with marked direction (0.2 mm < width < 1 mm), joint deterioration with loss of material and detachment, all affecting around 30% of the sample.

These data will be further compared and discussed in the context of the new sample results (Paragraph 3.6.2).

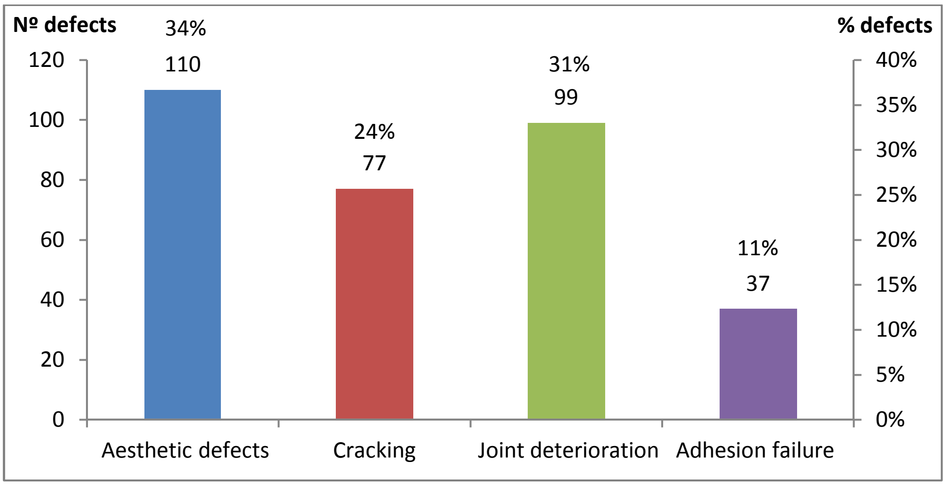


Figure 3.40 - Façade percentages according to the anomalies detected

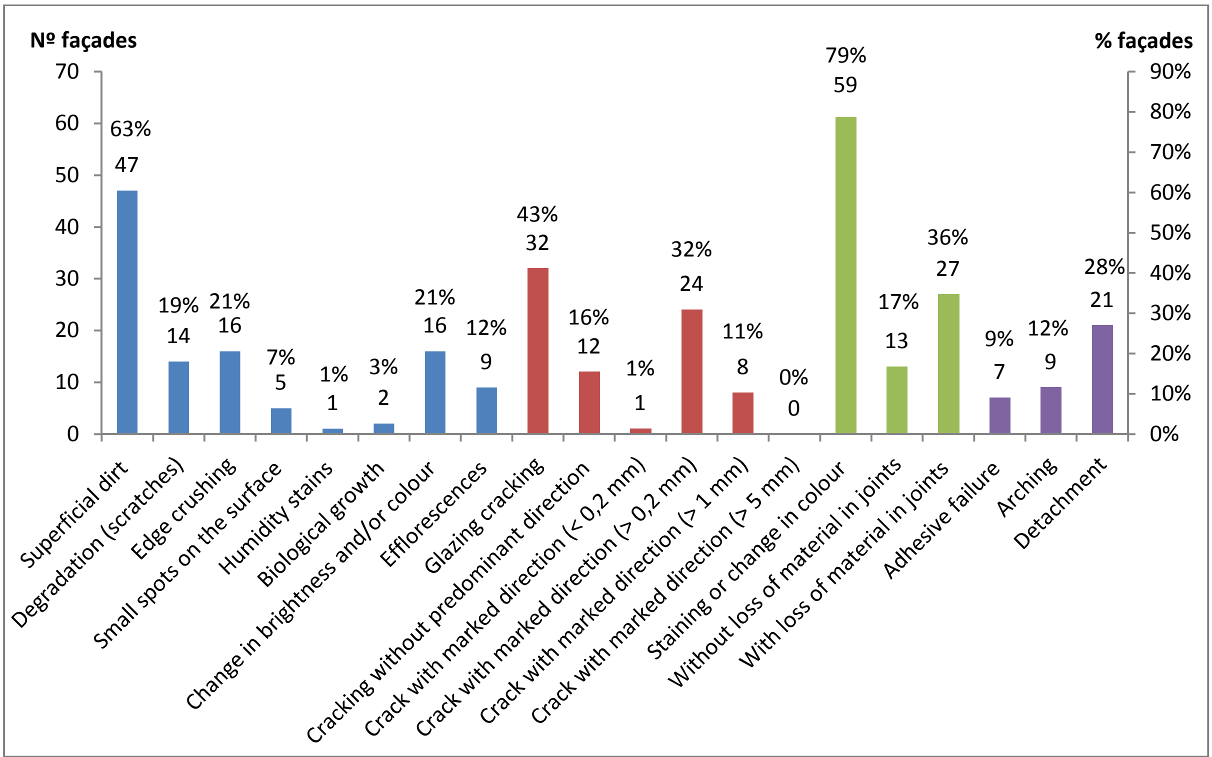


Figure 3.41 - Façade percentages according to the anomalies detected

3.5 Methodology

3.5.1 Inspection sheet

Before dealing with the field work, which constitutes the third and last part of the current chapter, the techniques and the prerequisite for the field work will be briefly described. The aim of the *in situ* inspections has been previously determined in paragraph 3.2, i.e. the annotation of the defects of the ceramic external wall claddings. These data have to be further used as a basis for the application of the factor method. For this reason, two kinds of information must be gathered: the state of deterioration of the claddings, for the calculation of the reference service life (RSL) and the estimated service life (ESL), and the façades characteristics, whose purpose is to determine the factor method coefficients.

Particularly, paragraph 2.3 describes the degradation mechanisms that have to be identified during the inspections: the anomalies affecting the ceramic claddings have been classified and the related degradation levels have been defined.

On the other hand, in the previous section (paragraph 3.4) some information that characterizes the claddings and the environmental conditions has already been specified. The latter have been chosen on the basis of the factor method calculation and the factors that compose it.

From the union of these requirements comes the inspection checklist, which has been used during the field work to take note of the required data for each façade of the sample. The inspection sheet had been previously developed by Sousa (2008); it has been maintained, with some changes. The structure is based on the factor method's multiplicative factors and it is organized in this manner:

1. Façade characterization
    - Orientation
    - Year of conclusion
    - Façade type
    - Ceramic wall cladding area
2. Material's quality, finishing, or treatment
    - Tiles size
    - Surface
    - Tiles colour
3. Characteristic of the design
    - Substrate
    - Existence of joints
    - Peripheral protections
    - Corner protections
4. Outdoor environmental conditions
    - Pollution exposition
    - Wind/rain action
    - Humidity exposition
    - Distance from the sea
5. Maintenance level
    - Regular maintenance
    - Ease of inspection
6. Anomalies
    - Aesthetic defects
    - Cracking
    - Joint deterioration
    - Adhesion failure

The inspection sheet can be seen in Annex 1. Instead, in Annex 2 there is an example of a filled checklist, with the related photographic register.

3.5.2 Methodology adopted for the field work

In this section it will be shortly explained how the *in situ* inspections have been carried out. The adopted methodology had been previously defined by Gaspar (2009), and it has already been utilized by other authors, contextually to the service life prediction of different building components (Sousa, 2008; Silva, 2009; Emídio, 2012). It consists of the visual assessment of the degradation level of a significant sample, constituted by different age façades. The foundations of this work were based on the studies of Bone et al. (1989) and Watt (1999). In these last, the aspects to be considered before the field work are defined. The same have been taken into account also for the current inspections; these are:

- Target: collection of quantitative information (façade characteristics and affected areas) and qualitative information (anomalies and degradation levels);
- Information survey: *in situ* visual inspections, with the aid of the inspection sheets;
- Required technical means: digital camera, measuring tape, software applications (CAD®) and spreadsheets;
- Compliance with the minimum technical/human requirements;
- Previous information gathered related to the inspected façades, in particular about the age;
- Definition of time limits and budget.

Some clarifications: for the façades of limited extension and featuring ease of inspection, the cladding surface area has been assessed by multiplying the area of a single tile by the total tiles number. The same goes for the areas affected by the anomalies. For the wall cladding of greater size, this evaluation has been carried out with the aid of photographs, further elaborated with Photoshop®, and sketches, later reproduced in scale with AutoCAD®.

Concerning the age, this had been defined in paragraph 3.4.1. In order to date the façades, it two different procedures have been used. The first source of information is the Lisbon Municipal Archive (*Câmara Municipal de Lisboa*). Here the construction works and edifications are catalogued and all the information about the buildings can be gathered. But it may happen that the archive data are incomplete, or not usable for the current study. For example, the maintenance works on façades less than 3 m high do not require any authorization and are not registered. Therefore, this source has been completed with the information given by the tenants; the latter have been consulted as often as possible.

A detailed description of the procedure presented above, particularly concerning the areas measurement, can be found in the "Manual de inspecção técnica de fachadas" (Gaspar, 2009).

3.6 Field work results analysis

3.6.1 Collected data

The collected sample consists of 122 façades (Annex 3); two of these have been excluded. All the chosen buildings are located in Lisbon. More precisely, they are situated in 29 different parishes, which are: Mártires, Prazeres, Santos-o-Velho, Alvalade, Benfica, Alto da Pina, São João, Lumiar, Campo Grande, São João de Brito, São Domingos de Benfica, São Paulo, São Vicente de Fora, São Miguel, Santiago, Sé, Madalena, Lapa, Santa Engrácia, Santo Condestável, São Mamede, Sacramento, Santa Maria de Belém, Santa Isabel, Coração de Jesus, São Jorge de Arroios, Santa Catarina, Mercês and Santa Maria dos Olivais. The reason why these constructions are so scattered around the city, is that it has been tried to get a sample as complete as possible. The fact that all the façades of the sample are located in the same city, limits the applicability of the method in contexts with different climates. For this, the gathered sample includes claddings that feature different situations, in terms of environmental conditions and façade characteristics.

The number of the inspected façades comes from Table 3.11; as mentioned, the calculated minimum number is indicative. In fact, in order to fill gaps in some variables, it has been necessary to collect a few more elements than expected. The 120 new claddings have been eventually combined with the sample of Sousa (2008), which includes 75 façades. Therefore, the final sample that has been used as a basis for the service life prediction consists of 195 ceramic external wall claddings.

Excluded cases

Two façades have been removed from the sample, because the detected defects were not related to a normal degradation evolution; both of them feature poor execution. As a proof of this fact, after the overall degradation evolution assessment, these have shown a very high value of severity degradation, if compared with the age.

The first case concerns a building located in São Mamede. Here the façades had been recently repaired (2010), contextually to the refurbishment of the entire house. But, in spite of the young age of the cladding, it features widespread joints deterioration with loss of material (Figure 3.42). As the date of the refurbishment that was found in the archives of the Lisboa Municipality has been confirmed by the tenants and the neighbours, this has been considered reliable. The only explanation for this degradation severity is the bad execution, causing the cladding elimination from the sample.

The second element that has been removed is a façade located in Santo Condestável. This building is 47 years old. It presents glaze cracking and joints deterioration with loss of material. But the most severe anomaly is the adhesive failure: this increase the severity value up to 46.4%. Also in this case the cause of such a bad deterioration has been found in a deficient execution of the façade. As seen in Figure 3.43, the mortar has not been properly pressed, with the result of adhesive failure and detachment.

Figure 3.42 - Façade featuring joints deterioration

Figure 3.43 - Excluded façade: the mortar has not been adequately pressed

3.6.2 Results analysis

An analysis of the outcomes of the inspections has been made. The steps followed are the same of paragraph 3.4; which means to first analyze the claddings characteristics and then the detected anomalies. Besides this, the cladding characterization has been divided according to the different aspects that influence the degradation evolution: age of the façade, environmental conditions and claddings features.

Characterization of the claddings age

Concerning the age of the collected sample, Figure 3.44 shows how the highest percentage refers to the claddings that are between 50 to 59 years old (21%), followed by the 10 to 19 and the 40 to 49 years old ranges (19% of the sample). This reveals the mentioned purpose of filling the detected gaps of the sample of Sousa (2008). As seen in Figure 3.45, the distribution of the façades age of the final sample is rather uniform: all the percentages fall within the range between 10% and 15%.

The only exception is represented by the claddings dated 40 to 49 years old, which feature a higher number of elements. In fact, during the data collection, a sizeable amount of buildings refurbished in that period has been found.

The uniform age distribution reached after the field work will ensure that a reliable degradation curve can be gotten.

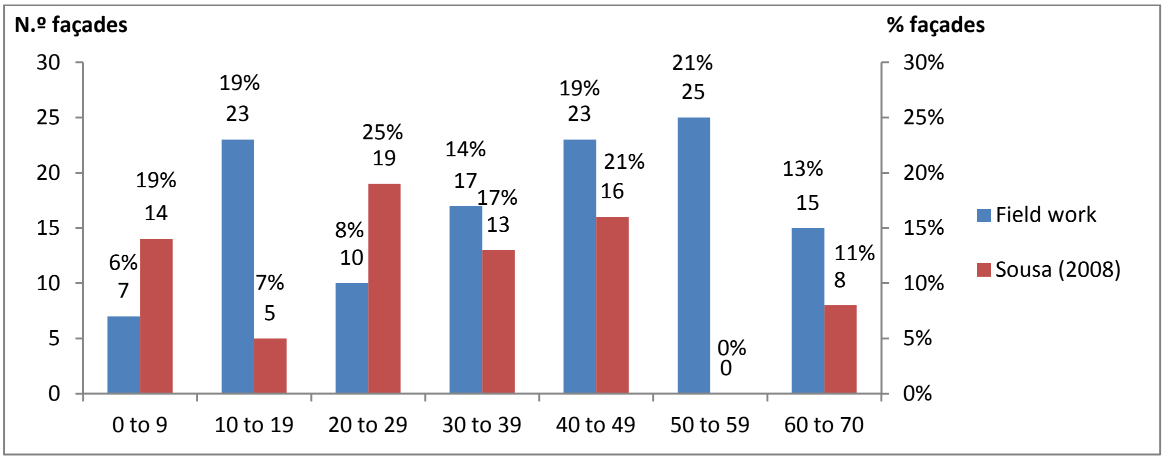


Figure 3.44 - Comparison between the results of Sousa (2008) and the current work

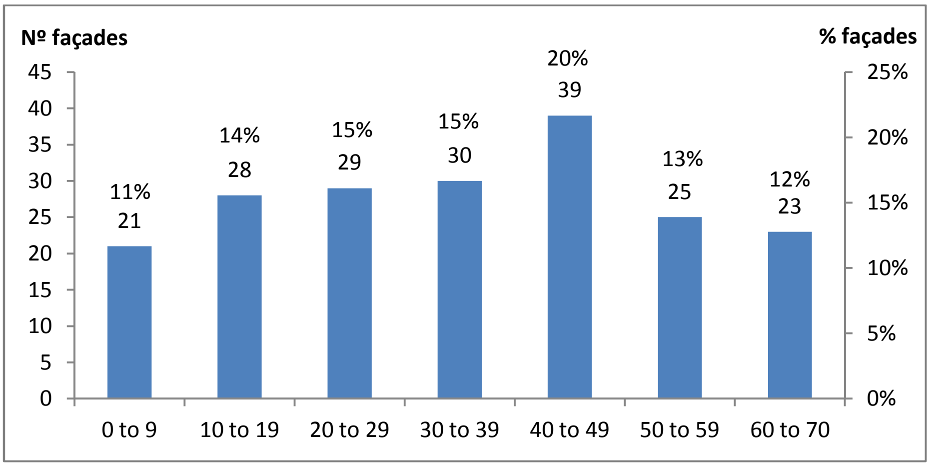


Figure 3.45 - Final sample data according to façades age

Characterization of the claddings location

The first parameter taken into account is the distance from the sea. In this case as well, the aim was to level the amounts of data concerning the different variables. The results are shown in Figures 3.46 and 3.47; the latter concerns the final sample values. It is clear how the total numbers of façades of each category are quite similar, improving the uneven distribution of the sample of Sousa (2008).

On the other hand, the outcomes regarding claddings orientation are illustrated in Figures 3.48 and 3.49. North oriented façades are predominant; despite that, the uniformity of the previous sample has been maintained.

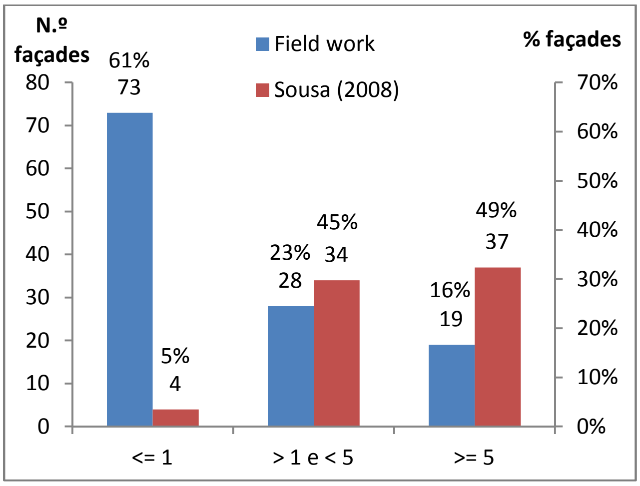


Figure 3.46 - Comparison between the results of Sousa (2008) and the current work

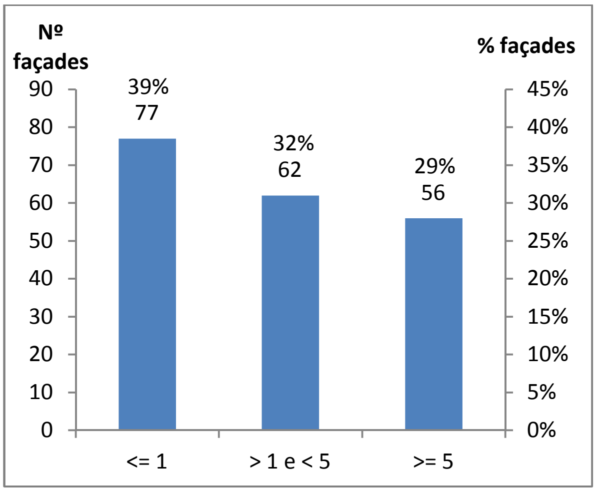


Figure 3.47 - Final sample data according to distance from the sea

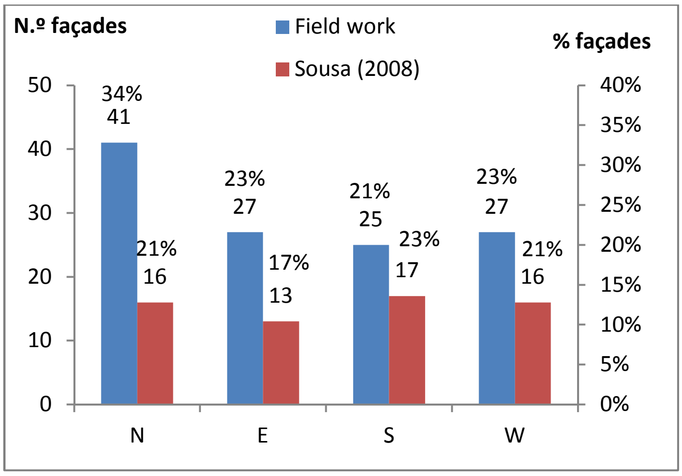


Figure 3.48 - Comparison between the results of Sousa (2008) and the current work

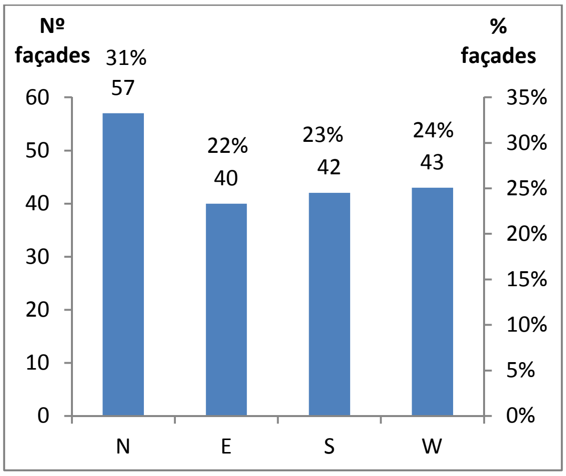


Figure 3.49 - Final sample data according to façades orientation

Figure 3.50 illustrates the comparison between the results of the two samples (2008 and 2012), in the matter of the wind and rain intensity. Here it had been noticed a large lack of elements featuring the severe exposition. After the field work, the number of claddings exposed to a moderate atmospheric agents' action is circa the double of the others (Figure 3.51); but the discrepancy between the other variables is not relevant (27% and 23%). Therefore, these amounts are considered enough to obtain reliable outcomes.

The same goes for the humidity exposition. In the final sample the gap existing in the outcomes of Sousa (2008) has been narrowed (Figures 3.52 and 3.53).

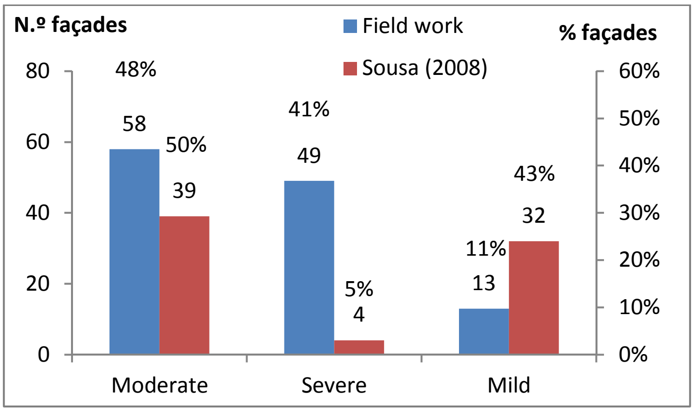


Figure 3.50 - Comparison between the results of Sousa (2008) and the current work

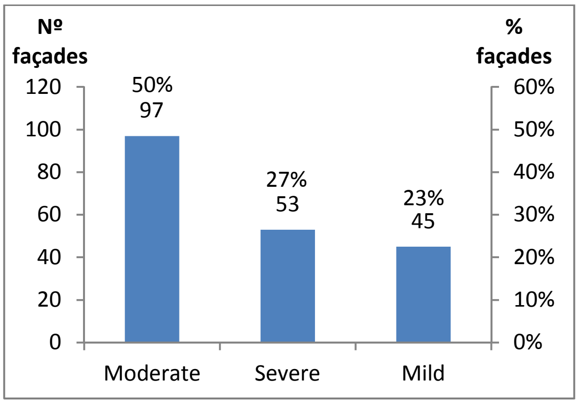


Figure 3.51 - Final sample data according to wind/rain action

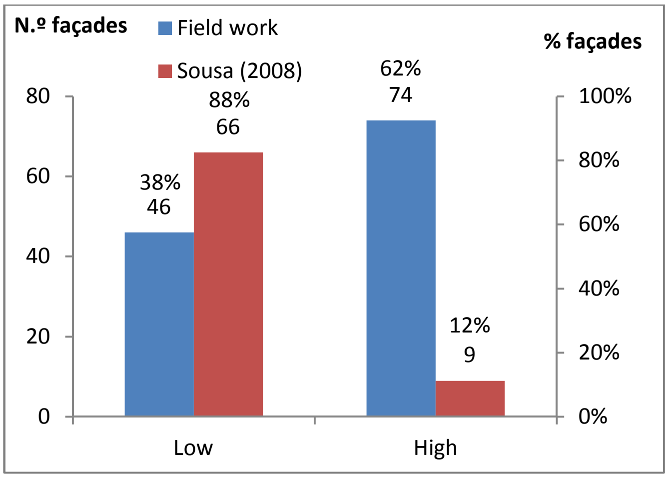


Figure 3.52 - Comparison between the results of Sousa (2008) and the current work

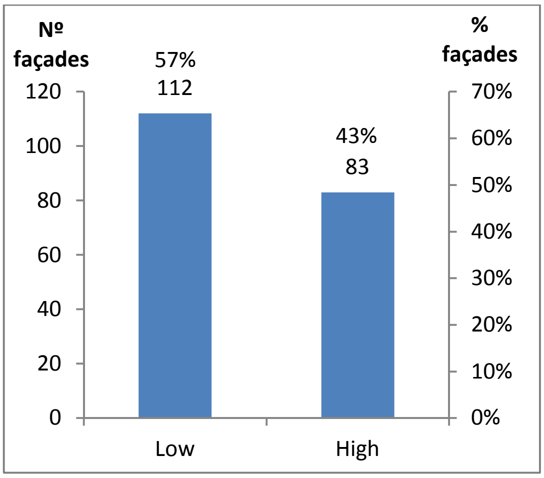


Figure 3.53 - Final sample data according to humidity

Characterization of the claddings type

As mentioned in paragraph 3.4.1, the variables that concern the characteristics of the ceramic external wall claddings have been considered. For three of these factors (precisely the surface, the size and the colour of the tiles) it has not been possible to reach the minimum number of required inspection, in order to level the percentages of the different sub-factors. This is due to the actual proportion of the latter within the ceramic façades population.

The tiles surface falls within the above-described case. During the data collection it has been noticed how the percentage of the not glazed tiled façades is significantly lower than that of the glazed one. This is even more visible in older buildings: the traditional ceramic tiles (*azulejos*), very common in the old quarters of Lisbon, are always tin-glazed. As the number of the old buildings analyzed is higher than the others (Paragraph 3.6.2), the glazed façades are also more numerous (Figures 3.54 and 3.55).

The same goes for the colour. It has been chosen to maintain the white coloured tiles separated from the light ones. But in this manner, it has not been possible to reach the target percentages of these features (Figure 3.56). The analyzed light tiled façades are nearly twice the dark ones, reaching a quite similar final value (Figure 3.57, respectively 51% and 41% of the sample). On the other hand, the number of white ceramic walls is not high enough to lead to any result.

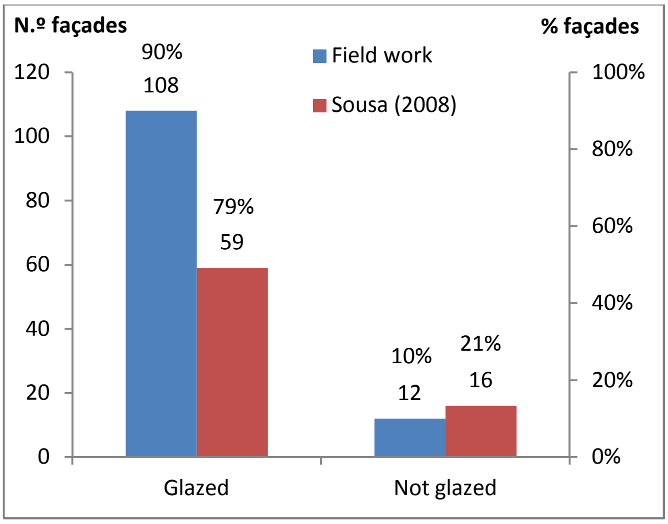


Figure 3.54 - Comparison between the results of Sousa (2008) and the current work

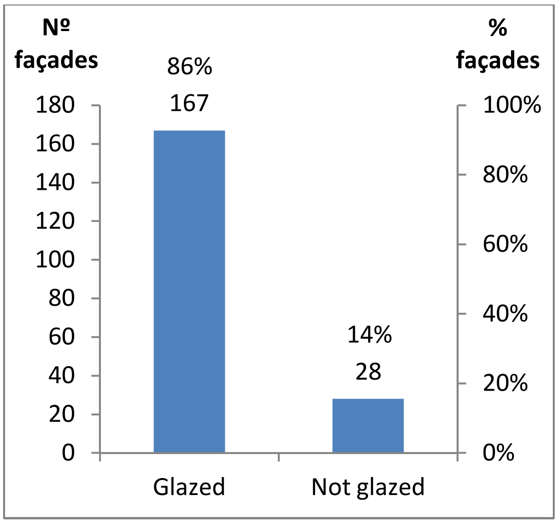


Figure 3.55 - Final sample data according to tiles surface

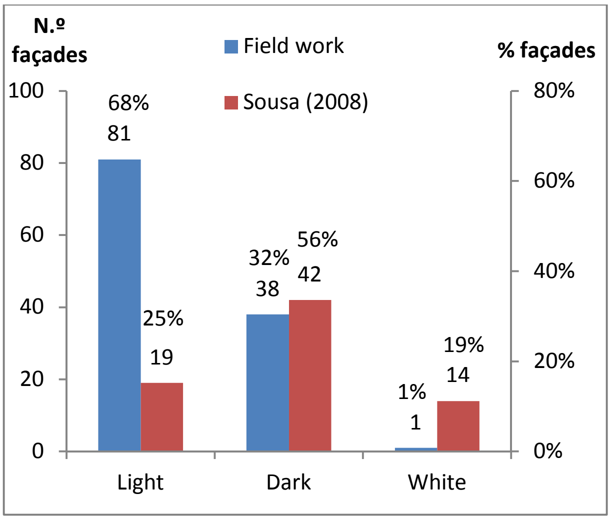


Figure 3.56 - Comparison between the results of Sousa (2008) and the current work

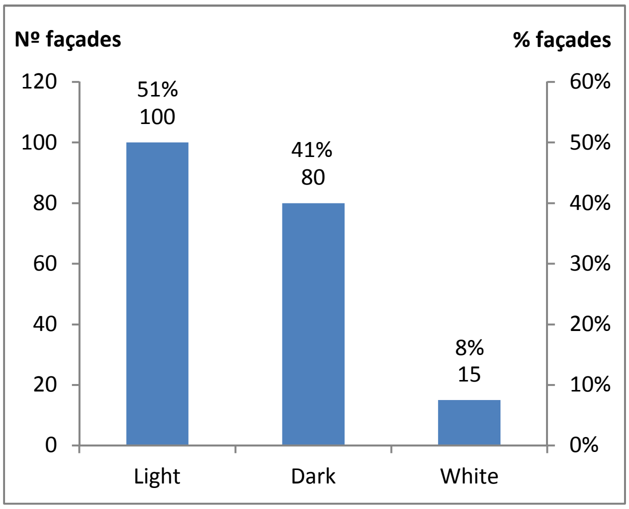


Figure 3.57 - Final sample data according to tiles colour

Concerning the tiles size, the issue is the same as for the surface. All the traditional tiles feature sizes of 14 x 14 cm or 15 x 15cm. For this reason, the gap between the two variables not only does not decrease, it rather increases, until reaching the values of 84% and 16% (Figures 3.58 and 3.59).

The last factor to be analysed is the claddings substrate. In this case the final sample turns out to be sufficiently uniform to be considered reliable. A greater number of masonry buildings has been inspected

(Figures 3.60 and 3.61), achieving the intended purpose of narrowing the discrepancy of the sample of Sousa (2008).

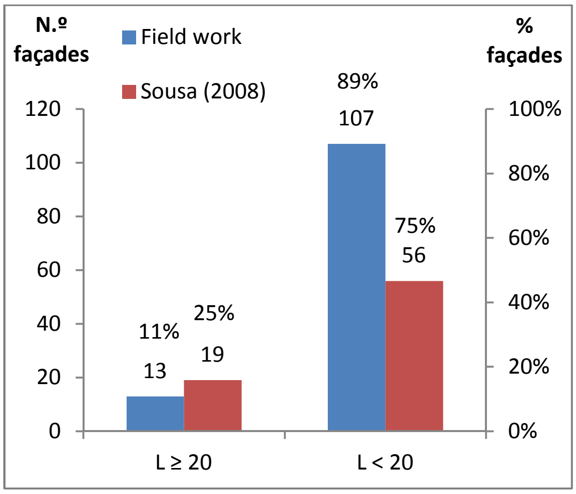


Figure 3.58 - Comparison between the results of Sousa (2008) and the current work

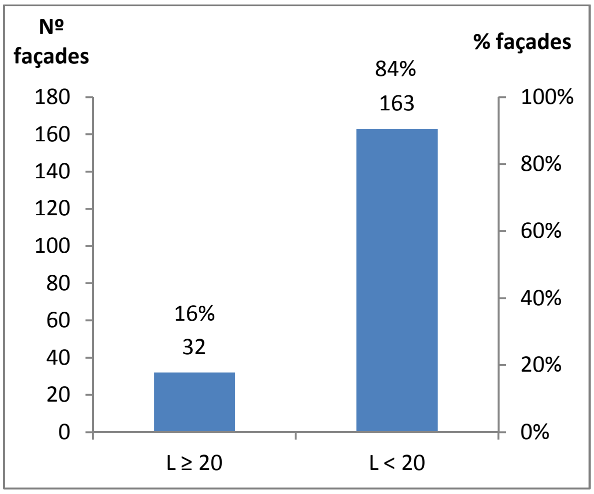


Figure 3.59 - Final sample data according to tiles size

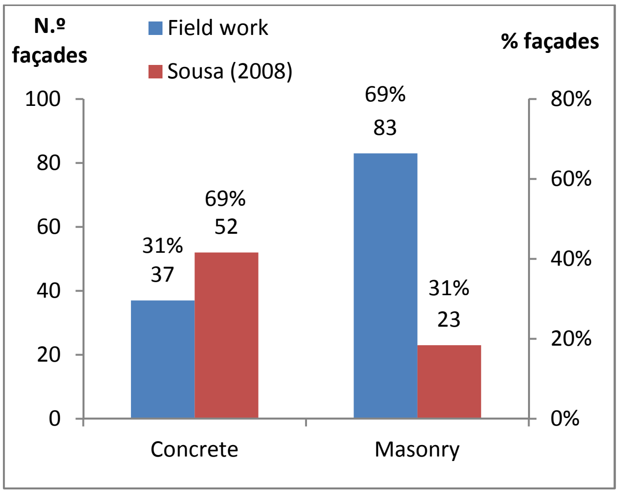


Figure 3.60 - Comparison between the results of Sousa (2008) and the current work

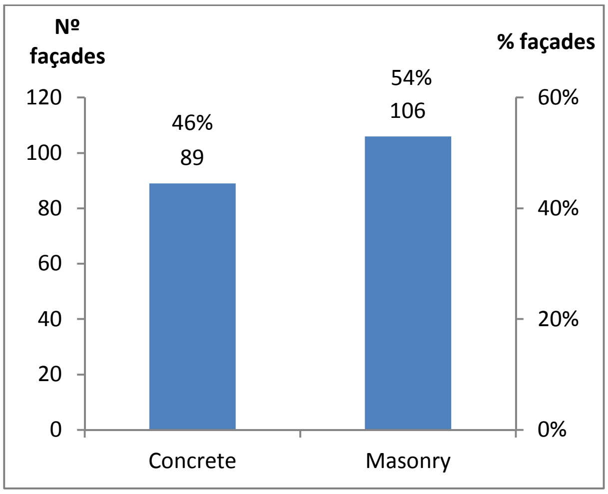


Figure 3.61 - Final sample data according to claddings substrate

Analysis of the anomalies detected

The defects noted during the inspections are worth being separately discussed. Also in this section the outcomes of the field work are compared with the studies of Sousa (2008); alongside these are shown the final sample statistics.

Concerning the percentages of the observed anomalies, it is clear that these change only slightly for the new sample. The majority is still represented by the aesthetic defects (45%), as shown in Figure 3.62. The joints deteriorations are the second most common defects, followed by cracking. Also in this case, the less widespread defect is adhesion failure (11%). Figure 3.63 illustrates the outcomes regarding the final sample; it can be noticed that the percentages related to the current work are more influential than the others. This is due to the fact that the number of façades inspected in the current filed work is higher than the number of claddings belonging to the 2008 sample (120 to 75).

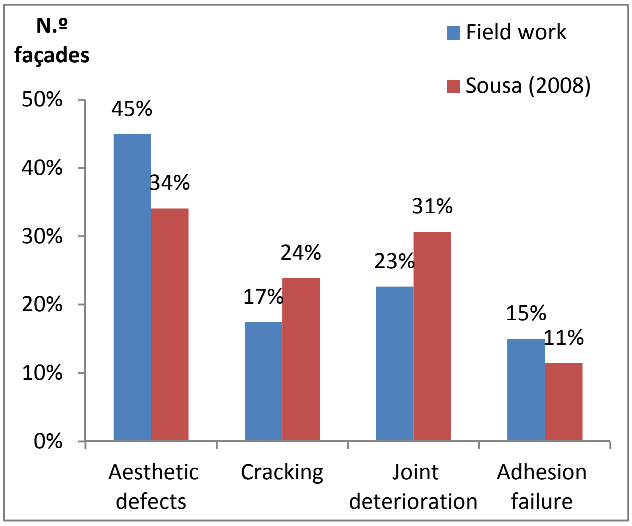


Figure 3.62 - Comparison between the results of Sousa (2008) and the current work

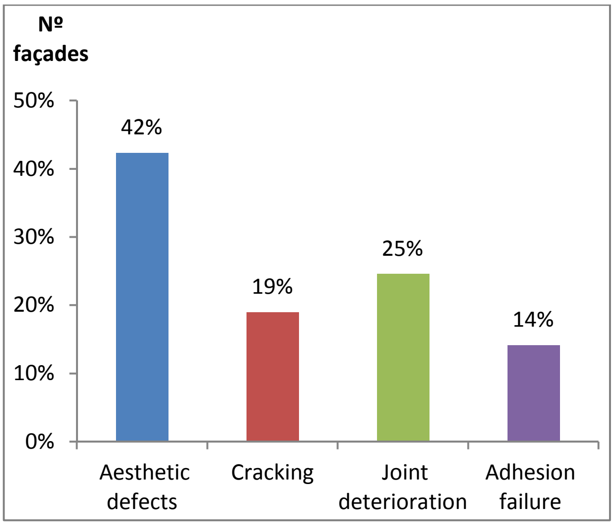


Figure 3.63 - Final sample data according to the anomalies percentages

Figures 3.64 and 3.65 illustrate the results expressed for each defect. In this case, some remarkable differences between the two samples can be seen. As shown in Figure 3.64, the number of façades affected by aesthetic anomalies is generally higher than the one of the sample of Sousa (2008). For cracking, two considerations must be made. Cracking without predominant direction's percentage is considerably higher than Sousa (2008); the opposite goes for the cracks with marked direction (0.2 mm < width < 1 mm). But larger than these are the differences concerning joints deteriorations (with/without loss of material) and especially adhesive failure. In this case, in spite of the notable difference (63% to 9%), the amount of façades that feature lack of adhesion is considered reliable. In fact, whenever it was possible, the tiles cohesion with the substrate has been controlled by tapping on the cladding.

Figure 3.65 summarizes the situation, displaying the percentages concerning the union of the two samples. One can observe the most common defects affecting the ceramic external wall claddings, as they have been noted during the field work. These are:

- Superficial dirt (affecting 81% of the façades) and edge crushing (58%) for the aesthetic anomalies;
- Glazed cracking and cracks without predominant direction (respectively, 50% and 48%);
- Change in the colour and deterioration with loss of material, concerning the joints (69% and 65% of the claddings);
- Adhesive failure (42%).

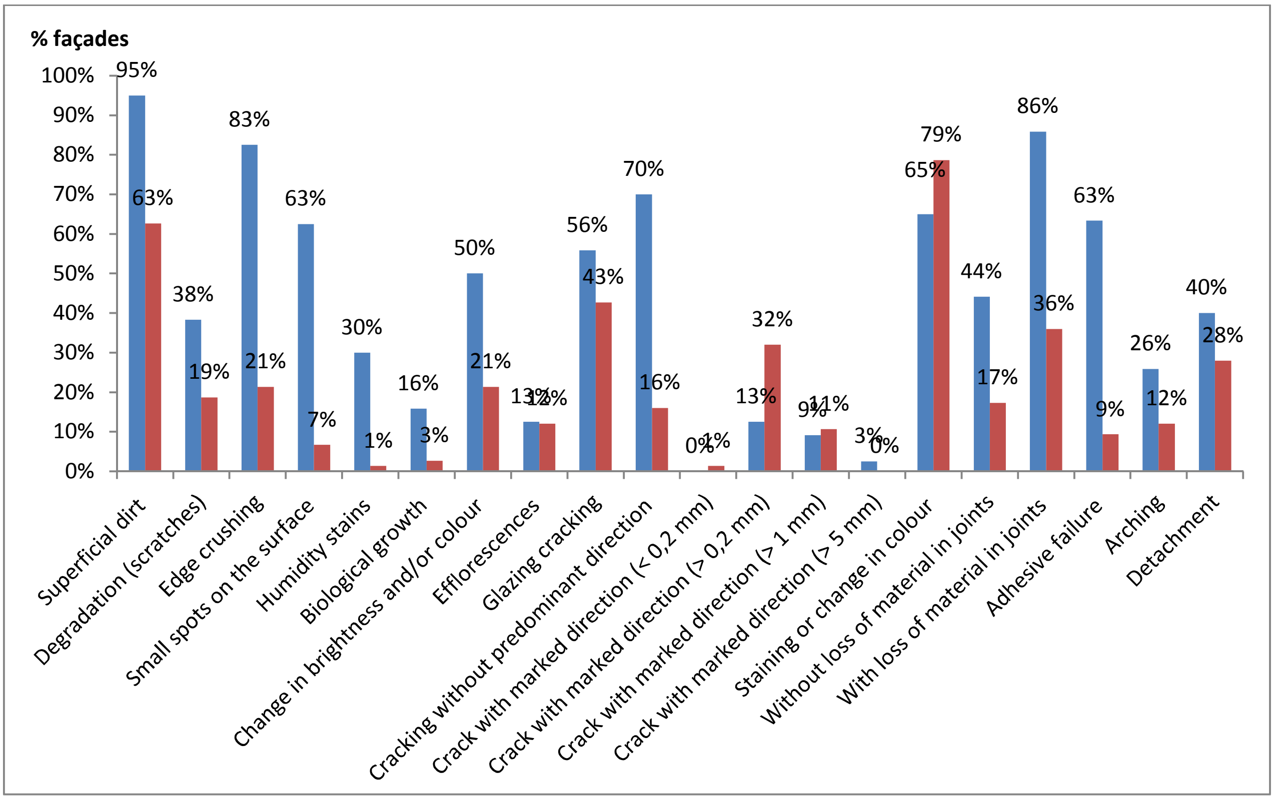


Figure 3.64 - Comparison between the results of Sousa (2008) and the current work

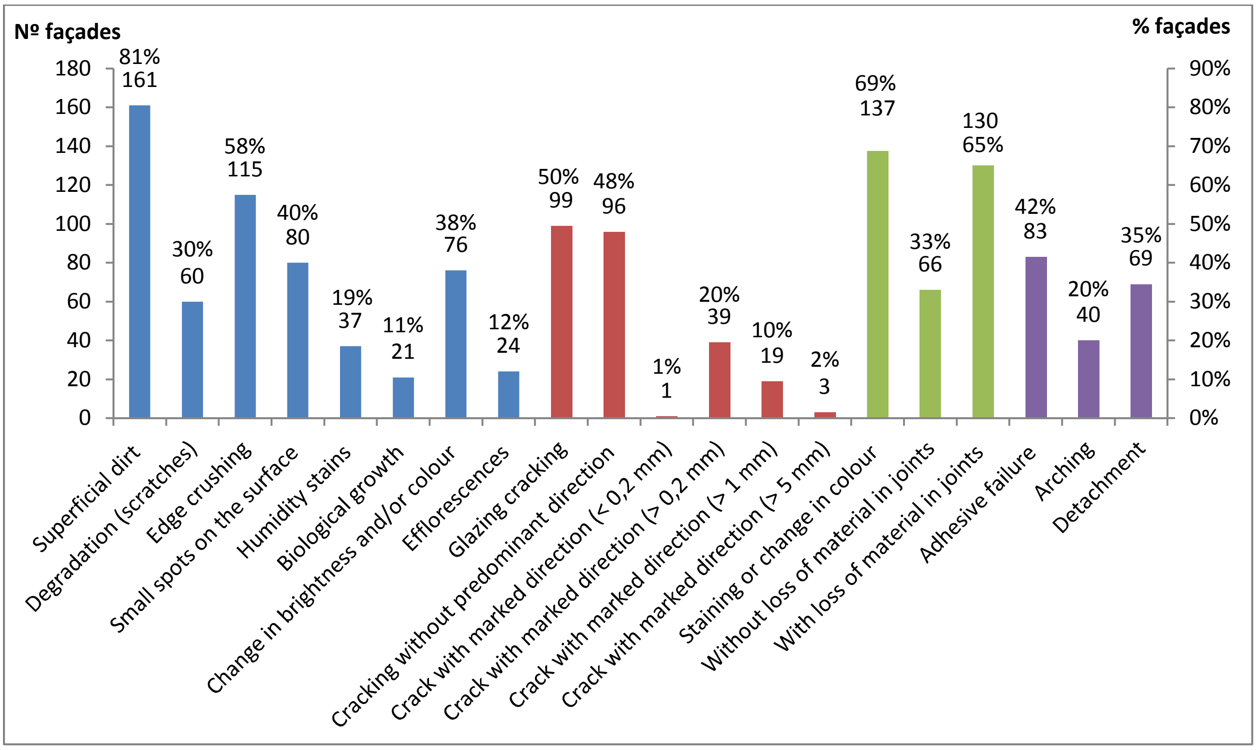


Figure 3.65 - Defects percentages for the total sample

Joints are confirmed as a critical part of ceramic claddings, and the one to which more attention should be paid. Only the superficial dirt is more common within the inspected façades. The reason for such a high percentage can be found in the widespread lack of maintenance, as will be confirmed by the further analysis concerning this aspect. But generally, the defects just listed may be connected with another cause: lack of design. As explained in chapter 2, stresses between the tiles and the substrate, resulting from lack of proper design, may originate edge crushing, cracking and joints deterioration.

Taking now into account the levels of the degradation, in both samples the majority of the detected defects feature level 1. This means, these affect only a reduced portion of the wall. Figure 3.66 shows the comparison between the two samples, whereas Figure 3.67 shows the statistics for the sum of these.

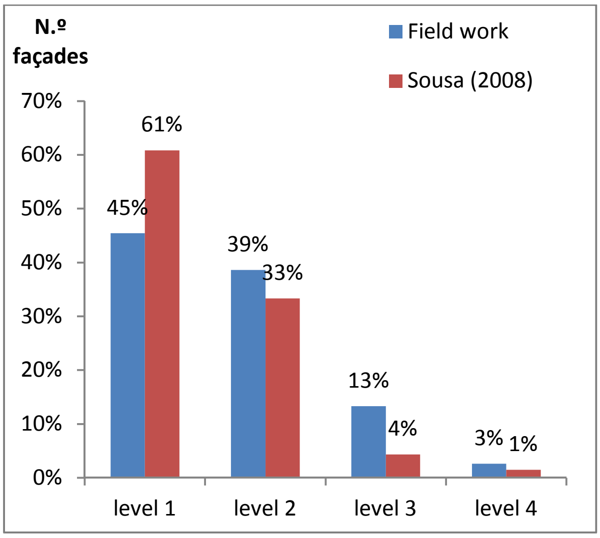


Figure 3.66 - Comparison between the results of Sousa (2008) and the current work

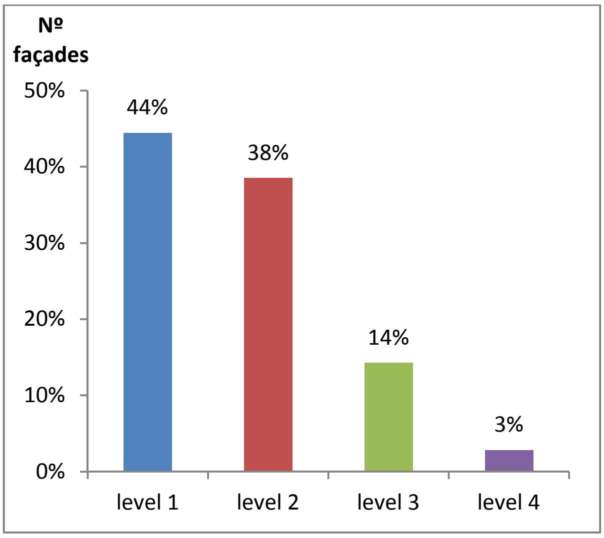


Figure 3.67 - Final sample data according to the levels of degradation

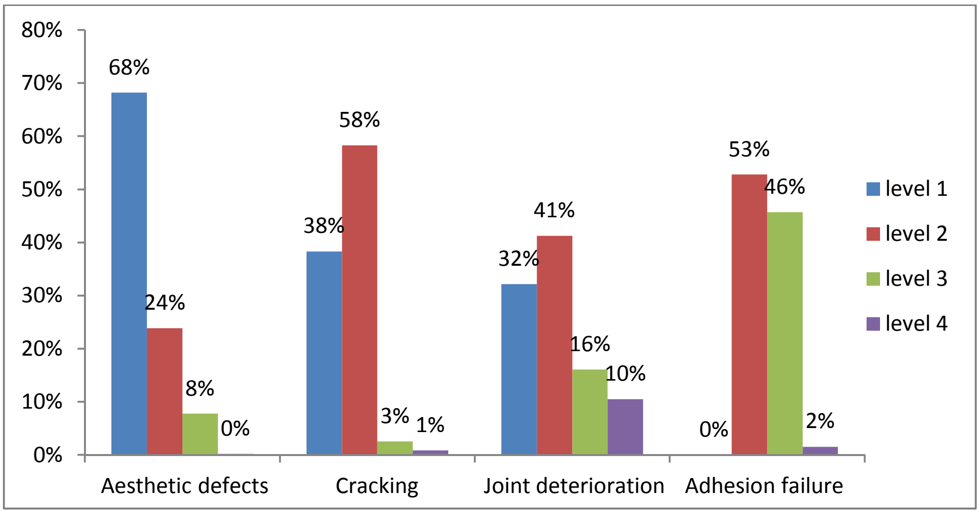


Figure 3.68 - Final sample data according to the detected anomalies and the levels of degradation

Even more interesting is Figure 3.68, showing the crossing of the data concerning the anomalies and the levels of degradation. This graph illustrates the percentages of the degradation levels of the defects for each group of anomalies. The data relate to the final sample. About the aesthetic defects, 68% feature level 1, which means that they generally affect a small portion of the cladding area (less than 10%). Only the superficial dirt usually affects a larger area; but it is always considered to be in the lowest level of degradation, no matter how high the percentage of the affected area is.

About the other groups of defects, level 2 is predominant, with frequencies around 50%. This means that around half of the ceramic façades present:

- Between 0 and 30% of cracked area or deteriorated joints (without loss of material);
- Between 0 and 10% of deteriorated joints (with loss of material);
- Between 0 and 20% of area featuring adhesion failure.

Concerning the last groups of anomalies, level 3 also shows a high percentage (46% of the total defects); this is due to the localized detachment, which falls within the aforementioned category when the affected area is between 0 and 10% of the cladding's area.

3.7 Conclusions

This chapter dealt with the field work that has been carried out. As stated in the introduction, the steps that have characterized this stage of work are three: the analysis of the previous studies, then the identification of the information to be gathered and finally the execution of the *in situ* inspections and the description of their results.

It was shown how a prior analysis led to a partial revision of the sample of Sousa (2008). From this one proceeded to the estimation of the necessary data. The field work led to a new sample, which has been added to the previous one. The final sample consists of 195 façades, which have been analyzed according to the different factors that affect the degradation evolution of the claddings. These factors have been gathered in three main groups, concerning age, location and façade features. Most of the variables led to good results in terms of uniformity in the sample. The analysis of the detected defects, carried on the previous section, concludes this chapter.

4 DEGRADATION MODELS

4.1 Introduction

This chapter deals with the assessment of the degradation evolution for external ceramic claddings, leading to the definition of the service life. First, a brief contextualization will be carried out, concerning the theoretical basis of the study. These consist of the concepts of limit state of service life and the adopted degradation model, focusing on the overall degradation severity value evaluation. The second part presents the analysis of the results of the field work, taking into consideration all the factors that characterize the claddings and affect the deterioration process.

4.2 Service life estimation methodology

4.2.1 Definition of limit state of service life

The service life is the first topic that needs to be taken into account in order to pursue the purposed goal. This concept has been studied in chapter 1. As mentioned, the acceptable limit of service life is related to the performance standards of the component. In other words, the service life of a building component reaches its end when the latter no longer meets the set requirements. The requirements depend on the context and the tenants, and concern aspects of aesthetics, functionality and safety.

Once the minimum requirements have been established, these must be related to the qualitative information regarding the anomalies that affect the claddings. In chapter 2, the analysis of the defects has led to classifying the state of degradation of the ceramic façades in five levels (from 0 to 4). The first one concerns façades that do not present any visible degradation; level 4 concerns claddings featuring generalized degradation (Table 4.1).

According to this categorization and the demands to meet, level 3 is fixed as the limit state of service life for the ceramic external wall claddings. That is when the degradation level stops being slight and begins to be considered moderate, featuring serious localized defects or generalized slight anomalies. This choice has been done in order to give continuity to studies previously carried out on the durability of building components (Gaspar, 2002; Gaspar, 2009; Sousa, 2008; Silva, 2009; Emídio, 2012; Ximenes, 2012). Referring to chapter 2, Table 4.2 resumes the defects that feature a ceramic cladding that has reached the end of its service life. It can be seen how the minimum requirements are no longer fulfilled. From the aesthetical point of view, the façade shows defects in more than half of the area. On the other hand, cracking and joints deterioration make the building component no longer functional for its purpose. Also the safety is jeopardized by the beginning of the tiles detachment.

Table 4.1 - Degradation levels definition

Degradation levels	Cladding state of conservation
Level 0	No visible degradation
Level 1	Good condition
Level 2	Slight degradation
Level 3	Moderate degradation
Level 4	Generalized degradation

Table 4.2 - Anomalies affecting a façade that has reached the end of its service life

Anomaly		% area of the ceramic cladding
Aesthetic defects	Superficial dirt	-
	Degradation (scratches)	> 50%
	Edge crushing	> 50%
	Small spots on the surface	> 50%
	Humidity stains	> 50%
	Biological growth	> 30%
	Change in brightness and/or colour	> 50%
	Efflorescences	> 30%
Cracking	Glazing cracking	-
	Cracking without predominant direction	> 30%
	Crack with marked direction	> 1 mm
Joint deterioration	Staining or change in colour	-
	Without loss of material in joints	> 30%
	With loss of material in joints	> 10%
Adhesion failure	Adhesive failure	> 20%
	Arching	> 20%
	Detachment	> 0%

4.2.2 Degradation models

The overall degradation level of a building has been defined in paragraph 3.3.1 as the qualitative level or the quantitative index which shows the overall performance of that building (Gaspar, 2008). In that section some topics have been disclosed. These are the severity of the degradation and the degradation curve.

The method adopted for the assessment of the degradation level had been determined by Gaspar (2002) and Gaspar (2009). It is about the calculation models with which to evaluate the quantitative index mentioned above, in order to statistically compare the claddings' state of conservation. The starting point for the application of the method is represented by the information collected during the visual inspections.

Throughout the field work the data concerning the degradation of the façades have been noted, with the aid of the inspection sheets defined in paragraph 3.5.1. The information gathered consists of:

- The anomalies that affect the façades;
- The cladding area affected;
- The cladding total area;
- The level of degradation of each defect.

These are the basis for the quantification of the degradation level, as defined by Gaspar (2009). From the data just listed the author studied several numerical indexes that can express the state of preservation of the plaster renderings. The following parameters have been defined (Gaspar, 2009):

E - Extension of the degradation of the facade, obtained by the ratio between the affected area and the total cladding's area;

A_w - Weighted affected area of the façade. This is obtained by the product between the area affected by the anomaly and the related level of degradation;

E_w - Extension of the cladding's weighed degradation, obtained by the ratio between the weighted affected area and the total cladding's area;

S_w - Severity of degradation, obtained by the ratio between the weighted affected area and the maximum degradation extension;

$E_{w,rp}$ - Extension of the cladding's weighed degradation, considering the relative importance of the defects. This is obtained by the ratio between the affected area weighted with the relative coefficients and the total cladding's area;

$S_{w,rp}$ - Severity of degradation, considering the relative importance of the defects; this is obtained by the ratio between the affected area weighted with the relative coefficients and the maximum degradation extension.

Each of these indexes represents a specific concept expressing the state of degradation of a building component. The indexes also represent the steps through which the author obtained the weighted severity ($S_{w,rp}$). The latter is considered the best among all to quantify the overall degradation, for two reasons. First, it takes into account the relative importance of each defect, giving greater weight to the anomalies considered to be more serious than the others (for instance adhesive failure, or detachment). Furthermore, the weighted severity is a percentage value that can assume a value between 0% and 100%, turning out to be easy to understand. In fact, the other indexes feature values that exceed 500%, not being immediately understandable as the weighted severity. Regarding the formula, this had been detailed in the previous chapter (Gaspar, 2009):

$$S_{w,rp} = \frac{\sum(A_n \cdot k_n \cdot k_{a,n})}{A \cdot \sum(k_{max})} \qquad \text{Equation 4.1}$$

Where:

$S_{w,rp}$ - severity of the degradation of the normalized façade, expressed in percentage;

A_n - area of façade affected by defect n, in square meters;

k_n - degradation level for defect n, with $k_n \in \{1, 2, 3, 4\}$;

$k_{a,n}$ - relative importance of the defects detected; if no specification exists, $k_{a,n} = 1$;

A - exposed cladded area of façade, in square meters;

k_{max} - sum of the weighting coefficients equals to the highest level of degradation of A area cladding; it has the value of 15 (3 + 4 + 4 + 4 - aesthetic defects, cracking defects, joint deterioration defects, detachment defects).

For the reasons set out above, the severity index ($S_{w,rp}$) has been used in the current work to quantify the overall degradation of the façades. The same had been done in previous studies concerning the prediction of the service life of natural stone wall claddings (Silva, 2009; Emídio, 2012). It was also decided not to explicit herein neither the other formulas, nor the steps that have led to the determination of the weighted severity index. In fact, it is considered not strictly necessary for the development of the dissertation. For a more detailed description, one can consult the work of Gaspar (2009).

4.2.3 Weighting coefficients

A separate explanation has to be given for the weighted coefficients ($k_{a,n}$) that define the relative importance of the detected anomalies. These have been introduced by Gaspar (2009), which studied several scenarios for the E_w index, on the assumption of a hierarchy between the various anomalies. In fact, it is supposed that not all the pathologies are equally important. This method allowed calculating values ($E_{w,rp}$ and $S_{w,rp}$) that are considered to be more realistic and reliable than the previous one.

Silva (2009) also used this method. Each weighting coefficient has been evaluated by the author based on the factors that define the severity of a defect, which are:

- The required performance;
- The propensity to originate new anomalies;

- The restoration cost.

The work of Sousa (2008) is based on the just listed studies. The author determined weighted coefficient for every anomaly concerning the ceramic external wall claddings. These values have been kept and used in the current degradation assessment. Table 4.3 reports the coefficients ($k_{a,n}$) conferred to each defect. One can notice how the values attach importance to the anomalies that involve a greater severity of the degradation. At the same time, the less severe defects are proportionally calculated.

Table 4.3 - Relative importance of the defects detected

Aesthetic defects	$K_{a,n}$	Cracking	$K_{a,n}$	Joint deterioration	$K_{a,n}$	Adhesion failure	$K_{a,n}$
Superficial dirt	0.25	Glazing cracking	0.25	Staining or change in colour	0.25	Adhesive failure	1.50
Degradation (scratches)	0.60	Cracking without predominant direction	1.00	Without loss of material in joints	1.00	Arching	1.50
Edge crushing	0.60	Crack with marked direction	1.00	With loss of material in joints	1.50	Detachment	2.00
Small spots on the surface	0.60						
Humidity stains	0.60						
Biological growth	1.00						
Change in brightness and/or colour	0.60						
Efflorescences	1.00						

The definition of the factors that compose the formula of Gaspar (2009) concludes the explanation of the degradation model that has been adopted in the current work. The severity degradation has been calculated for all the elements that are part of the sample. As stated before, previous works in terms of service life prediction (Sousa, 2008; Silva, 2009; Emídio, 2012; Ximenes, 2012) have clearly ascertained how the index calculated with the weighting coefficients ($S_{w,rp}$) gives better results in terms of reliability than the severity degradation that does not consider the relative importance of the anomalies (S_w). For this reasons, the calculation without the weighted importance of the defects will not be examined in this dissertation.

4.2.4 Relationship between the severity and the cladding condition

The last step that characterizes the methodology, leading to the service life estimation, is the setting of the relationship between the calculated overall degradation severity and the actual state of conservation of the façades. This means to relate the quantitative and the qualitative indexes of degradation. The first one is represented by the severity ($S_{w,rp}$), in percentage. About the qualitative evaluation, this concerns the anomalies affecting the façade.

As mentioned, the assessment of the state of the preservation has led to the assignment of 5 levels of degradation (from 0 to 4) and has set the service life limit for the ceramic claddings at level 3 (moderate degradation). At this point, it is necessary to correlate each degradation level with a certain range of the degradation severity values. The works previously listed, which concern the prediction of service life, had defined this aspect, basing on the studies of Gaspar (2009). The outcomes of each of them are slightly different, depending on the different building component that was being analysed. Regarding the current dissertation, the subdivision adopted by Sousa (2008) has been maintained; Table 4.4 shows the results of this classification. The limit state of service life for the ceramic external wall claddings correspond to a value of the degradation severity equal to 20%.

Table 4.4 - Correspondence between the degradation indicators

Degradation levels	Sw,rp
Level 0	Sw,rp ≤ 1%
Level 1	1% < Sw,rp ≤ 6%
Level 2	6% < S w,rp ≤ 20%
Level 3	20% < S w,rp ≤ 50%
Level 4	S w,rp ≥ 50%

In order to give a general visual idea of the set categorization, the pictures below show ceramic claddings featuring values of $S_{w,rp}$ that involve a change of the degradation level. Figure 4.1 concerns a façades that does not present visible degradation ($S_{w,rp}$ around 1%). The façade in Figure 4.2 has a severity value of around 6%; it is visible how it features mainly aesthetical defects (superficial dirt). Figure 4.3 shows an external cladding that has reached the end of its service life ($S_{w,rp}$ around 20%). One can notice the widespread aesthetical anomalies, as the emergence of some serious defects like joints deterioration and detachment; this causes the non-fulfilment of the aesthetical, functional and safety requirements of the ceramic cladding. The façade of Figure 4.4 is far beyond the limit state of service life ($S_{w,rp}$ over 50%), being affected by extensive serious anomalies, such as generalized detachment.

Figure 4.1 – Degradation level 1

Figure 4.2 – Degradation level 2

Figure 4.3 - Degradation level 3

Figure 4.4 - Degradation level 4

4.3 Evolution of the degradation of ceramic external wall cladding

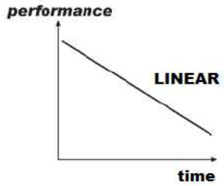
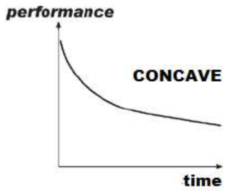
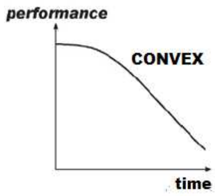
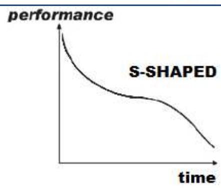
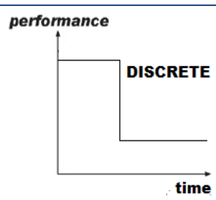
4.3.1 Theoretical foundations

Once calculated the degradation severity index ($S_{w,rp}$) for each façade forming part of the sample, the results have been graphed; the degradation curve has addressed this need. As said in paragraph 3.3.1, this is a function that graphically expresses the evolution of the degradation over time. It also clearly shows the loss of performance of the building components during its life.

Precisely for this purpose, different types of deterioration patterns were studied by Shohet et al. (1999). The authors defined four typical patterns of deterioration paths (linear, concave, convex and S–shaped), depending on the degradation mechanisms involved. The variables used to plot the graphs are time and building component's performance. The functions are shown in Table 4.5; each chart type is correlated with a general explanation of the causes of the degradation. Gaspar (2002) introduced also discrete phenomena, which cannot be expressed by a continuous function; a typical instance of such anomaly is vandalism (*graffiti*). In the current work it has been decided not to consider the latter, since they cannot be related to a normal degradation evolution and cannot be foreseen in any way (Table 4.5, the fifth line). Furthermore, as it will be further explained, the S-shape deterioration path has revealed itself as the closest to reality; this makes it meaningless the modelling of discrete phenomena. For this reason "*graffiti*" has been removed from the list of defects taken from the study of Sousa (2008), as mentioned in chapter 2.

Furthermore, Shohet and Paciuk (2004) studied "an empirical method for the prediction of the service life of building components, based on an evaluation of their actual performance and on the identification of failure mechanisms affecting their durability". In that work, the concept that is the basis for the current analysis can clearly be seen. In fact, once the minimum required component performance is defined, plotting of the degradation curve enables the identification of the service life (Figure 4.5). The same idea is expressed by Gaspar and de Brito (2005); Figure 4.6 shows the correlation between qualitative data (the rating of degradation according to different levels) and quantitative numerical data.

Table 4.5 - Deterioration paths (Shohet et al., 1999; Gaspar, 2002)

Degradation curve	Deterioration cause
	This pattern is typical in situations where a permanent deterioration agent exerts a continuous and consistent impact on the cladding. This pattern is manifested in the effect of erosion by wind, the decay caused by intensive UV radiation
	This shape represents the action of chemical and physical agents on claddings such as stucco and natural stone
	This path characterises physical or chemical phenomena, such as concrete shrinkage, that cause physical failure of the entire system of exterior cladding
	It represents a deterioration mechanism that changes its intensity over time. The pattern appears when certain building details are lacking, a situation that makes a visual impact shortly after the end of construction. Then the major mechanism becomes the physical reaction, which takes longer to affect the strength of materials. When that process ripens, the deterioration accelerates, and its impact becomes visible
	It is related to phenomena that cannot be expressed by a continuous function, as they can randomly occur at any moment of the service life of the component.

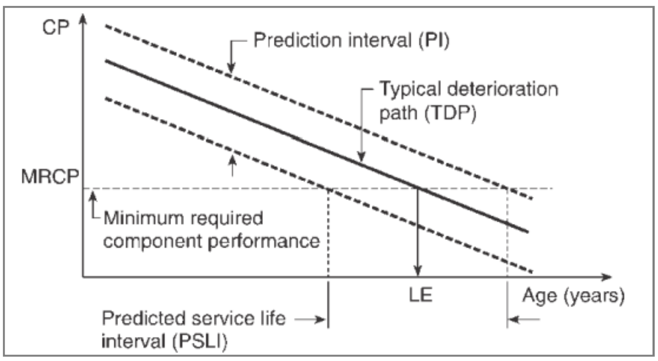


Figure 4.5 - Determination of life expectancy by means of typical deterioration path (Shohet and Paciuk, 2004)

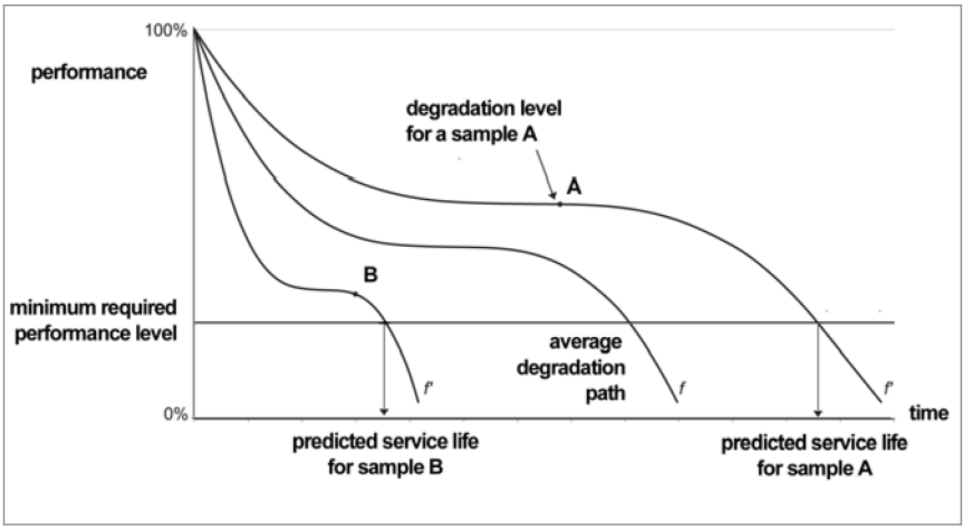


Figure 4.6 - Degradation path and service life prediction of a building element (Gaspar and de Brito, 2005)

4.3.2 Service life prediction for the collected sample

Based on the theoretical assumptions made in the previous paragraph, the degradation evolution's graph has been plotted and the average curve has been calculated. The chart features time in the abscissa axis and degradation severity percentage in the ordinate axis. As mentioned, the latter represents both the loss of performance and the degradation level of the façades of the sample. The results of the degradation model application (Gaspar, 2009) to the sample are described next.

The first aspect to be characterized is the comparison between the outcomes of the two different samples that form the basis of the current study. Figure 4.7 shows the union between the new collected sample (dots highlighted in yellow) and the sample of Sousa (2008), coloured in blue.

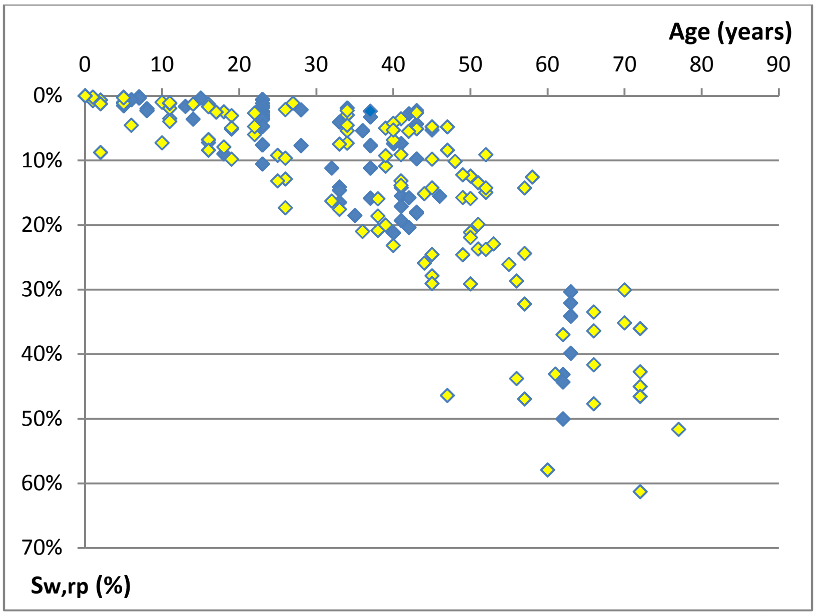


Figure 4.7 - Overall degradation evaluation: comparison between the two samples

At this stage, the degradation curve has not been plotted, in order to focus the attention on the confrontation between the data. It can be seen that the two samples have given similar outcomes, featuring a rather uniform distribution. To be noticed is also how the purpose of filling the gap between 45 and 62 years has been achieved, which allows tracing the descending part of the curve. Concerning the next charts, they will take into account the entire sample, resulting from the union of the two works (2008 and 2012).

The degradation curve is seen in Figure 4.8: in this chart the trend line corresponding to the average of the severity values has been traced. Some aspects need to be underlined:

- At first, two curves have been drawn; one features a linear regression, whereas the other is a 3rd-order polynomial trend line. As happened in the analysis of the results of Sousa (2008) carried out in Chapter 4, the second fits much better to the points of the graph. This is evidenced by the difference in the R-squared values of the two curves (0.7053 to 0.5913). For this reason, only the polynomial regression line will be taken into account for further analysis;
- Regarding the deterioration paths mentioned above, the result features an S-shaped pattern. The S-shape curve can be better observed in the following analysis, in which the variables characterizing ceramic claddings are compared. But in the current case, the typical initial bend of the S-shaped curve is minimal; it may mean that the short time impact of the lacking details of the façades has little influence on the degradation processes. Instead, the physical and chemical mechanisms prevail and the line has a significant decrease, taking a convex pattern. This in turn means that the physical and chemical phenomena, which take longer to affect the strength of the cladding, are crucial for the evolution of the degradation. In the long run they reveal greater weight than other degradation mechanisms: for instance atmospheric agents, which on the contrary feature a linear path;
- The last aspect to be noticed in Figure5.8 concerns the two red dots. They represent the façades that have been taken out from the sample, as explained in paragraph 3.6.1. Both of them present an overly high degradation severity value considering the age.

Figure 4.9 illustrates the final outcome of the overall degradation evaluation for the current sample; this chart is the basis for the service life estimation. As mentioned, the excluded cases and the linear trend line are no longer considered. The R-squared value is equal to 0.7665, proving the good correlation within the dots of the graph. The considerations concerning the deterioration pattern, which have been done for the charts in Figure 4.8, apply also to Figure 4.9.

About the service life calculation, Figure 4.10 highlights the set degradation levels. The red lines represent the limits of the severity degradation ranges stated in Table 4.4. As mentioned, the limit state of service life has been fixed at level 3 (moderate deterioration), which corresponds to $S_{w,rp}$ = 20%. Based on the graphical output, the average service life expected for the ceramic claddings is approximately equal to 50 years. This result will be discussed further, within the analysis of the degradation evolution's results.

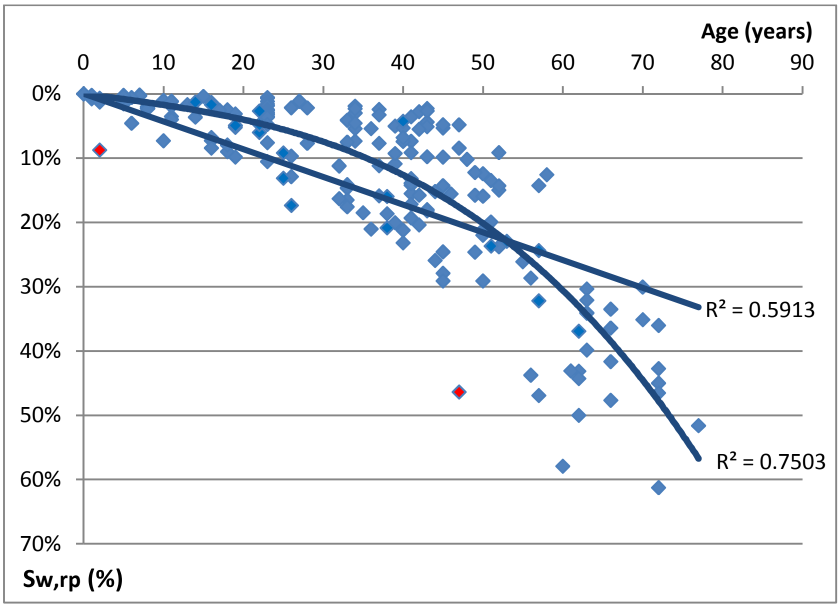


Figure 4.8 - Degradation curves based on the final sample

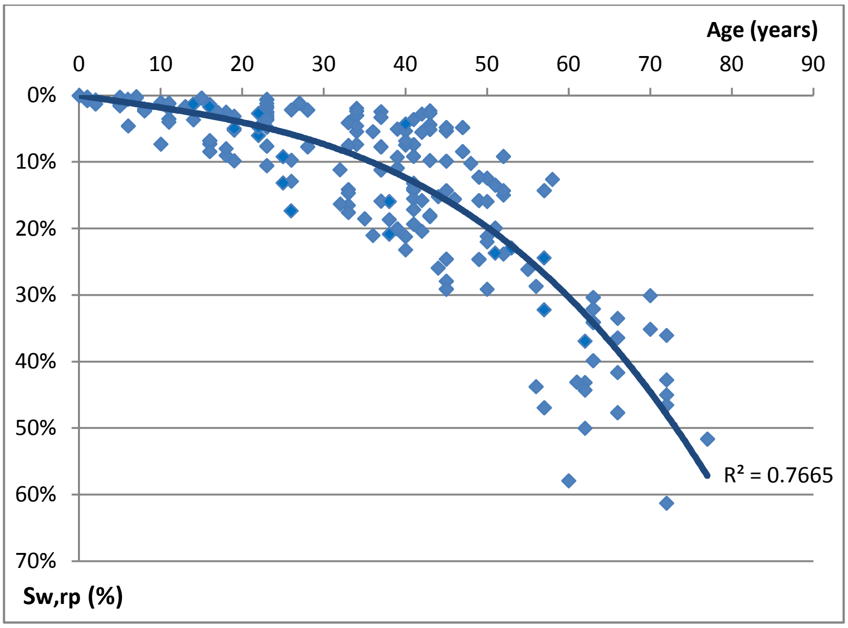


Figure 4.9 - Overall degradation evolution for ceramic external wall claddings

The statistics about the sample's elements distribution according to their level of degradation have been studied. Figure 4.11 shows how the majority of the façades inspected presents a slight degradation (levels 1 and 2, respectively 35% and 33% of the sample). Generally, the amount of claddings decreases for the more severe levels, reflecting the degradation curve slope. This outcome is not comparable to the one obtained by Sousa (2008), since the author used a different degradation model and a different formula, as mentioned in paragraph 3.3.1. Instead, considering the results of Emídio (2012), also in that case it was found that level 1 features the greatest amount of elements; such quantity decreases with increasing levels of deterioration.

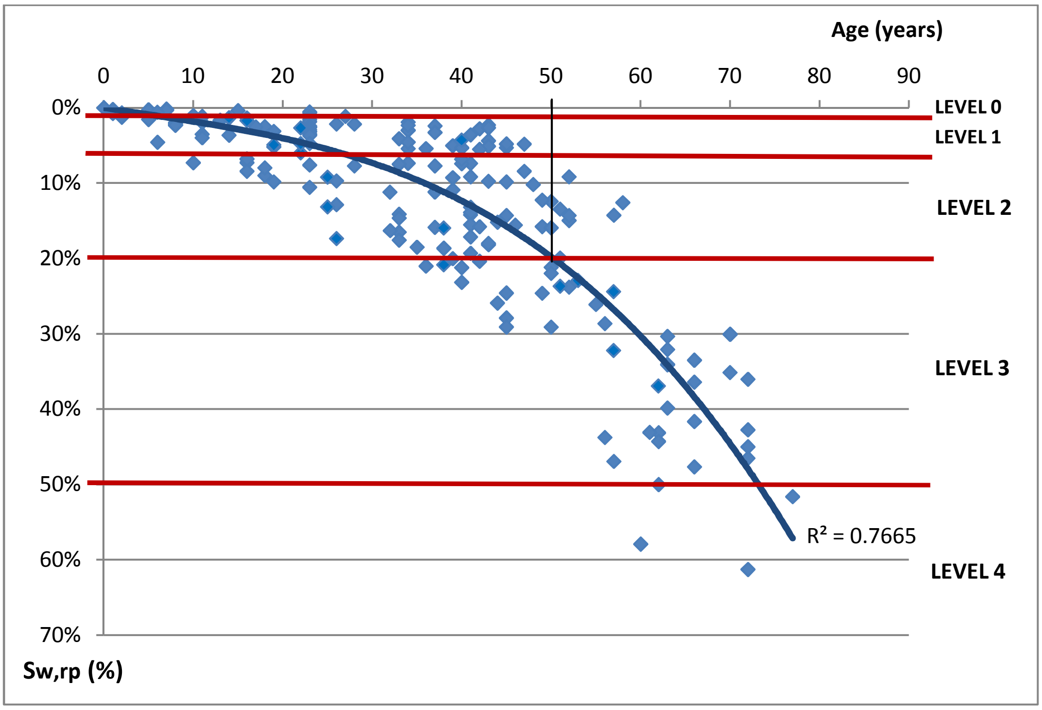


Figure 4.10 - Service life prediction for ceramic external wall claddings

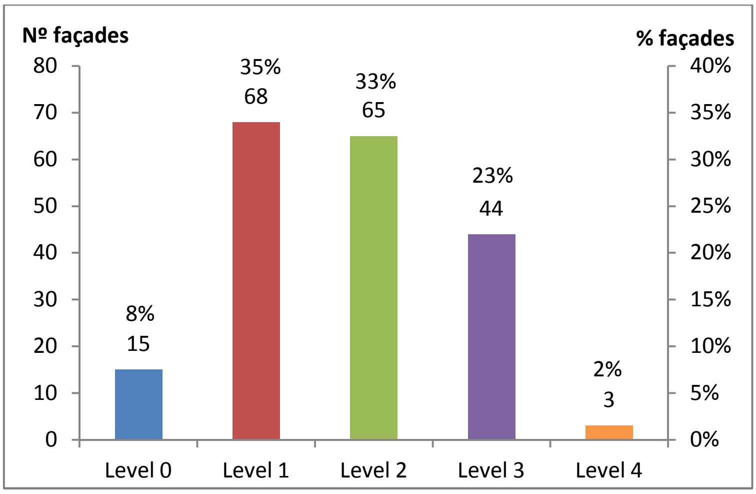


Figure 4.11 - Sample distribution according to the degradation levels

To conclude the assessment of the expected life, an interesting survey of the component execution level has been done. The output concerning the 195 claddings of the final sample has been compared with the degradation severity evaluated for the excluded façades. The latter are constituted by the claddings that have been removed from the sample of Sousa (2008) and from the current field work (respectively paragraphs 3.3.2 and 3.6.1). The purpose is to see how grossly poor execution or missing design can affect the service life of a building component. Figure 4.12 shows the results of this analysis. The two regression lines are markedly separated. Despite the fact that the claddings featuring inadequate level of execution are too few to plot a polynomial curve, both trend lines feature a good R-squared value. This clearly proves how insufficient attention to aspects of design and installation can cut by half the life of a cladding. In fact, the estimated service life for the ceramic claddings characterized by poor execution is equal to 24 years.

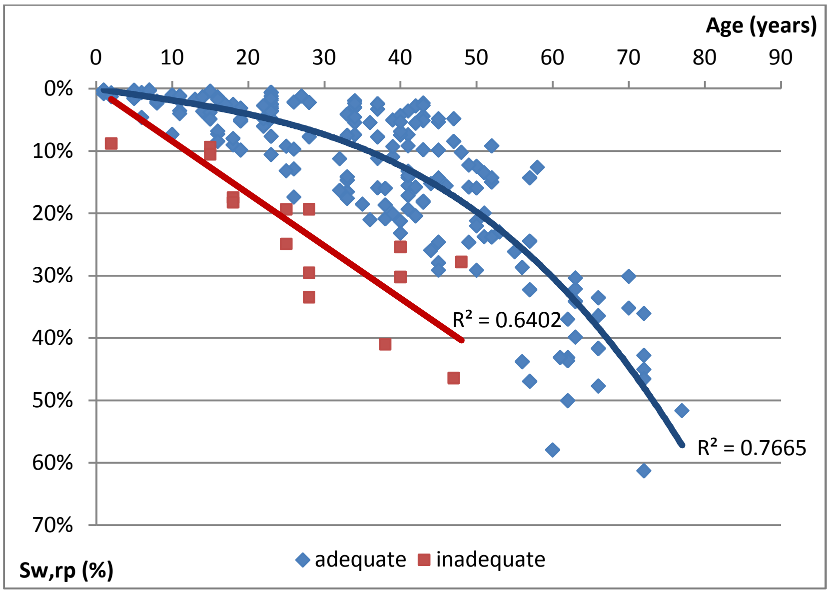


Figure 4.12 - Overall degradation curve according to level of execution

4.3.3 Degradation curve according to the different characteristics of the claddings

The outcomes have been analyzed according to the different factors that influence the degradation evolution of ceramic claddings. As it will be seen further, these also represent the factors that are the basis of the factor method's calculation. The same characterization had been done for the sample of Sousa (2008) in paragraph 3.4.1. The aspects considered concern location of the building, features of the building component, characteristics of the design and maintenance level.

Analysis according to the location of the building

The cladding location is strictly related to the atmospheric agents' action. In fact, different positions involve a change in the environmental conditions. The first factor that has been considered in this regard is distance from the sea. As mentioned, the proximity to the sea entails a more aggressive environment. Figure 4.13 confirms this theory: the trend line that refers to the buildings located next to the river Tagus' mouth (distance < 1 km) shows a faster degradation, if compared with the others. The difference is not large but it is clear. Furthermore, the claddings located between 1 km and 5 km from the sea feature a slightly worse situation than those further away. Furthermore, except for the regression line that graphs the building located more than 5 km from the sea, the R-squared values are rather high (0.7656 and 0.7702). Along with the considerations just listed, these values lead to consider the output reliable.

Regarding the orientations of the façades the results are not as clear. Figure 4.14 illustrates how all the curves are superimposed. East and west regression lines have a similar path, whereas north and south feature an easier deterioration: in addition to this, south features the worst condition. On the contrary, all the coefficients of determination have a high value, indicating how the distribution is consistent. This may lead to the conclusion that the south orientation does not entail a better environmental condition. Generally, it must be said that the outcomes regarding the cladding orientation are rather inconclusive.

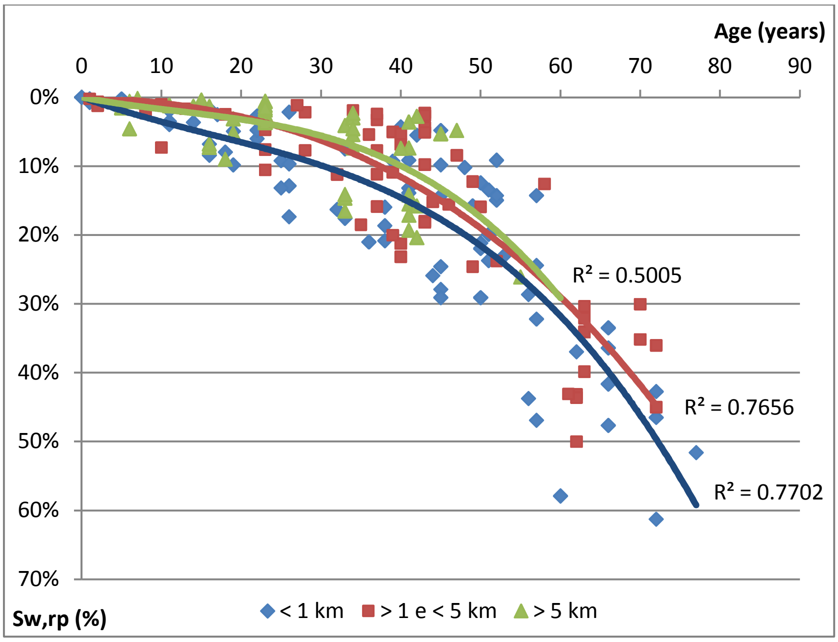


Figure 4.13 - Overall degradation curve according to distance from the sea

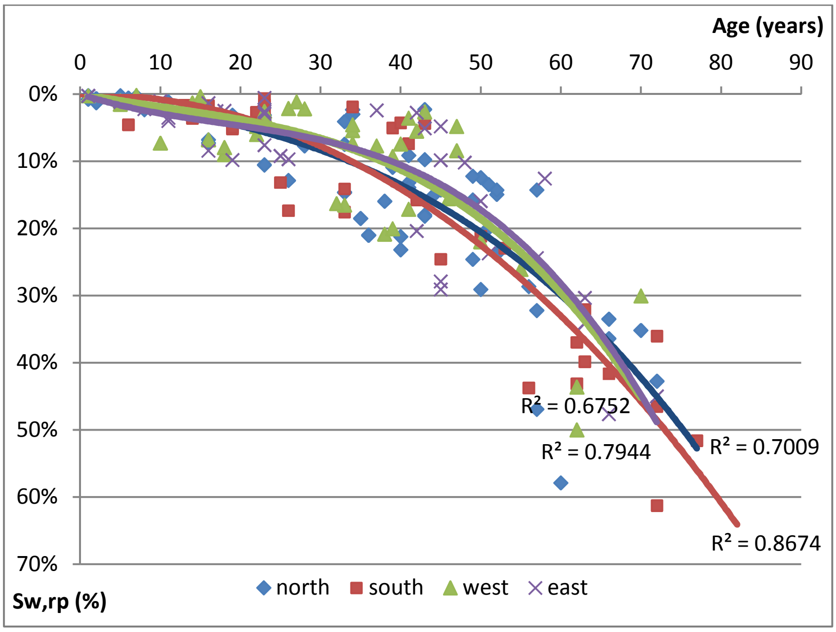


Figure 4.14 - Overall degradation curve according to façade orientation

Concerning wind and rain action, the chart shows a good result (Figure 4.15). The curve referred to the claddings that are more seriously affected by the atmospheric agents is lower than the others. On the other hand, mild influence of wind and rain is characterized by the highest curve, meaning a slower degradation. As for the proximity to the sea chart, lines are distinct, though the distance among them is small.

The last aspect that concerns the buildings location is humidity exposure. In this case the outcome confirms the result obtained by Sousa (2008): the regression lines are markedly separated, with a variance of 5 years between them (Figure 4.16). As expected, the lower curve represents the claddings featuring a higher humidity level, while the buildings located in areas in which humidity exposition is low may live 5 years longer. The reliability of the outcome is also confirmed by the high values of the coefficients of determination: 0.7687 and 0.7739.

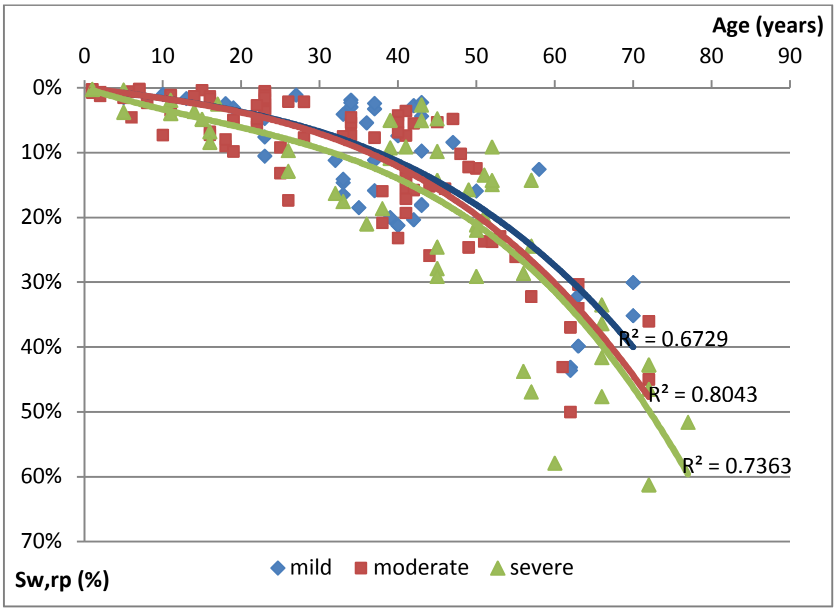


Figure 4.15 - Overall degradation curve according to wind/rain action

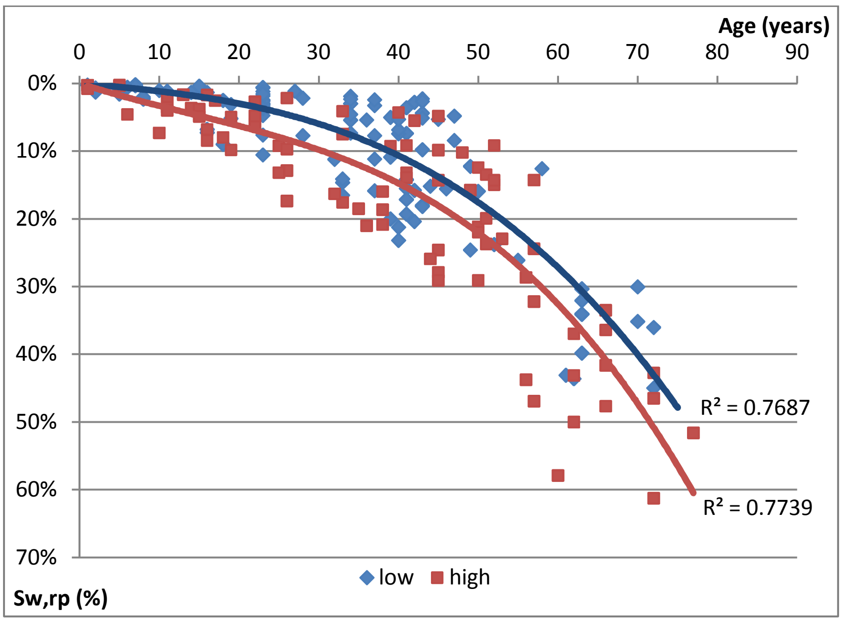


Figure 4.16 - Overall degradation curve according to humidity exposure

Analysis according to the cladding type

The second aspect influencing the degradation process of ceramic claddings concerns the characteristics of the tiles themselves. These are: surface, colour and size. In this case, it has been more difficult to reach the minimum required number of façades determined in Chapter 4, thus compromising the charts reliability. The cause has been widely explained, contextually to the field work results' analysis; it is the real proportion between the amounts of different types of tiles that are used for external wall claddings.

The tiles surface graph gives an example (Figure 4.17). As noticed, the final number of inspected façades featuring not glazed tiles is not enough to trace a reliable curve. This trend line is linear and the R-squared value is low (0.4642). So, whereas the curve referred to the glazed tiled façades shows a good result, the one concerning the not glazed tiles does not reach any conclusion.

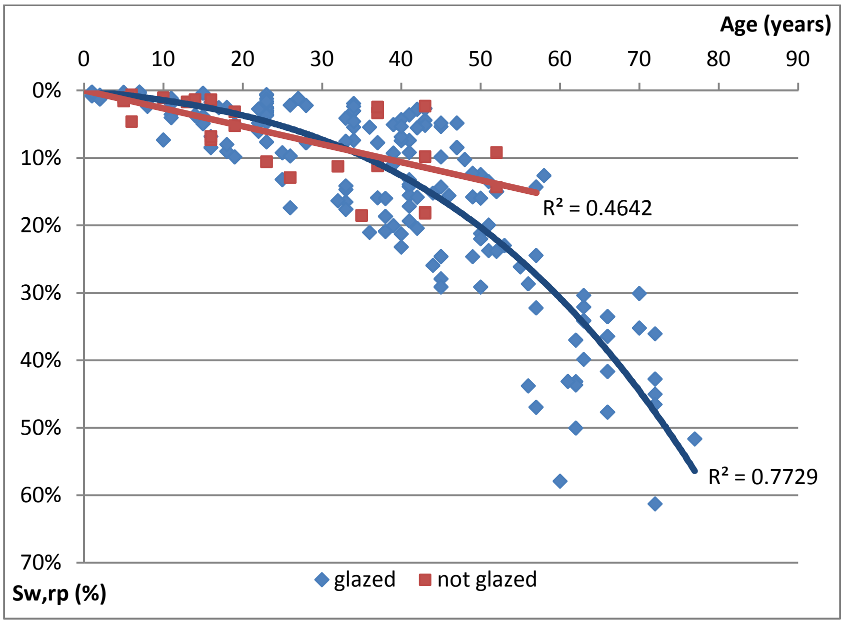


Figure 4.17 - Overall degradation curve according to tiles surface

The same happens with the colour (Figure 4.18). Although the R^2 coefficients are rather high (values higher than 0.7), the layouts of the curves are inconsistent. The light coloured claddings were expected to show a slightly better condition, but the lines cross at approximately 30 years. Concerning the white coloured tiles, it was not possible to reach a sufficient number of elements to plot a graph. In fact, only 15 white claddings have been collected during the field work. As mentioned in paragraph 3.6.2, this is an indication of the infrequent use of this type of tile.

On the contrary, the outcome referred to the tiles size is rather appreciable. This can be seen in Figure 4.19. Despite the few elements featuring size larger than 20 cm, the curve shows an R-squared value equal to 0.62. Furthermore, after an initial segment in which the two lines overlap, the curve related to the bigger tiles shows a slightly faster degradation, as expected (Wetzel, 2010).

Characteristics of the design

The design characterization considers the substrate type and the existence of peripheral joints and peripheral protections. Figure 4.20 concerns the first one; the regression lines show a R^2 coefficient around 0.7, meaning a good correlation within the dots. In this case the amount of collected claddings featuring the two substrates is similar. However, the shortage of concrete substrates older than 57 years old must be noticed. The reason is the difficulty in finding concrete buildings built before the 50s; in fact, the old neighbourhoods of Lisbon are mainly composed of traditional masonry houses. This gap jeopardizes the reliability of the final segment of the curve. Nevertheless, the latter is clearly separated from the other one, meaning a slightly slower degradation for concrete, compared to the masonry building's façades.

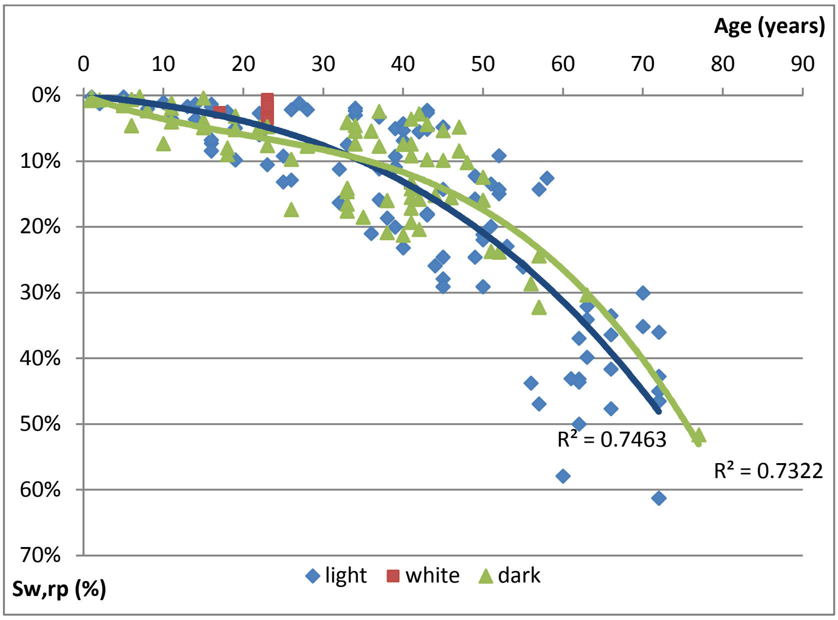


Figure 4.18 - Overall degradation curve according to tiles colour

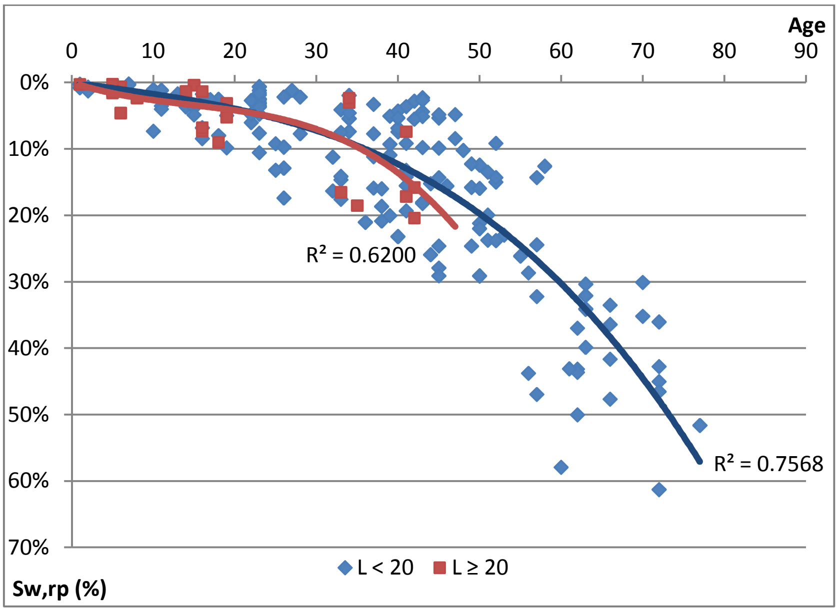


Figure 4.19 - Overall degradation curve according to tiles size

About the peripheral joints (Figure 4.21), the results clearly show almost no separation between the trend lines; this difference is even smaller for the peripheral protections (Figure 4.22). The high R-squared values prove a good correlation within the points. The conclusion that can be drawn from these data is that the above mentioned joints and protections do not affect the deterioration evolution of the façades. Or better, they affect it minimally. In fact, the influenced area (near the borders of the cladding surface) is too small to have influence in the calculation of the degradation severity, which considers the whole cladding area.

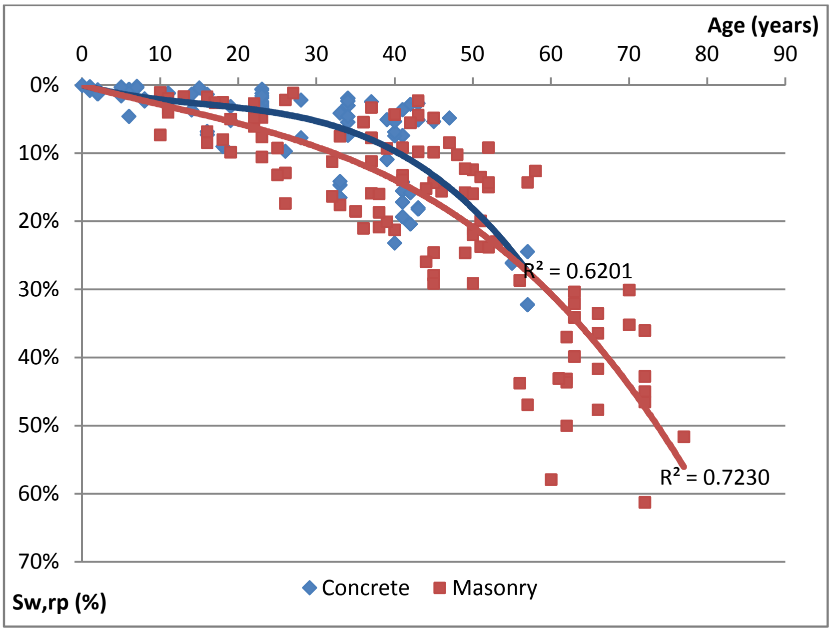


Figure 4.20 - Overall degradation curve according to substrate

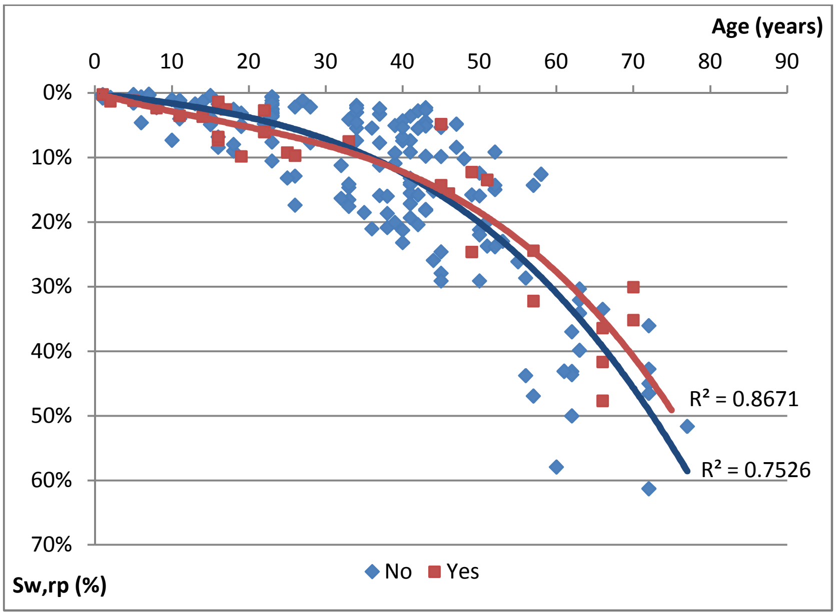


Figure 4.21 - Overall degradation curve according to existence of peripheral joints

Maintenance level

The maintenance level is part of the factor method calculation, as the evaluation of the ease of inspection. The influence on the expected service life has been analysed for both variables. Concerning the second one, Figure 4.23 shows how the difference between the two curves is irrelevant. The buildings characterized by unfavourable conditions of inspection feature almost exactly the same deterioration path as the façades that are easier to examine. About the definition of the two parameters, this refers to Emídio (2012). That is, buildings with more than 3 floors, or that have a shape that prevents the inspection, are among those difficult to analyse. Anyhow, it can be seen how the supposed unfavourable conditions do not really affect the global result of the inspection.

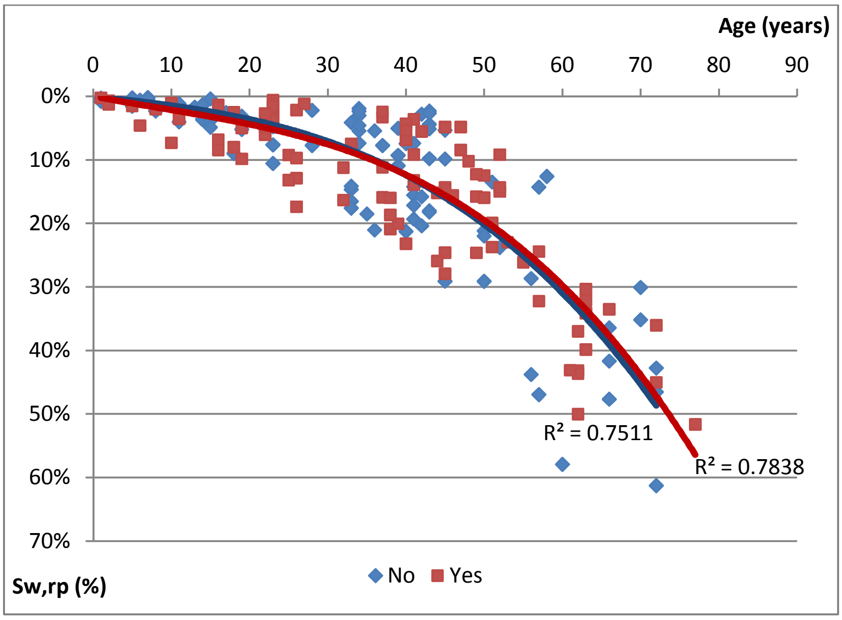


Figure 4.22 - Overall degradation curve according to existence of peripheral protections

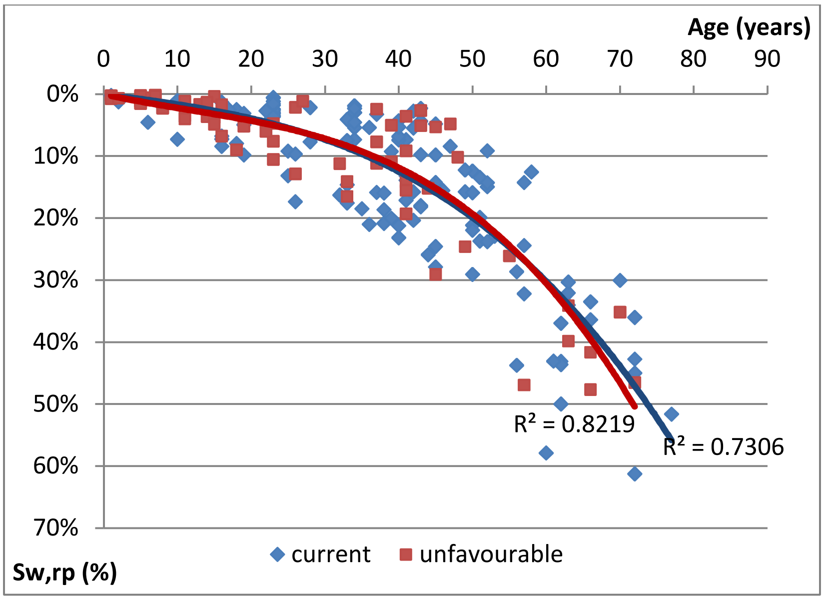


Figure 4.23 - Overall degradation curve according to ease of inspection

More interesting is the output concerning the claddings maintenance. Gathering this information during the field work was rather difficult. The problems in getting reliable data from the sources (Municipal Archive and tenants) have been mentioned in the previous chapter. Looking at Figure 4.24 it can be noticed how the amount of claddings that were subjected to maintenance is low. The shortage of elements leads to a low R^2 value (0.3434). In spite of this, the path is clear: the curve that refers to maintained claddings is higher than the other, meaning a slower degradation process. Interesting also is the fact that a stretch of the polynomial line runs externally to the graph, until the age of 20 years.

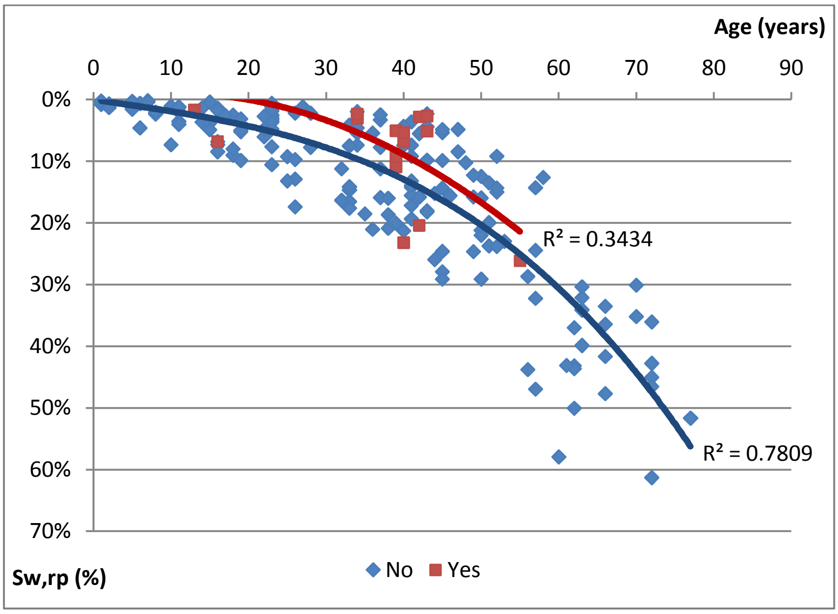


Figure 4.24 - Overall degradation curve according to maintenance level

A possible interpretation of such a result is this: at the beginning of the building life, maintenance can annul the impact of decay. In other words, if a ceramic cladding is maintained since its entry into service, after 20 years it could be still considered as practically new. The moment the degradation starts to be visible is the moment in which the more serious mechanism of degradation come into action. These have been mentioned in paragraph 4.3.1 as the chemical and physical mechanisms that affect the strength of the building component. This could also be confirmed by the S-shaped curve mentioned in paragraph 4.3.2: the slope of the obtained trend line, which indicates the effect of the more severe anomalies, begins at around 20 years. This means that a regular maintenance can remedy the initial less serious deterioration, delaying the normal degradation process. In fact, maintained façades feature a service life 4 years longer than the others (54 to 50), showing how a regular upkeep may extend the service life of ceramic façades. These data confirm the crucial importance of maintenance, already mentioned in Chapter 2.

Table 4.6 resume the service life values calculated with the method of Gaspar (2009) for all the factors affecting the deterioration evolution. Generally, the variation between such values is rather small, in the range of 5 years at the most. These outcomes will be used during the application of the factor method.

4.3.4 Discussion of the results

The expected service life for ceramic external wall claddings evaluated through the model of Gaspar (2009) is 50 years. The value obtained by the current work has been compared with the results of previous studies carried out by different authors. The values taken into consideration are shown in Table 4.7.

Table 4.6 - Service life according all degradation factors

Analysed factor		Life expectancy
Execution level	Adequate	50
	Inadequate	24
Sea distance	< 1 km	48
	> 1 e < 5 km	51
	> 5 km	53
Orientation	N	50
	S	47
	W	52
	E	53
Rain/wind action	Severe	49
	Moderate	51
	Mild	53
Humidity expositoin	Low	53
	High	48
Surface	Glazed	50
	Not glazed	-
Colour	Light	49
	Dark	54
	White	-
Size	L < 20	51
	L ≥ 20	46
Substrate	Masonry	49
	Concrete	52
Peripheral joints	Y	52
	N	49
Peripheral protections	Y	51
	N	50
Ease of inspection	Current	50
	Unfavourable	51
Manteinance	Y	54
	N	50

Table 4.7 - Service life evaluated by different authors

Reference	Service life (years)	Variation range (years)
BCIS (2001)	35	20 / 50
Shohet and Paciuk (2004)	18 (1) 27 (2)	15 / 21 (1) 24 / 29 (2)
Sousa (2008)	18	-
Sousa (2008) (3)	48	-
Sousa (2008) (4)	50	-

(1) - Public and corporative buildings
(2) - Residential buildings
(3) - After the application of the model of Gaspar (2009)
(4) - After the analysis carried out in Chapter 4

Sousa (2008) achieved a service life value of 18 years. However, this outcome cannot be directly compared with the actual study. In fact, as mentioned in paragraph 3.3.1, the author used a different calculation formula to evaluate the overall degradation severity. In the same section, an update of the outcome of Sousa (2008) has been made. Figure 4.2 has shown how, after the application of the model of Gaspar (2009), the expected service life changes from 18 to 48 years. A similar value has been obtained after the analysis of the sample of Sousa (2008) carried out in the previous chapter, leading to some façades exclusions. In this case, the predicted service life for ceramic claddings turned out to be equal to 50 years old (Figure 4.22). Therefore, the value achieved by the field work is indeed confirmed by the study of Sousa (2008).

Sousa (2008) debated the result of 18 years old by doing researches in literature. Two sources had been found: BCIS (2001) and Shohet and Paciuk (2004). Regarding the first one, the service life of ceramic claddings was estimated to be 35 years. This value is substantially lower than the one just obtained (50 years). Even lower are the values achieved by Shohet and Paciuk (2004). In this case the service life had been evaluated separately for public and residential buildings (respectively 18 and 27 years old), based on different required performance levels.

The work of Shohet and Paciuk (2004) involved an in-depth research on previous studies, dealing with the prediction of the life expectancy of building components. The evaluation had led to the development of an empirical method, supported by an extensive field survey and followed by statistical analyses. Such method established an evaluation of the building component performance based on two rating scales (physical and visual); these are presented in Tables 4.8 and 4.9. The rating of 40 refers to residential buildings, in which owners seek to minimize maintenance costs. On the other hand, the 60-level refers to situations in which components are required to perform at high levels (for instance public and corporate buildings).

Table 4.8 - Description of physical rating scale (Shohet and Paciuk, 2004)

Rating	Description of features
20	Significant portions of the cladding have peeled or fallen off. Cracks wider than 5 mm have developed
40	Cracks wider than 1 mm have developed on 5% or more of the cladding area. Portions of the cladding have fallen off
60	Cracks 0.5 mm wide cover less than 5% of the total cladding area. Up to 3% of cladding elements have fallen off
80	Capillary cracks have developed on portions of the cladding. Single cladding elements have fallen off
100	Cladding is complete and undamaged. No cladding elements have fallen off. Some capillary cracking may be present

Table 4.9 - Description of physical rating scale (Shohet and Paciuk, 2004)

Rating	Description of features
20	Significant portions of the cladding are missing or incomplete. Cracks have developed on the cladding surface
40	Damage is localized. Micro-organisms have developed over one third or more of the cladding area
60	Cladding surface is not uniform due to physical damage or discolouring
80	Cladding surface is not uniform due to minor cracks, fallen-off tiles, micro-organisms or distinctions in cladding colour
100	Cladding surface is undamaged and uniform (no visible cracks or missing elements and no discolouring)

Concerning the degradation evaluation, a considerable difference relative to the model of Gaspar (2009) has to be noticed, examining how the current outcomes may not be directly compared to the results of Shohet and Paciuk (2004). First, a diverse rating method for the component performance has been used. In addition to this, the current model takes into account a great number of defects; many of them were not considered by Shohet and Paciuk (2004), e.g. joints deterioration and adhesive failure. As seen in Figure 4.65, these are also among the most commonly defects observed during the field work, affecting respectively 65% and 42% of the inspected façades.

The large collected sample (195 claddings), the significant statistics obtained and the confirmation of the values of the work of Sousa (2008) can lead to the conclusion that the current assessment of ceramic claddings life expectancies is reliable. However, one must not forget the limits of the evaluation method, proved by the differences within the results of other authors. As mentioned, both visual inspections and degradation models have limitations. The first one is affected by the difficulty in obtaining some information and the subjectivity of the evaluation. On the other hand, the overall degradation assessment is characterized by a simplification of a very complex phenomenon. These considerations lead to not consider the value obtained as definitive, rather indicative.

4.4 Conclusions

As stated, this chapter has dealt with the overall degradation evolution assessment. The aim is to predict the service life of ceramic external wall claddings. In order to quantify the claddings deterioration, the model developed by Gaspar (2009) has been used. In the second part of the chapter the analysis of the results obtained has been carried out.

The degradation average curve for the collected sample has been drawn. The calculated expected life for ceramic claddings is 50 years. The outcomes survey has considered all the different factors that influence the deterioration evolution, leading to statistically significant results in most of the cases. In particular, the comparison between the degradation evolution of claddings featuring adequate and grossly inadequate level of execution is meaningful. The life expectancy for building components characterized by an inadequate level of execution is cut by half. This is a clear proof of the importance of the façade design and the proper installation of the cladding system.

The expected life has been then discussed and contextualized with previous studies that concern the service life prediction. The value achieved will be the basis for the factor method application that is presented in the next chapter.

5 APPLICATION OF THE FACTOR METHOD

5.1 Introduction

This chapter proposes a deterministic methodology for the prediction of service life of ceramic external wall claddings. Such methodology is based on the factor method, which represents the last step of the current study, leading to the achievement of dissertation's goal. The works of Gaspar (2009) and Emídio (2012) have been taken into account: both authors applied the factor method in the context of service life evaluation, respectively for renderings and stone claddings.

In the current section, each multiplier factor part of the factor method formula has been analysed and evaluated. Such analysis begins with the RSL calculation and ends with the evaluation of the ESL for each cladding of the sample, by improving the weighting coefficients. To do this, the chapter has been structured in three parts:

- First, preliminary surveys have been made. The expected service life of each element of the sample has been evaluated. This has allowed attributing a weight to each factor influencing the façades durability;
- The second part concerns the calculation of the reference service life (RSL) of ceramic external wall claddings;
- In the last section, the estimated service life (ESL) is calculated, improving the multiplying coefficients that are part of the factor method formula. For this, variables have been studied for several scenarios, in which each of them is weighted.

5.2 Preliminary evaluations

5.2.1 Extrapolation of the degradation curve for each point

In the previous chapter, the application of the model of Gaspar (2009) has resulted in the overall degradation severity calculation, which has led to plot the average degradation curve (Figure 5.9) for ceramic external façades. In addition to this, the same author developed several methodologies to extrapolate a reliable degradation curve for all dots of the chart (Gaspar, 2002). These are the method of homothetic transformation, the method of rotation, the method of translation, the method of conversion factor to the value of ordinates and the method of conversion factor to the value of abscissas. The last two methodologies have been also applied by Emídio (2012), to evaluate the expected service life for each façade of the sample. Despite its simplicity, the authors' outcomes clearly showed how the methodology that gives the most satisfactory results is the method of conversion factor to the value of ordinates. Basically, this consists on the identification of a k factor that relates the ordinates of the graph points.

Bearing in mind the results obtained by the two authors, in the current work the method above mentioned has been applied. The k factor has been evaluated for the sample's claddings. More specifically, this is the ratio between the overall degradation severity of each element of the sample ($S_{w,rp}$ A) and the corresponding severity value of the average curve ($S_{w,rp}$ M), for the same age. Figure 5.1 illustrates this concept. The function that relates the dots ordinates and allows the calculation of the regression line for all of them is as follows:

$$f' = k \cdot (f) = k \cdot a \cdot x^3 + k \cdot b \cdot x^2 + k \cdot c \cdot x \qquad \text{Equation 5.1}$$

Where:

f Average degradation curve function;

f' Degradation curve for each dot function;

k Relation factor. Referring to Figure 5.1, k = $S_{w,rp}$ A/$S_{w,rp}$ M;

a, b, c Constants of the 3rd-order polynomial average curve.

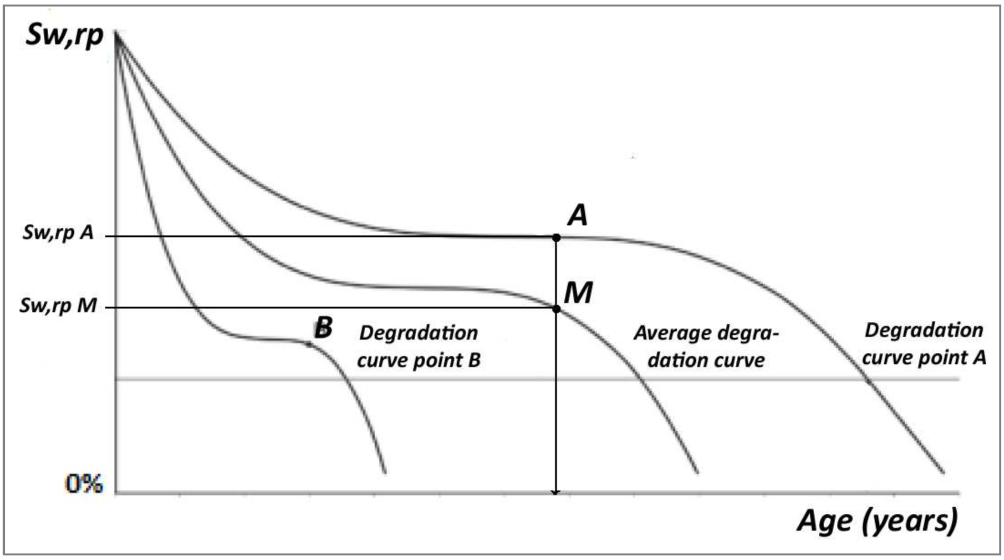


Figure 5.1 - Method of conversion factor to the value of ordinate (Gaspar, 2002)

An example of the calculation is given in Table 5.1. It concerns the first five claddings part of the sample. On the other hand, Figure 5.2 shows the graphical outcomes of the calculation performed; in particular, the curves comprised the upper and lower limits of the sample. The service life values corresponding to such limits are 116 years and 23 years, respectively. There is a big difference between these two values, testifying how the expected service life can considerably change, as a function of all the parameters considered.

Table 5.1 - Expected service life evaluation for the first five elements of the sample

Code	Age points	$S_{w,rp}$ points	Age average curve	$S_{w,rp}$ average curve	k	Service life
Ed. 1	14	3.63%	14	2.67%	1.36	43.5
Ed. 2	41	9.14%	41	12.98%	0.70	58.5
Ed. 3	26	12.86%	26	5.88%	2.19	34.0
Ed. 4	55	26.10%	55	24.60%	1.06	49.0
Ed. 5	26	2.14%	26	5.88%	0.36	76.0

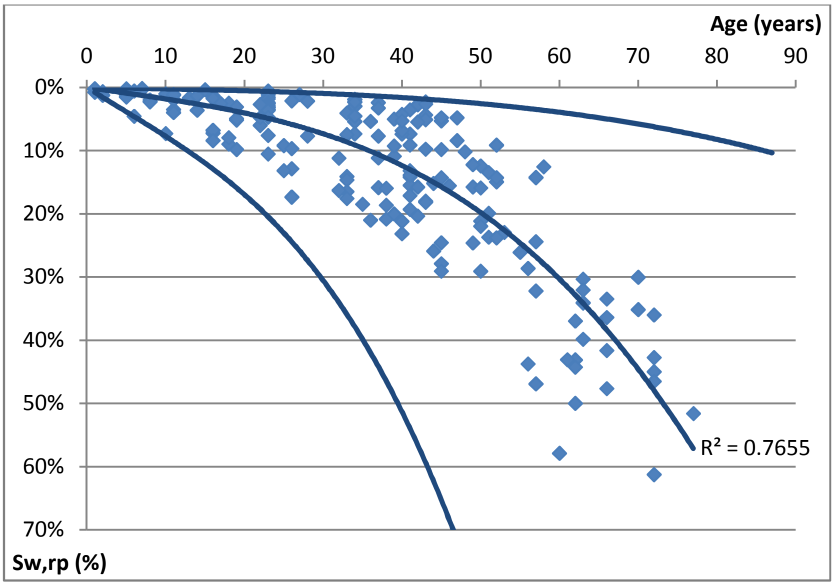


Figure 5.2 - Degradation curve: upper and lower limits

The function just introduced is also the base of the study reported in Figure 5.3. Here external curves have been traced so as to exclude 10% of the points. 5% of dots left out have been selected from the upper ones. Conversely, 5% have been picked from the lower outliers. The aim is to evaluate a possible range, that comprises 90% of the cases. In this way, there is 90% of probability that an inspected cladding features such a condition.

The outcome shows important data: the range of 90% probable service life values is approximately between 35 and 75 years. Notable is also the fact that most of the excluded elements feature a young age, especially for the lower trend line. This suggests how the evaluations concerning young building components have a greater impact on the results. Nevertheless, the range outcome is not completely balanced and uniform around the average degradation curve, which features a service life of 50 years.

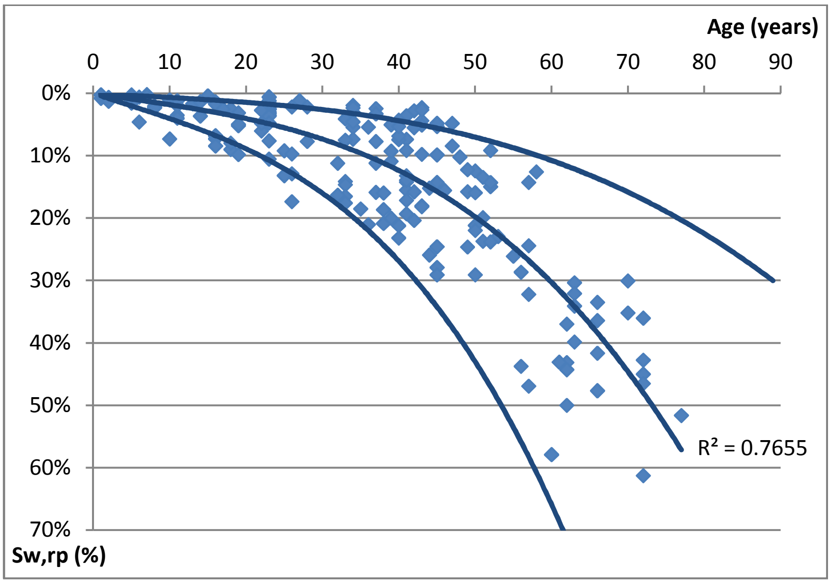


Figure 5.3 - Degradation curve: 90% sample range

5.2.2 Analysis of service life distribution over time

Data obtained in the previous section have been used to plot another significant graph, which is shown in Figure 5.4. It concerns the service life distribution over time. In this case, the abscissa axis features time, whereas the ordinate axis represents the expected service life of each cladding. The latter has been evaluated in the previous section through the method of conversion factor to the value of ordinates; it is about the intersection of the curve concerning each point with level 3 of degradation ($S_{w,rp}$ = 20%). The trend line in Figure 5.4 represents the average value of the graph dots: the expected average service life evaluated with the method of conversion factor turns out to be 55 years.

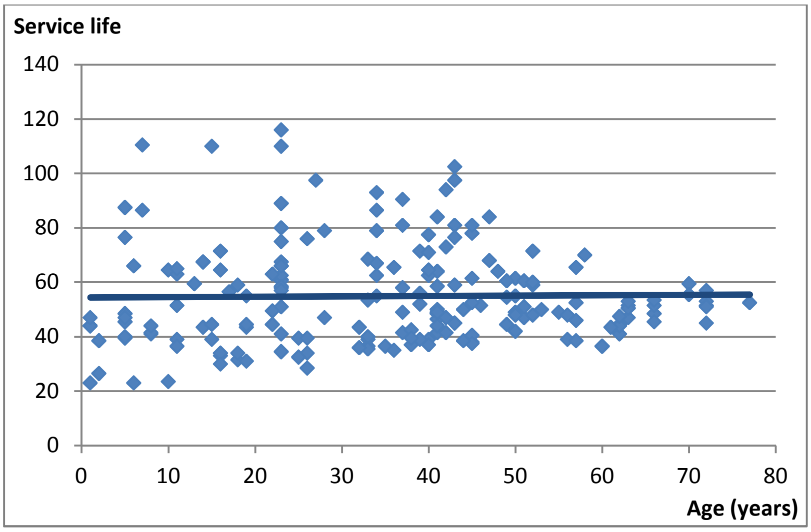


Figure 5.4 - Service life distribution over time

In this chart, the more horizontal the line is, the more the chart is reliable. Therefore, one can see that the output is very satisfactory. Nevertheless, there are some scattered values. In fact, as seen in Figure

5.1, some façades feature a rather improbable expected service life, up to 116 years. Such values are considered not to be representative for the study that is being carried out. Emídio (2012) developed a criterion to limit the range of the values obtained; the same concept has been applied in the current work. The point of reference is the average service life calculated in the previous chapter, through the degradation curve (50 years). Then, cases that feature a service life that is greater than twice or less than 25% the average will be excluded (range between 12.5 and 100 years). Five cases have been removed; all of them feature values above 100 years. The final chart is illustrated in Figure 5.5. Here, average service life is equal to 53 years.

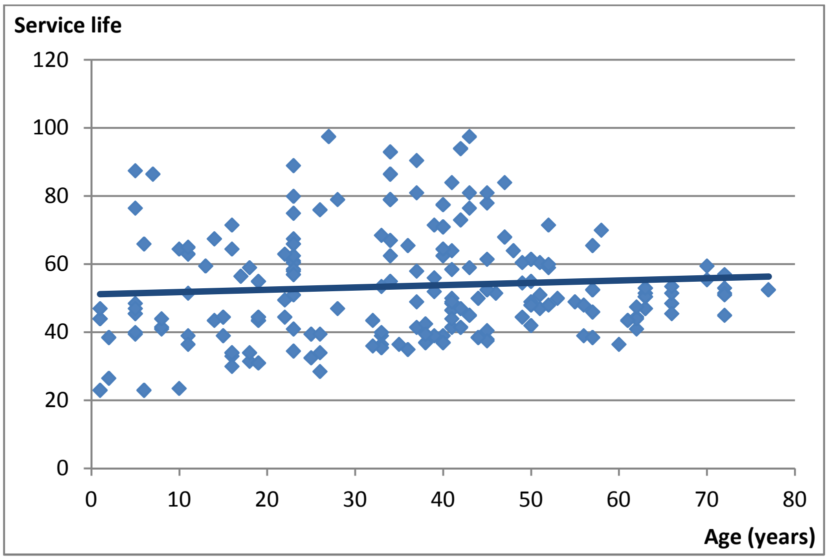


Figure 5.5 - Service life distribution over time without outliers

This regression line is slightly less horizontal than in Figure 5.4. Despite this, it has been chosen to maintain the chart without outliers. The reason is that the second service life value (53 year) is closer to the one calculated by the overall degradation curve, making results more coherent; more than this, the excluded outliers are considered not representative for the application of a statistical model.

As for the degradation curve outputs, the result has been analysed according to the various factors affecting the durability of ceramic façades. The same variables classification has been maintained; it concerns location, cladding characteristics, design and maintenance level. It is anticipated that in most of the cases, service life/time charts have confirmed the outcomes that have been achieved in the previous chapter. But first, data concerning the well installed claddings have been compared with the expected life of the claddings removed from the sample in sections 3.3.2 and 3.6.1. The output is shown in Figure 5.6. Also the analysis at issue reveals a marked difference between the two factors in terms of average service life: 53 to 23 years. This confirms the considerations made in the previous chapter, concerning the extreme importance of proper execution and adequate design of the ceramic tiled façades (Chew, 2004; Morais, 2007).

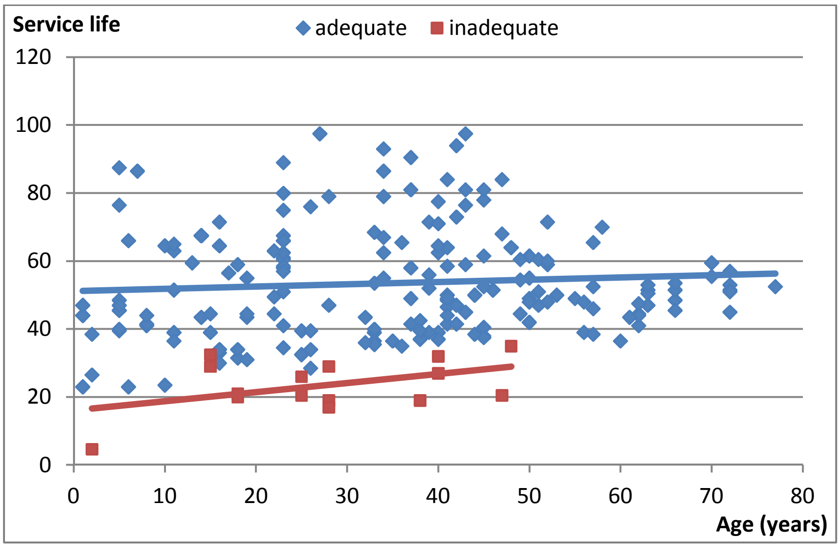


Figure 5.6 - Service life distribution over time according to execution level

Analysis according to the location of the building

Regarding the building location, the first factor to be considered is distance from the sea. Results are clear, both in terms of dots correlation and deterioration outputs, i.e. regression lines are almost parallel. In addition to this, Figure 5.7 shows how buildings located near the river bank deteriorate faster than the ones at a greater distance, in full accordance with results obtained so far. The same goes for orientation: as in previous surveys, the chart does not reach any satisfactory conclusion (Figure 5.8). The curves are roughly horizontal, but no difference has been found in the life expectation of the various orientations.

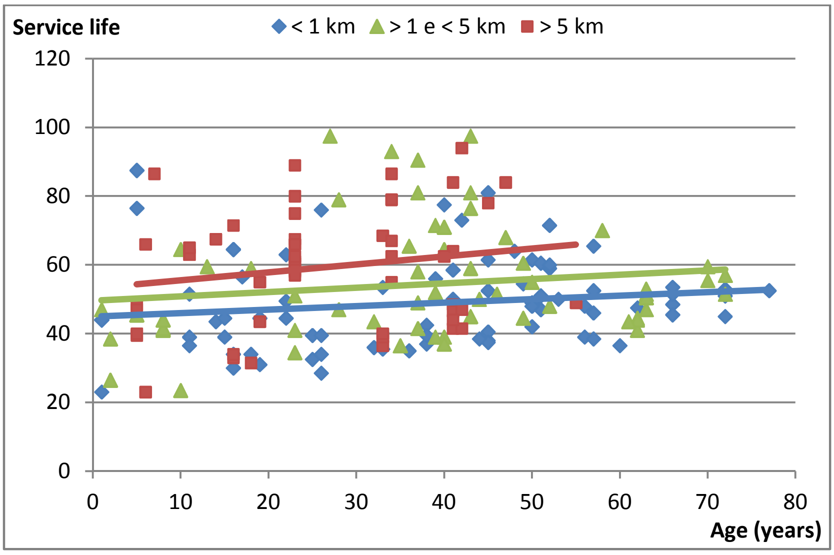


Figure 5.7 - Service life distribution over time according to distance from the sea

Concerning the effect of the atmospherics agents, the graph can be related to the one concerning distance from the sea; the lowest line correspond to the worst environmental condition, whereas the upper one refers to the mild action of rain and wind (Figure 5.9). However, in this case the distance between the lines is smaller; this probably indicates less influence of atmospheric agents on the components deterioration, if compared to air salinity. Instead, humidity exposure gives the clearest result, in terms of degradation curve. Figure 5.10 stresses how this factor significantly affects the cladding performance.

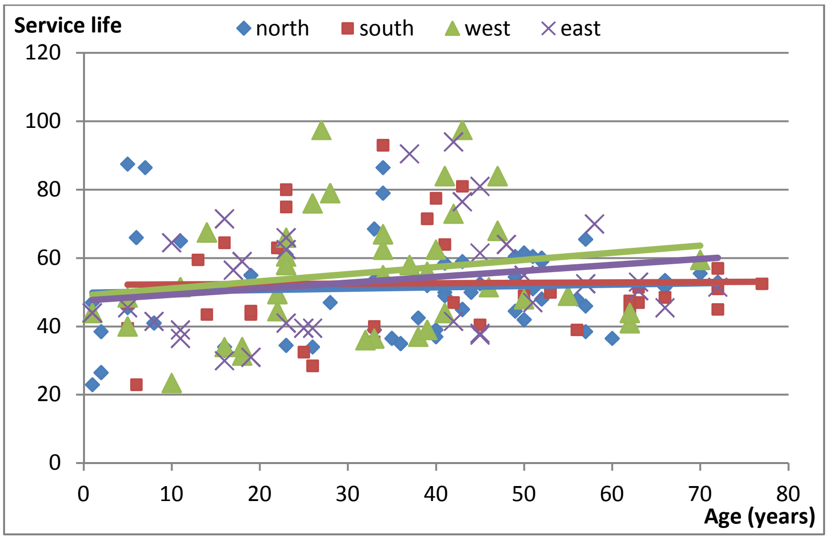


Figure 5.8 - Service life distribution over time according to orientation

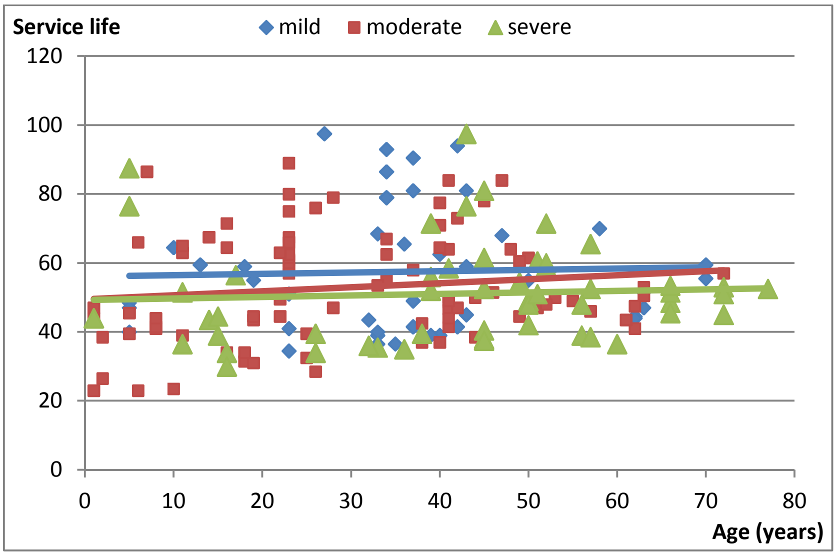


Figure 5.9 - Service life distribution over time according to wind/rain action

Analysis according to the cladding type

The claddings characteristics concern tiles surface, colour and size. The first two variables have given similar results: the distance between the average lines is inconsistent (Figures 5.11 and 5.12). Furthermore, regression lines cross each other, compromising the reliability of the graph. In both cases this is probably due to lack of elements (not glazed and larger tiles respectively). The reason for this gap has been widely explained during the previous surveys. Nevertheless, the degradation model of Gaspar (2009) gave a better result regarding the tile size analysis; that is, façades featuring tiles larger than 20 cm had seemed to deteriorate faster than the others. This has not been confirmed by the current chart.

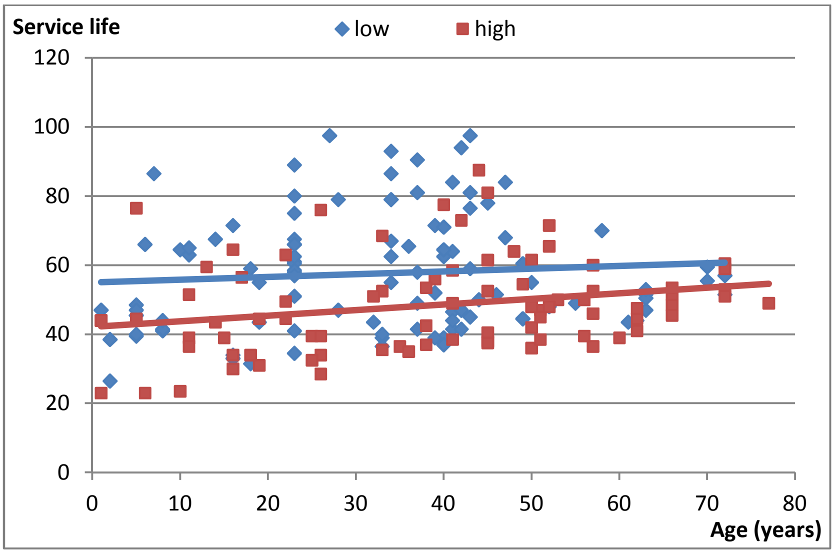


Figure 5.10 - Service life distribution over time according to humidity exposure

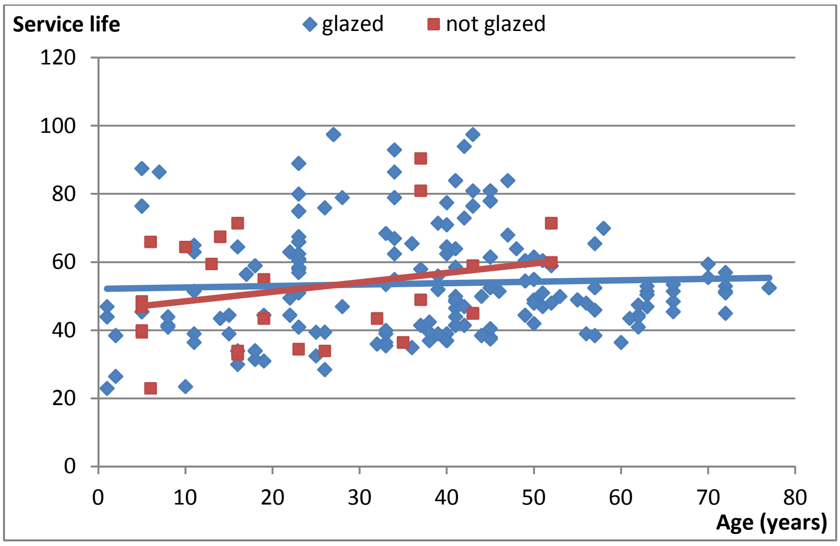


Figure 5.11 - Service life distribution over time according to tiles surface

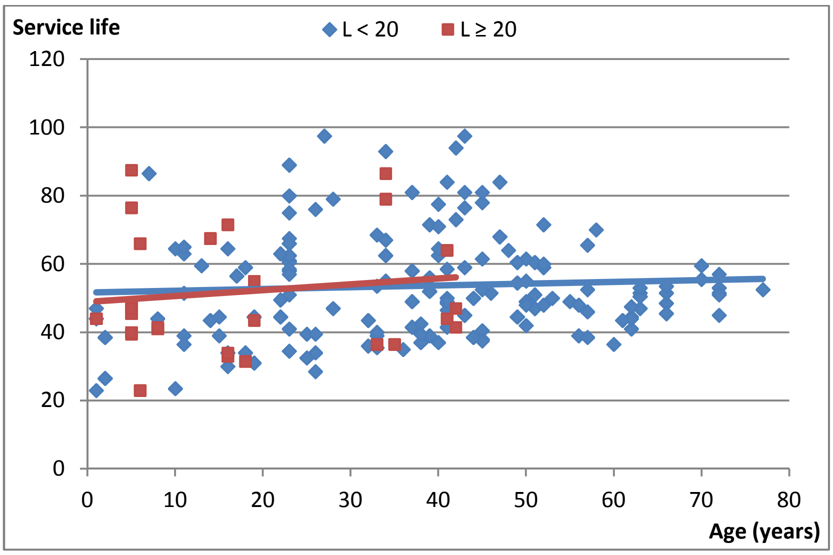


Figure 5.12 - Service life distribution over time according to tiles size

The outcome concerning tiles colour is slightly worse. Lines cross themselves and the estimation of an average service life for white claddings is impossible (Figure 5.13). Generally, considering both analyses carried out (degradation curve and service life distribution) the colour of tiles represents the most inconclusive outcome.

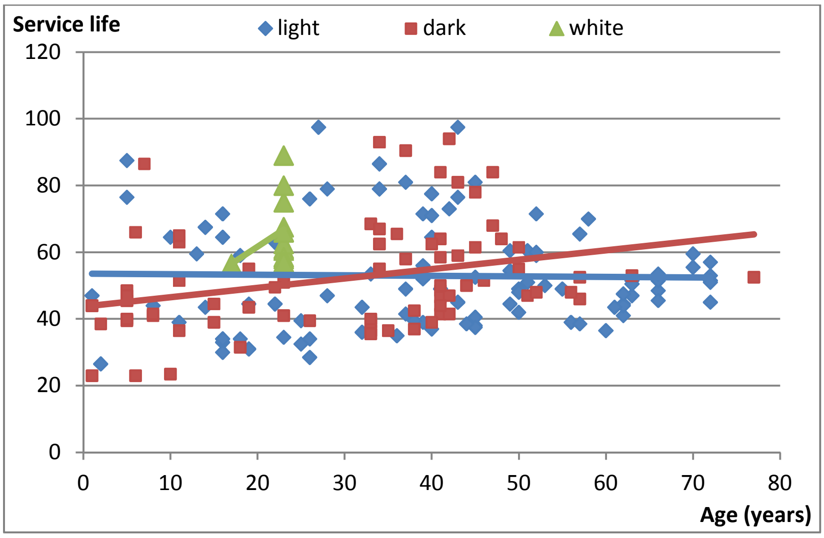


Figure 5.13 - Service life distribution over time according to tiles colour

Characteristics of the design

Substrate is the first factor that is gathered in the façade design characteristics. Figure 5.14 proves how concrete leads to a slower degradation. In fact, the two variables show a consistent difference in service life expectation. Masonry features an average of 50 years, whereas claddings laid on concrete substrate last on average 57 years. The reliability of this data is partially questioned by the slope of the regression line. Nevertheless, the fact that both degradation analyses gave a similar output concerning such factor, leads to think that concrete substrate indeed positively influences the claddings performance. Finally, Figure 5.14 clearly shows the shortage of elements featuring concrete substrate and age greater than 60 years, as well as the absence of masonry structures younger than 10 years.

Concerning peripheral joints and protections, the outcomes are presented in Figures 5.15 and 5.16. Regression lines are overlapping; in addition to this, claddings with peripheral joints gave worse result than the façades that does not have any, which does not make sense. The cause is probably traced to the lack of data regarding protected façades. For this, both analyses are considered inconclusive.

Maintenance level

As for the results of the degradation severity graph plotted in the previous chapter, ease of inspection seems not to affect the durability of the component. Figure 5.17 illustrates that since the average service lives are equal.

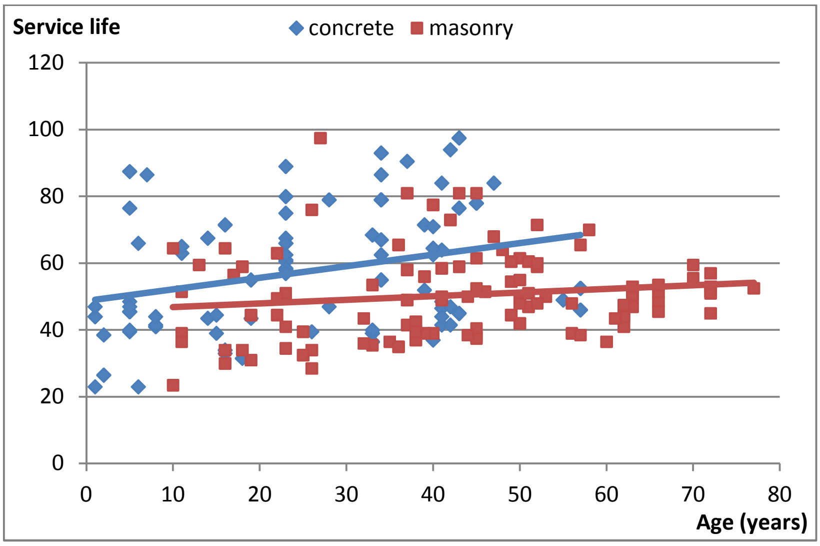


Figure 5.14 - Service life distribution over time according to substrate type

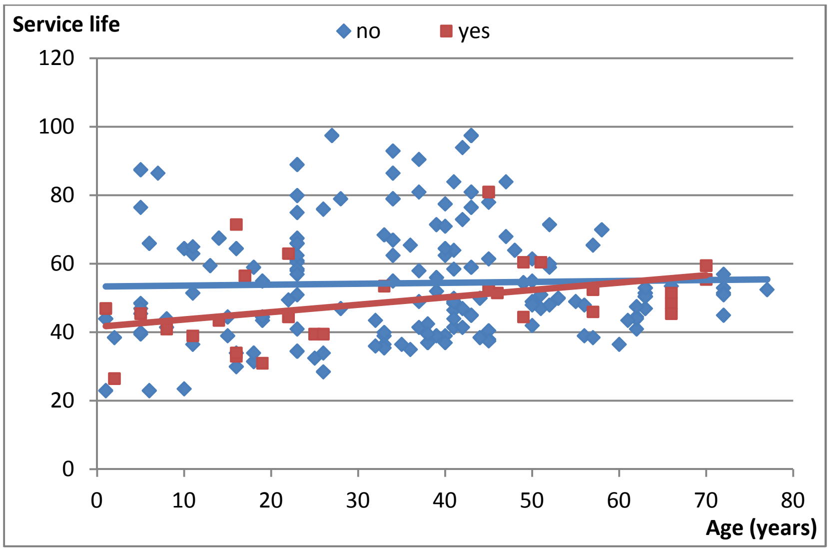


Figure 5.15 - Service life distribution over time according to peripheral joints

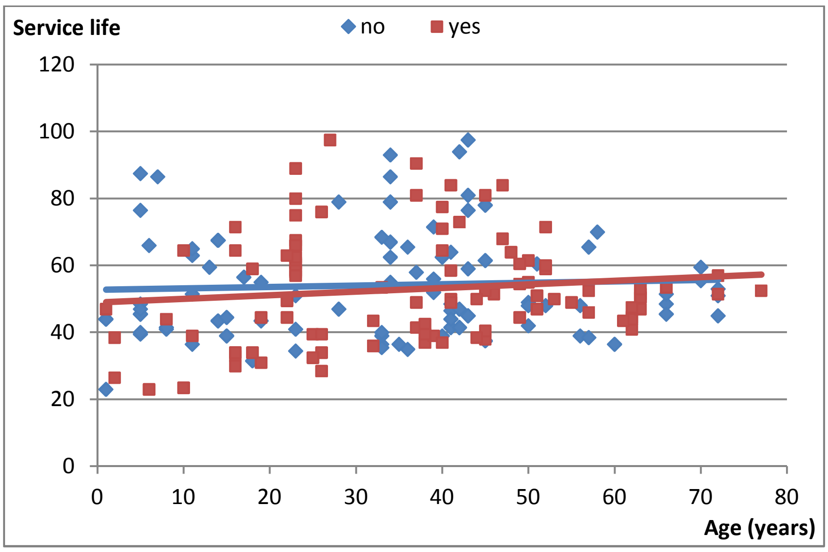


Figure 5.16 - Service life distribution over time according to peripheral protections

The situation is quite different for maintenance level (Figure 5.18). The upper line refers to claddings that have been maintained during their lifetime; these are only a few. Nevertheless, the outcome clearly shows how the latter feature a higher expected life: 66 years *versus* 52 years of average service life for the non-maintained façades. Such data are considered to need further investigation, but establish the unquestionable benefit of a regular maintenance.

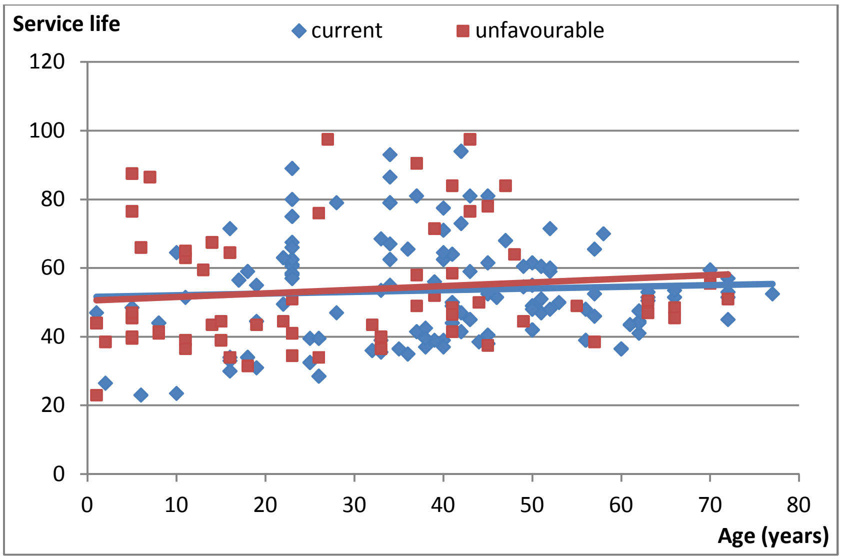


Figure 5.17 - Service life distribution over time according to ease of inspection

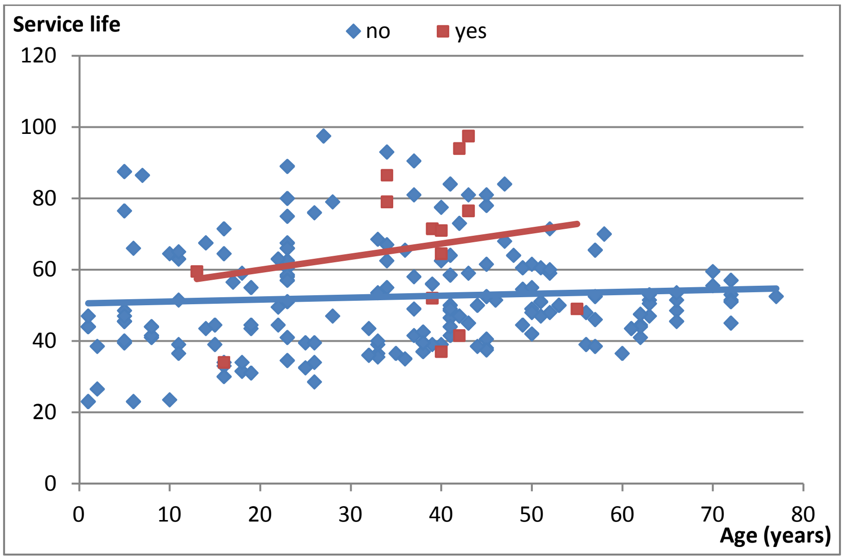


Figure 5.18 - Service life distribution over time according to maintenance level

To conclude the characterization of the outcomes, according to factors affecting the durability, Table 5.2 resumes the service life average values calculated with the method of conversion factor to the value of ordinates. Despite the fact that in some cases graphical results have not been clear, comparing Table 5.2 with Table 5.6, it can be noticed how values obtained with the method at issue are similar and as credible as the one evaluated in the previous chapter.

Table 5.2 - Service life according the factors affecting the claddings performance

Analysed factor		Life expectancy
Execution level	Adequate	53
	Inadequate	23
Sea distance	< 1 km	48
	> 1 e < 5 km	54
	> 5 km	59
Orientation	N	51
	S	53
	W	56
	E	53
Rain/wind action	Severe	51
	Moderate	53
	Mild	57
Humidity exposure	Low	58
	High	48
Surface	Glazed	54
	Not glazed	50
Colour	Light	53
	Dark	52
	White	66
Size	L < 20	54
	L ≥ 20	52
Substrate	Masonry	50
	Concrete	57
Peripheral joints	Y	49
	N	54
Peripheral protections	Y	53
	N	54
Ease of inspection	Current	54
	Unfavourable	53
Manteinance	Y	66
	N	52

5.2.3 Weighting of the factors affecting ceramic claddings durability

The last preliminary step to RSL calculation is the study regarding the factors that affect the loss of performance of the building component. These have been previously introduced, in the context of the analyses concerning the field work outcomes and the overall degradation evolution. The above mentioned study consists in the application of the data gathered so far to the factor method. This has been presented in Chapter 1, within the theoretical foundations of service life prediction. In that section it has been examined in depth; evolution, scope and limits concerning the methodology have been presented. As mentioned, the calculation formula is as follows:

$$ESL = RSL \cdot A \cdot B \cdot C \cdot D \cdot E \cdot F \cdot G \qquad \text{Equation 5.2}$$

This formula resumes three important concepts: estimated service life (ESL), reference service life (RSL) and weighting factors. Exactly the latter have be taken into account for the evaluation of the RSL, which will be debated in the next section. In the current section, the independent variables affecting the claddings durability have been identified and classified, according to the multiplying factors that are part of the factor method calculation. As noticed, the variables that have been used as a basis for the graphical analysis previously carried out correspond to the sub-factors of the methodology. In fact, as stated in section 3.3.3, the field work results' survey has been made according to this classification.

In the context of this categorization, a weighting value is conferred to each variable. Such coefficients assume the values of 0.8, 0.9, 1, 1.1, 1.2, referring to the work of McDuling (2006). The author established five categories for each factor that influences the durability: e.g., concerning environmental conditions, the rating consists in: favourable, less favourable, slightly aggressive, aggressive and very aggressive level. This classification fits with the weighting coefficients quantification applied in the current work (Table 5.3). It is recalled that such weighting coefficients are not definitive, but only used for the reference service life evaluation.

Table 5.3 - Quantification of sub-factors proposed by McDuling (2006)

Level	k value
Favourable	1.2
Less favourable	1.1
Slightly aggressive	1
Aggressive	0.9
Very aggressive	0.8

A - Material's quality, finishing, or treatment

This aspect considers the characteristics of the tiling system. In Chapter 2 ceramic wall claddings have been typified, according to the various features of the building component and the tiles themselves. Within this survey, ceramic tiles have been categorized according to the manufacturing process and physical properties. Nevertheless, examining these characteristics has been considered non-functional for the factor method application, besides being a rather complex matter. Furthermore, because of the impossibility of collecting information on materials composition, the joints filling grout and bedding mortar have also not been considered in the current classification. The variables that have been collected in this category are surface, colour and size of the ceramic tiles. The identification of such characteristics during the visual inspections is immediate but significant, especially for the surface type, which directly influences the water absorption of tiles.

Considering the results obtained for these variables, Table 5.4 shows the data collected so far. It is about the average service life evaluated with the two purposed methods: the degradation curve (Chapter 4) and the service life distribution over time (section 5.2.2). As seen in Table 5.4, some sub-factors have been attributed to each variable (surface, colour and size). In this way, the claddings features can be efficiently expressed. More in detail, surface can be glazed or no glazed. Concerning the other factors, these have been subjectively categorized in this way: light coloured tiles have been separated from the dark and the white ones. Regarding the size, a medium size (20 cm) has been chosen as discretion value.

Table 5.4 - Factors weighting proposal according to material's characteristics

A - material's quality, finishing, or treatment			Degradation curve average	Service life distribution average	K value
A1 - surface	K1	Glazed	50	54	1
	K2	Not glazed	-	50	0.9
A2 - color	K1	Light	49	53	1
	K2	Dark	54	52	1
	K3	White	-	66	1.1
A3 - size	K1	L < 20	51	54	1
	K2	L ≥ 20	46	52	0.9

Concerning the weighting values conferred, these are shown in the "k value" column of Table 5.4. The attribution of such coefficients is based on the average service life calculated and the intrinsic material properties. In Figure 5.11 glazed tiles have shown a higher average than the others, whereas the degradation curve did not reach any conclusion for this matter. For this consideration, an unfavourable value (0.9) has been attributed to the not glazed tiles. About the colours, no clear conclusions have been reached. White façades feature a very high estimated service life; however, considering the extreme shortage of elements, only a slightly improving coefficient has been chosen for this sub-factor (1.1). Finally, tile size has given better outcomes in terms of reliability: larger tiles have shown a faster degradation, leading to a 0.9 value.

B - Characteristics of the design

The design of a ceramic external façade mainly concerns the joints design: splitting joints, structural joints and peripheral joints. Regarding the first ones, very few claddings presented this type of joints. In fact, these are mostly used in large façades, whereas in the current work the number of elements featuring a size that requires this type of joints is low. This has not allowed plotting any chart. The same goes for structural joints: no graph has been drawn for this design characteristic. Instead, many buildings present peripheral joints; this has allowed calculating a reliable average service life. In addition to this, also peripheral protections are have been inserted in the design feature's categorization.

The last factor considered is the substrate type: this can be concrete or masonry. Substrate influences the laying operation and, as seen in the graphical outputs, the expected life of the building component. In fact, both analyses have shown a slower degradation process for concrete substrates, leading to the attribution of a coefficient equal to 1.1. Instead, the analyses concerning peripheral joint and protections detected no remarkable difference in the results. This has led to the attribution of a neutral value. Table 5.5 illustrates this.

C - Characteristics of execution on site

The analysis of the influence of the quality of the execution on site yielded a significant outcome. The difference in expected life for adequate and inadequate installations is unquestionable. It is recalled that the façades featuring poor execution have been removed from the sample. For this reason, they will not be taken into account in the context of the factor method application. The k value conferred to the claddings featuring inadequate installation is 0.5; it is not included in the values listed in Table 5.3, but it proportionately weights the age variance (Table 5.6).

Table 5.5 - Factors weighting proposal according to design characteristics

B - characteristic of the design			Degradation curve average	Service life distribution average	K value
B1 - substrate	K1	Masonry	49	50	1
	K2	Concrete	52	57	1.1
B2 - peripheral joints	K1	Yes	52	49	1
	K2	No	49	54	1
B3 - peripheral protections	K1	Yes	51	53	1
	K2	No	50	54	1

Table 5.6 - Factors weighting proposal according to execution on site

C - characteristic of execution on site			Degradation curve average	Service life distribution average	K value
C1 - level of execution	K1	Adequate	50	53	1
	K2	Inadequate	24	23	0.5

D - Indoor environmental conditions

This variable has not been considered for the factor method application; in fact, the internal conditions of use do not affect the external wall cladding.

E - Outdoor environmental conditions

On the other hand, outdoor environmental conditions play an important role on the loss of performance of façades. Generally, this is also the factor that most depends on the building location, considering both macro and micro areas. Therefore, it is one of the causes of the limitations of the factor method's application mentioned in Chapter 1. In fact, the climate of Lisbon features specific conditions that are not applicable in other sites, and vice-versa. For example, the inspected ceramic claddings are usually not affected by cycles of freezing and thawing. This fact limits the applicability of the method in contexts that feature substantial differences in climatic conditions.

Concerning the sub-factors categorization, the atmospheric agents considered in the current work are: influence of rain and wind, distance from the sea and humidity exposure. In addition to this, façade orientation has been taken into account, given the substantial effect of the temperature on adhesive strength (Chew, 1999).

All the variables have yielded reliable results, with the exception of façade orientation. The outcomes are shown in Table 5.7. Regarding the assignment of the weighting values to each sub-factor, this has been taken from McDuling (2006). A 0.8 value has been assigned to the variable that showed a substantial difference in the expected service life (very aggressive conditions). Instead, sub-factors that have proved a slightly variance in the evaluated service life have been assigned 0.9 and 1.1 values (aggressive and less favourable conditions respectively). Finally, medium environmental conditions were assignment a value of 1.

Table 5.7 - Factors weighting proposal according to outdoor environmental conditions

E - outdoor environmental conditions			Degradation curve average	Service life distribution average	K value
E1 - façade orientation	K1	North	50	51	0.9
	K2	East	53	53	1
	K3	South	47	53	1
	K4	West	52	56	1.1
E2 - wind/rain action	K1	Mild	53	57	1.1
	K2	Average	51	53	1
	K3	Severe	49	51	0.9
E3 - distance from the sea	K1	< 1 km	48	48	0.8
	K2	> 1 and < 5 km	51	54	1
	K3	> 5 km	53	59	1.1
E4 - humidity exposure	K1	High	48	48	0.8
	K2	Low	53	58	1

F - Construction's conditions of use

The collection of information concerning the condition of use of the claddings turns out to be rather difficult. Too many variables need to be taken into consideration; besides this, some of them could not be modelled. An example is *graffiti*. As mentioned in section 4.3.1, they have not been considered in the current study, since they cannot be related to a statistic degradation evaluation.

G - Maintenance level

In this case, two sub-categories were identified: the ease of inspection and the maintenance level itself. Concerning the first one, both graphical analyses proved that ease of inspection is non influential on the service life expectation. On the contrary, data concerning maintenance have given a clear result. A regular upkeep ensures slowing the degradation process, involving the attribution of a weighting value equal to 1.2 (Figure 5.8).

Table 5.8 - Factors weighting proposal according to maintenance level

G - maintenance level			Degradation curve average	Service life distribution average	K value
G1 - regular maintenance	K1	Yes	54	66	1.2
	K2	No	50	52	1
G2 - ease of inspection	K1	Current	50	54	1
	K2	Unfavourable	51	53	1

5.3 Calculation of the RSL

The evaluation of the reference service life is based on the work of Gaspar (2009). The author used the value obtained from the intersection between the average degradation curve and the minimum level of required performance, as a basis for the RSL calculation. In other words, it is approximately the expected service life calculated in Figure 5.10. Concerning ceramic claddings, such value is equal to 50 years.

Then, considering the decisive influence of RSL on the factor method application, Gaspar (2009) developed a method to make this value as reliable as possible. The author compared it with two other values, deduced from the application of the factor method. The same methodology had been adopted by Emídio (2012) and has been used in the current work. Therefore, the factor method has been inversely applied for each element of the sample, on order to evaluate the RSL. The expected service life value obtained in section 4.2.1 for every cladding has been used as the ESL. Concerning the multiplier coefficients, these consist in the weighting values assigned to each variable in the previous section, based on the field work results' analysis. The formula that has been used is:

$$ESL = RSL \cdot A \cdot B \cdot C \cdot D \cdot E \cdot F \cdot G \quad \rightarrow \quad RSL = \frac{ESL}{A \cdot B \cdot C \cdot D \cdot E \cdot F \cdot G} \quad \rightarrow \quad RSL = \frac{ESL}{0.8^x \cdot 0.9^y \cdot 1.1^z \cdot 1.2^k}$$

Where: Equation 5.3

ESL 50 years;

x number of occurrences of 0.8;

y number of occurrences of 0.9;

z number of occurrences of 1.1;

k number of occurrences of 1.2.

Once RSL has been calculated for every façade part of the sample, two values have been extrapolated. The first one corresponds to the average of RSL values concerning the elements that feature all the sub-factors equal to 1. In fact, the latter represent claddings characterized by standard conditions and, for this reason, they can be assumed as a benchmark for service life evaluation. The analysis identified 6 cases featuring such characteristics. The average of these values is equal to 51 years. A sample of the calculation (first five claddings of the sample) is shown in Table 5.9.

Table 5.9 - Reference service life evaluation for the first five elements of the sample

Code	ESL	Number of 0.8	Number of 0.9	Number of 1.1	Number of 1.2	RSL
Ed. 1	44	2	1	1	0	69
Ed. 2	59	2	2	0	0	113
Ed. 3	34	2	3	0	0	73
Ed. 4	49	0	0	3	1	31
Ed. 5	76	2	0	1	0	108

The second element of comparison is deduced from the same results. In this case the ratio ESL/RSL is evaluated (Table 5.10). Then, the ratios to which corresponds a standard deviation below 3% have been considered (8 cases) and the average of their values has been calculated. The result is 53 years.

Summarizing, the outcomes obtained with the aid of the methods of Gaspar (2002; 2009) are:

- RSL from the overall degradation graph → 50 years;
- RSL for the cases featuring all weighting coefficients equal to 1 → 51 years;
- RSL for the cases featuring ESL/RSL ratio's standard deviation < 3% → 53 years.

Table 5.10 - Reference service life evaluation for the first five elements of the sample: standard deviation

Code	ESL	RSL	ESL / RSL	Standard deviation
Ed. 1	44	69	0.63	28%
Ed. 2	59	113	0.52	39%
Ed. 3	34	73	0.47	45%
Ed. 4	49	31	1.60	69%
Ed. 5	76	108	0.70	21%

This considerations lead to set the reference service life for ceramic external wall cladding at 51 years, corresponding to the average of the three values just listed. To be noticed is that the ages obtained are scarcely different, demonstrating the validity of the findings.

5.4 Quantification of the factors

In the previous section the reference service life has been set at 51 years. This is the starting point to the proper application of the factor method. As mentioned, the weighting coefficients earlier assigned to each variable affecting the degradation process were not definitive; their main function was the calculation of the RSL. Therefore, the weighting values conferred have been improved. For this purpose several scenarios have been studied. It is about calculating iterations, whose purpose is to identify and adjust a list of weighting coefficients in order to maximize the reliability of the estimated ESL values. This methodology is based on the works of Gaspar (2009) and Emídio (2012).

Before the evaluation of the sub-factors, some acceptance criteria need to be stated. The aim is to obtain a global result that is as realistic as possible. Two acronyms will be used to simplify: FM and GM. The first refers to the values obtained by the application of the Factor Method; GM indicates the results of the Graphical Method (Figure6.5). The criteria are as follows:

- The outcomes of the application of the factor method need to be credible. For this reason, these have to be less than twice the average service life evaluated with the graphical method and higher than 25% that (13.25 years ≤ FM ≤ 106 years);
- The amplitude of ESL results evaluated through the factor method has to be less than, or equal to, those obtained by the graphical method ($FM_{max} – FM_{min} \leq GM_{max} – GM_{min}$);
- The average of the ratios between the results of the factor method and the graphical method must have a maximum variation of 5% from 1.00 (FM/GM ≤ 1.05);

- The standard deviation of the results has to be minimized;
- The cumulative frequency of the ratio FM/GM has to maximize the results around 1.00 (acceptance of 15%) and minimize the results above 1.50. In particular, FM/GM ≥ 0.85 at least in 50% of the sample and FM/GM ≤ 1.05 at most in 10% of the sample;
- The aim of the iterations is to maximize the number of cases falling within the following range: 0.85 ≤ FM/GM ≤ 1.15.

5.4.1 Scenarios

Scenario 1

This scenario takes into account the outcomes of the graphical method, which shows the expected service life distribution over time. The variance between the service life concerning each variable and the average (53 years) is calculated. The outcome is shown in Table 5.11.

Table 5.11 - Values obtained in scenario 1

Factors	Sub-factors	Service life	Age difference	K values	Final values
A1 - surface	Glazed	54	0	1.00	**1.00**
	Not glazed	50	-3	0.85	**0.85**
A2 - color	Light	53	-1	0.95	**0.95**
	Dark	52	-1	0.95	**0.95**
	White	66	12	1.60	**1.00**
A3 - tiles dimension	L < 20	54	0	1.00	**1.00**
	L ≥ 20	52	-2	0.90	**0.90**
B1 - substrate	Masonry	50	-3	0.85	**0.85**
	Concrete	57	4	1.20	**1.20**
B2 - peripherical joints	Yes	49	-5	0.75	**0.75**
	No	54	1	1.05	**1.05**
B3 - peripherical protection	Yes	53	-1	0.95	**0.95**
	No	54	1	1.05	**1.05**
C1 - level of execution	Adequate	53	0	1.00	**1.00**
	Inadequate	23	-30	0.50	**0.50**
E1 - façade orientation	North	51	-2	0.90	**0.90**
	East	53	0	1.00	**1.00**
	South	53	0	1.00	**1.00**
	West	56	3	1.15	**1.15**
E2 - wind/rain action	Mild	57	4	1.20	**1.20**
	Average	53	-1	0.95	**0.95**
	Severe	51	-2	0.90	**0.90**
E3 - distance from the sea	< 1 km	48	-5	0.75	**0.75**
	> 1 and < 5 km	54	-1	0.95	**0.95**
	> 5 km	59	4	1.20	**1.20**
E4 - humidity	High	48	-5	0.75	**0.75**
	Low	58	3	1.15	**1.15**
G1 - regular mantainance	Yes	66	12	1.60	**1.60**
	No	52	-3	0.85	**0.85**
G2 - easie of inspection	Current	54	-1	0.95	**0.95**
	Unfavourable	53	-2	0.90	**0.90**

For each year of difference, a variation of 0.05 (from 1) is assigned to the weighting coefficient (k value); e.g., façades featuring not glazed tiles' life expectancy is equal to 50 years, 3 years below the average. Therefore, the fourth column shows a negative value (-3). A value of 0.05 has been removed from 1 for each year of difference, leading to the coefficient (0.85). Two aspects need to be clarified. First, many sub-factors feature a trend that does not correspond to expectations: this is because of the values' decimals approximation (e.g. glazed tiles). More than this, the white claddings' final value has been modified. The reason is in the shortage of elements featuring this sub-factor: such shortage precludes assigning a value as high as 1.60. The outcomes of the scenarios will be further discussed.

Scenario 2

The basic concept of this scenario is exactly the same of the previous one. But it takes into account the degradation curve chart instead of the service life distribution over time. In this case, the average value is equal to 50 years. The considerations regarding lack of elements and values approximation, which have been done for the previous case, apply also to scenario 2 (Table 5.12).

Table 5.12 - Values obtained in scenario 2

Factors	Sub-factors	Service life	Age difference	K values	Final values
A1 - surface	Glazed	50	-1	0.95	**0.95**
	Not glazed	-	-	-	**1.00**
A2 - color	Light	49	-2	0.90	**0.90**
	Dark	54	3	1.15	**1.15**
	White	-	-		**1.00**
A3 - tiles dimension	L < 20	51	0	1.00	**1.00**
	L ≥ 20	46	-5	0.75	**0.75**
B1 - substrate	Masonry	49	-2	0.90	**0.90**
	Concrete	52	1	1.05	**1.05**
B2 - peripherical joints	Yes	52	2	1.10	**1.10**
	No	49	-2	0.90	**0.90**
B3 - peripherical protection	Yes	51	0	1.00	**1.00**
	No	50	-1	0.95	**0.95**
C1 - level of execution	Adequate	51	0	1.00	**1.00**
	Inadequate	24	-27	-0.35	**-0.35**
E1 - façade orientation	North	50	-1	0.95	**0.95**
	East	53	3	1.15	**1.15**
	South	47	-4	0.80	**0.80**
	West	52	1	1.05	**1.05**
E2 - wind/rain action	Mild	53	2	1.10	**1.10**
	Average	51	0	1.00	**1.00**
	Severe	49	-2	0.90	**0.90**
E3 - distance from the sea	< 1 km	48	-3	0.85	**0.85**
	> 1 and < 5 km	51	1	1.05	**1.05**
	> 5 km	53	2	1.10	**1.10**
E4 - humidity	High	48	-3	0.85	**0.85**
	Low	53	2	1.10	**1.10**
G1 - regular mantainance	Yes	54	3	1.15	**1.15**
	No	50	-1	0.95	**0.95**
G2 - easie of inspection	Current	50	-1	0.95	**0.95**
	Unfavourable	51	0	1.00	**1.00**

Scenario 3

In this scenario it has been chosen to assign to all the sub-factors a weighting value equal to 1. The aim is to study the outcome of a neutral model.

Scenario 4

This simulation has been carried out based on ISO 15686. Therefore, the values conferred are 0.8, 1, and 1.2, depending on the condition considered, as done in section 5.2.3. The age variation previously evaluated in scenario 1 and scenario 2 has been considered relevant and has been taken as reference point. Then, the weighting coefficients are assigned case by case, considering the actual characteristics of the sub-factors. Table 5.13 shows the values set conferred.

Table 5.13 - Values obtained in scenario 4

Factors	Sub-factors	Final values
A1 - surface	Glazed	**1.00**
	Not glazed	**0.80**
A2 - color	Light	**1.00**
	Dark	**1.00**
	White	**1.00**
A3 - tiles dimension	L < 20	**1.00**
	L ≥ 20	**0.80**
B1 - substrate	Masonry	**1.00**
	Concrete	**1.00**
B2 - peripherical joints	Yes	**1.00**
	No	**1.00**
B3 - peripherical protection	Yes	**1.00**
	No	**1.00**
C1 - level of execution	Adequate	**1.00**
	Inadequate	**0.80**
E1 - façade orientation	North	**1.00**
	East	**1.00**
	South	**1.00**
	West	**1.00**
E2 - wind/rain action	Mild	**1.20**
	Average	**1.00**
	Severe	**1.00**
E3 - distance from the sea	< 1 km	**1.00**
	> 1 and < 5 km	**1.00**
	> 5 km	**1.20**
E4 - humidity	High	**0.80**
	Low	**1.00**
G1 - regular mantainance	Yes	**1.20**
	No	**1.00**
G2 - easie of inspection	Current	**1.00**
	Unfavourable	**1.00**

Scenario 5

Scenario 5 follows the same concept as scenario 4; in this case, the values assigned to each sub-factor are not taken from ISO 15686, but consist of 0.9, 1 and 1.1. Results are shown in Table 5.14. The aim is to analyse the influence of small factors' variations on the degradation process affecting the ceramic façades.

Table 5.14 - Values obtained in scenario 5

Factors	Sub-factors	Final values
A1 – surface	Glazed	**1.00**
	Not glazed	**0.90**
A2 – color	Light	**1.00**
	Dark	**1.00**
	White	**1.00**
A3 - tiles dimension	L < 20	**1.00**
	L ≥ 20	**0.90**
B1 - substrate	Masonry	**1.00**
	Concrete	**1.00**
B2 - peripherical joints	Yes	**1.00**
	No	**1.00**
B3 - peripherical protection	Yes	**1.00**
	No	**1.00**
C1 - level of execution	Adequate	**1.00**
	Inadequate	**0.90**
E1 - façade orientation	North	**0.90**
	East	**1.00**
	South	**1.00**
	West	**1.00**
E2 - wind/rain action	Mild	**1.10**
	Average	**1.00**
	Severe	**1.00**
E3 - distance from the sea	< 1 km	**1.00**
	> 1 and < 5 km	**1.00**
	> 5 km	**1.10**
E4 - humidity	High	**0.90**
	Low	**1.10**
G1 - regular mantainance	Yes	**1.10**
	No	**1.00**
G2 - easie of inspection	Current	**1.00**
	Unfavourable	**1.00**

Scenario 6

The last scenario concerns an optimized assignment of the values to the various sub-factors. This manual iteration considers numbers to the third decimal place, in order to highlight even the minimal variation of results depending on the multiplier factors that are part of the factor method formula. Once again, the point of reference for such adjustment is represented by the k values previously obtained and the target is the maximization of the statistical indicators listed above. Table 5.15 shows the conferred weighting values assigned. Instead, Table 5.16 reports the calculation of the FM/GM ratios concerning the first five claddings of the sample; such ratios have been considered for the statistical analyses mentioned above.

Table 5.15 - Values obtained in scenario 6

Factors	Sub-factors	Final values
A1 - surface	Glazed	**1.050**
	Not glazed	**0.850**
A2 - color	Light	**1.000**
	Dark	**1.000**
	White	**1.025**
A3 - tiles dimension	L < 20	**1.000**
	L ≥ 20	**0.800**
B1 - substrate	Masonry	**1.000**
	Concrete	**1.000**
B2 - peripherical joints	Yes	**1.025**
	No	**1.000**
B3 - peripherical protection	Yes	**1.000**
	No	**1.000**
C1 - level of execution	Adequate	**1.000**
	Inadequate	**0.500**
E1 - façade orientation	North	**0.950**
	East	**1.000**
	South	**1.050**
	West	**1.050**
E2 - wind/rain action	Mild	**1.125**
	Average	**1.000**
	Severe	**0.975**
E3 - distance from the sea	< 1 km	**0.925**
	> 1 and < 5 km	**0.950**
	> 5 km	**1.050**
E4 - humidity	High	**0.900**
	Low	**1.050**
G1 - regular mantainance	Yes	**1.350**
	No	**1.000**
G2 - easie of inspection	Current	**1.000**
	Unfavourable	**0.950**

Table 5.16 - Example of the application of scenario 6

Code	RSL	A1	A2	A3	B1	B2	B3	C1	E1	E2	E3	E4	G1	G2	ESL Factor Method	ESL Graphical Method	FM/GM
Ed. 1	51	1.05	1.00	1.00	1.00	1.03	1.00	1.00	1.05	0.98	0.93	0.90	1.00	0.95	44.4	43.5	**1.022**
Ed. 2	51	1.05	1.00	1.00	1.00	1.00	1.00	1.00	0.95	0.98	0.93	0.90	1.00	0.95	39.2	58.5	**0.671**
Ed. 3	51	0.85	1.00	1.00	1.00	1.00	1.00	1.00	0.95	0.98	0.93	0.90	1.00	0.95	31.8	34.0	**0.934**
Ed. 4	51	1.05	1.00	1.00	1.00	1.00	1.00	1.00	1.05	1.00	1.05	1.05	1.35	0.95	79.5	49.0	**1.623**
Ed. 5	51	1.05	1.00	1.00	1.00	1.00	1.00	1.00	1.05	1.00	0.93	0.90	1.00	0.95	44.5	76.0	**0.585**

5.4.2 Results discussion

Table 5.17 resumes the statistical results obtained after the factor method application. It is about the analyses performed on the ESL values that have been calculated for each element of the sample. The output of the scenarios has been analysed separately:

- Scenario 1 shows the worst statistical result: many criteria are not fulfilled. The cause can be found in the fact that some k values have been applied based on the age trends calculated for variables with very few elements that are not statistically significant;

- Scenario 2 features slightly better results, although these cannot be considered satisfactory. Only one criterion is not respected (FM/GM ≥ 0.85 equal to 33.85%). The reason for such improvement is that generally the outcomes of the degradation curve charts feature a smaller change with age than the graphical method. Therefore, the influence of some sub-factors, which are not completely reliable, is lower, allowing achieving a more suitable result;
- Surprisingly, the third scenario has given rather good outcomes in terms of FM/GM ratio percentages: the values within the 15% acceptance range are 36.41% of the total. This is a clear index of how the weighting coefficient values that maximize the outcomes enhancement are close to 1.00, whereas many values conferred in the previous scenarios feature a conspicuous trend (e.g. high humidity exposure's coefficient has been evaluated 0.65 in scenario 1);
- Scenario 4 applies the coefficients given by ISO 15686 (0.8, 1 and 1.2). Results are good: this scenario has the lowest standard deviation, as seen in Table 5.16. Also the percentage of elements with a ratio FM/GM included in the range 0.85 - 1.15 is the second highest (45.64%);
- Significant are also the outcomes of scenario 5, concerning the assignment of a narrower range of values (0.9, 1 and 1.1). In this case, the highest percentage of elements featuring a ratio FM/GM greater than 0.85 has been achieved (69.23%). Such outcomes shows how both scenarios 4 and 5 turn out to be reliable and how the best weighting coefficients set should be something in between those iterations;
- This is exactly what has been done in scenario 6: the adjustment of the values has led to finding the best results in terms of ratios FM/GM < 1.05 (1.003), FM/GM ≥ 0.85 (69.23%) and FM/GM between 0.85 and 1.15 (47.69%).

Table 5.17 - Statistical analysis of the scenarios results

Scenarios		1	2	3	4	5	6
FM/GM average (< 1.05)		0.737	0.747	1.039	0.978	1.033	**1.003**
Standard deviation FM/GM		0.524	0.315	0.313	**0.287**	0.289	0.291
Amplitude of results	FM (years) (< GM)	148.13	69.14	0.00	56.78	37.89	58.32
	GM (years)	74.50	93.00	74.50	74.50	74.50	74.50
Extremes values FM	Max. (< 106 years)	156.22	83.65	51.00	88.08	74.70	89.70
	Min. (> 13.25 years)	8.09	14.51	51.00	31.30	36.81	31.38
FM/GM ≥ 0.85 (> 50%)		33.33%	33.85%	66.67%	64.10%	**69.23%**	**69.23%**
FM/GM ≥ 1.50 (< 10%)		8.21%	**1.54%**	5.13%	5.64%	7.18%	5.64%
0.85 ≤ FM/GM ≤ 1.15		14.87%	22.05%	36.41%	45.64%	41.54%	**47.69%**

The outcomes listed above can be considered globally satisfactory. The percentage values achieved by Gaspar (2009) and Emídio (2012) are similar to those obtained in the current work. The current studies also proved how the most reliable coefficient set has been achieved with the last iteration, which manually improves the weighting factors and minimize large deviations. Nevertheless, considering the results of Emídio (2012), better statistical outcomes have been reached for the application of ISO 15686. In fact, the author's second best percentage outcome has been reached with scenario 3 (assignment of the value of 1.00 to all the variables). Instead, the current work has found out how the values set given by the ISO norm can lead to a statistically significant outcome. However, one aspect must be noticed: the majority of sub-factor had a weighting coefficient equal to 1.00, especially in scenario 4 and scenario 5. In fact, assigning too many values equal to 0.8 and 1.2 would have reduced the reliability of ESL calculation. This means that some of the variables affect only slightly the claddings' loss of performance; for this reason, the survey concerning some of them has not been as conclusive as expected.

5.5 Conclusion

The current chapter represents the final step of the dissertation; the conclusions drawn from it are considered satisfactory, validating the work performed. Concerning the path followed, the goals stated in the introduction have been achieved.

More in detail, the preliminary study on tracing the degradation curve for each point of the chart has led to evaluating the expected service life for all the elements of the sample. This has allowed plotting a graph that shows the correlation between service life and time. The analysis of this result, according to the variables affecting the loss of performance of the component, led to the evaluation of an average service life value for each factor. Then, based on these outcomes (Table 5.2) and the ones regarding the overall degradation severity (Table 5.6) an indicative set of weighting coefficients has been identified. At this point, the factor method calculation has been applied; RSL has been obtained from the ratio ESL/weighting coefficients. Once the reference service life was calculated, the factor method has been applied again to all the sample's elements. This time, the aim was improving the weighting sub-factors values. Therefore, six scenarios have been studied, leading to the above discussed results.

In conclusion, the factor method application has allowed the evaluation of the reference service life (51 years) of ceramic external façades and the examination of many multiplying coefficients set. In particular, regarding such scenarios, two aspects have to be noticed:

- As expected, the best weighting coefficients combination has been reached with scenario 6, which concerns the optimization of values;
- In addition to this, the use of the values in compliance with ISO 15686 yielded better global results than Emídio (2012).

These considerations seem to testify the reliability of the factor method. In fact, despite the intrinsic limitations that characterize such methodology, the current dissertation has evidenced how its application on a sufficiently consistent sample can lead to significant results.

6 CONCLUDING REMARKS

6.1 Final considerations

In this section the main results of the dissertation have been synthesized. In terms of the steps that allowed reaching these results, the entire work performed was summarized, focusing on the most interesting findings of each stage. In addition to this, this study has brought to light some aspects worth being analysed more in-depth. For this reason, after discussing the outcomes obtained, a summary of possible developments regarding these aspects was done.

As stated, the dissertation falls within the line of research developed by Gaspar (2002, 2009), Sousa (2008), Silva (2009), Emídio (2012) and Ximenes (2012), concerning the service life prediction of buildings components based on field work data. In particular, Emídio (2012) applied the factor method to the service life evaluation of natural stone claddings, whereas Sousa (2008) dealt with service life of ceramic claddings. As the methodologies applied by these authors have proved to be effective in achieving the preset purposes, a similar approach was maintained in this study.

In addition to this, the aforementioned researches ascertained the importance of the service life prediction of building components. In fact, as mentioned in the introduction, proper knowledge on the durability of a component allows correctly designing the details and planning the maintenance operations that the component requires. These in turn are part of a broader perspective which involves reductions in costs and environmental impact: exactly the challenges that service life prediction proposes to overcome. Aware of the benefit of this work, this dissertation has set as its goal to deepen the knowledge concerning the durability of ceramic external walls.

In general, the goal stated was achieved, namely evaluating the Expected Service Life of the façades of the sample collected. In fact, factor method was applied, leading to fairly consistent outcomes.

6.2 General conclusions

This dissertation consists on four main stages, which are briefly discussed: information collection, field work and its prior preparation, application of degradation model and application of factor method.

The first stage regards a literature review, which has the purpose of enhancing the knowledge on direct adhered ceramic claddings and service life prediction. These subjects were debated at the beginning of the dissertation. At first, the concept of service life was examined, with particular attention to the factor method. Such attention is due to the fact that this study is the first approach to factor method application to ceramic exterior façades. The equation of the method is as follows (ISO 15686):

$$ESL = RSL \cdot A \cdot B \cdot C \cdot D \cdot E \cdot F \cdot G \quad \text{Equation 6.1}$$

Where:

ESL Estimated service life;

RSL Reference service life;

A Factor related to the quality of the materials;

B Factor related to the design level;

C Factor related to the execution level;

D Factor related to the interior environmental conditions;

E Factor related to the exterior environmental conditions;

F Factor related to the in-use conditions;

G Factor related to the level of maintenance.

At this point, the technology and pathology of ceramic claddings have been analysed, leading to the classification of the possible anomalies affecting ceramic claddings and the related causes. Table 6.1 shows the result of this categorization. In addition to this, defects have been rated according to their severity and their extent on the façade, setting five levels of degradation. Concerning the appraisal of the cladding system's components, particular attention was paid to the aspect of design, which represents one of the main causes of deterioration.

Table 6.1 - Pathology classification for ceramic external wall claddings

Anomalies	
Aesthetic defects	Superficial dirt Degradation (scratches) Edge crushing Small spots on the surface Humidity stains Biological growth Change in brightness and/or colour Efflorescences
Cracking	Glazing cracking Cracking without predominant direction Cracking with marked direction
Joint deterioration	Staining or change in colour Without loss of material in joints With loss of material in joints
Adhesion failure	Adhesive failure Arching Detachment

After defining the theoretical and technical foundations of the study, the outcomes of the work of Sousa (2008) were considered. As mentioned above, the author dealt with the evaluation of the degradation process affecting ceramic external cladding, in order to determine its average service life. As this work continues this line of research, the sample of Sousa (2008) was analysed. This author reached only partially satisfactory results: the reason is that some elements of the sample featured inadequate execution or deign errors, which make them not statistically significant. These claddings have been removed from the sample, obtaining more satisfactory statistical outcomes. As one can notice, the care that the aspects of design and execution require already emerged in this section.

Then, a characterization of the new sample was carried out; lacunas and shortages were highlighted, in order to define the data needed for a more complete research. The aspects considered during this phase correspond to the weighing coefficients of the factor method, i.e. the variables affecting the façades deterioration. At this point, *in situ* inspections were carried out. The claddings inspected were added to the sample of Sousa (2008), obtaining a 195 façades' sample. Statistical analyses on the field work's results close the section; this analysis showed how the purpose of narrowing the discrepancy of the sample of Sousa (2008) was achieved for most of the variables considered.

The third step of the work performed consists on the degradation model application. The methodology adopted was developed by Gaspar (2009). The author defined an equation that evaluates the overall deterioration of the cladding. The output of the calculation is a value named degradation severity ($S_{w,rp}$), which quantifies the qualitative information on the state of conservation of the façades. Such values allowed plotting a graph that shows the loss of performance of the claddings over time (Figure 6.1). As mentioned, the previous review on ceramic cladding system led to classifying the anomalies affecting it. This classification was used to establish the limit state of service life of this study, relating performance requirements and façades' state of conservation. The limit was set at level 3 (moderate deterioration), which corresponds to $S_{w,rp}$ = 20%. Figure 6.1 shows this threshold: the intersection of the average degradation curve with level 3 indicates the value of the expected service life for ceramic external cladding, which was set at 50 years.

Then, results were analysed according to all the variables that condition the durability of the component, leading to satisfying results in most of the cases. Once again, the basis for this classification is represented by the factor method's multiplying coefficients.

Besides the model just applied, Gaspar (2009) developed also an equation that allows determining the service life of all the elements of the sample. The application of this formula led to plotting another chart, which shows the expected service life values' distribution over time (Figure 6.2). In this case, the average predicted service life value of the elements of the sample is 53 years. These data confirms the one previously evaluated; in fact, the difference between these values is minimal (50 and 53 years). This fact, together with the statistical significance of the outcomes, is a proof of their reliability.

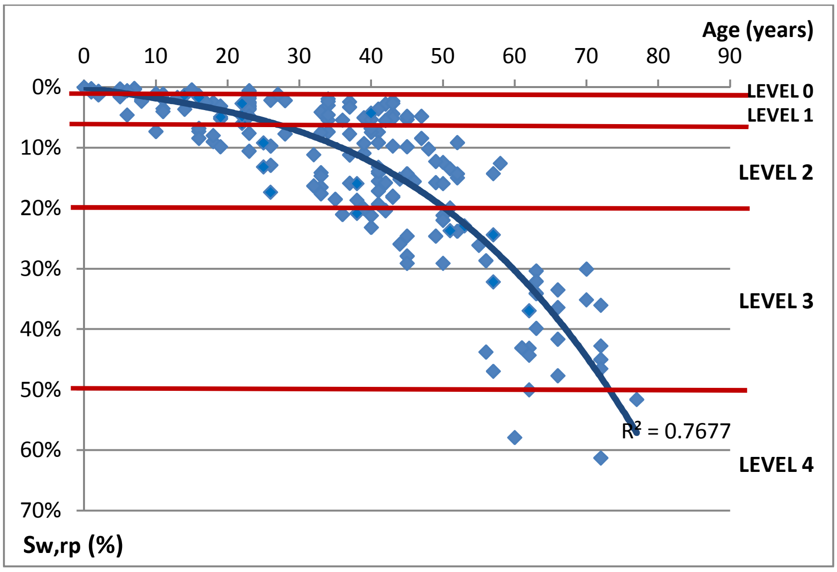


Figure 6.1 - Overall degradation evolution (Gaspar, 2009)

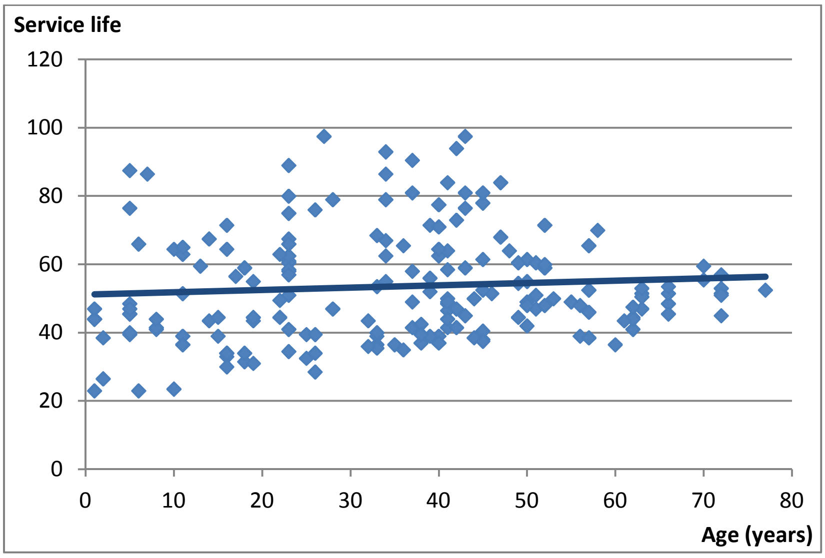


Figure 6.2 - Service life distribution over time

Also this step has been followed by the outcomes' survey, according to the variables previously defined. Results were satisfactory, and in general, they confirmed the ones obtained by the degradation curves analyses. More in detail, the factors that in both cases led to the clearest outputs are distance from the sea, atmospheric agents' action, humidity exposure, tiles' size, substrate type, maintenance level and execution level. Instead, orientation of the façade, tiles colour and surface, existence of peripheral joints and protection and ease of inspection gave inconsistent outcomes. Among the variables' analyses, it was chosen to report two of the most significant.

The first one regards maintenance. Figures 6.3 and 6.4 show how a regular upkeep results in a slower degradation process. The degradation curve (Figure 6.3) concerning maintained façades is higher and seems to even altogether stop the deterioration effects in the first years of life. Concerning the service life distribution over time, the separation between the regression lines is clear.

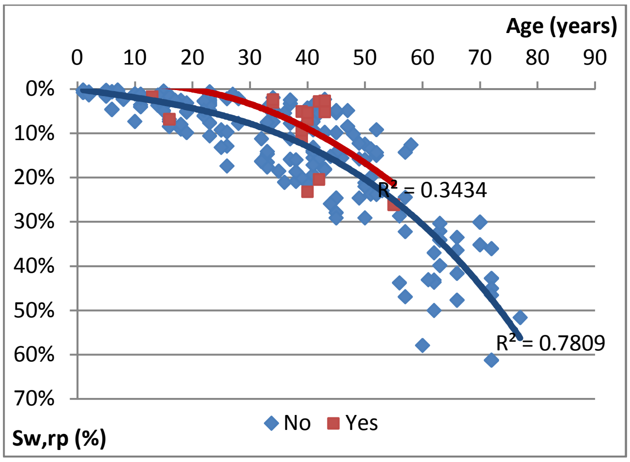


Figure 6.3 - Overall degradation curve according to the maintenance level

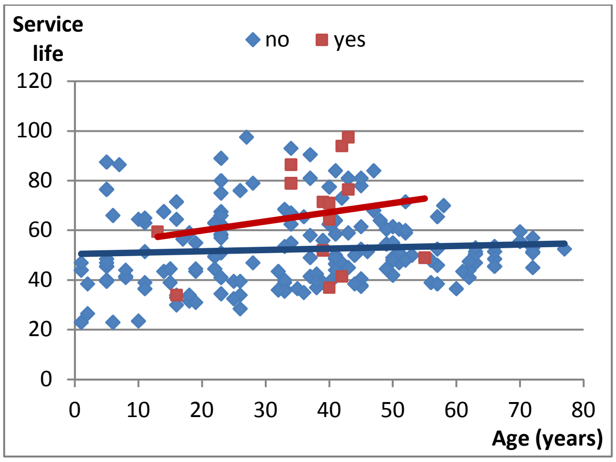


Figure 6.4 - Service life distribution over time according to the maintenance level

Also the outcomes according to the level of execution are worth being analysed in further detail. The fact that inadequate design and installation drastically reduces the expected life of the component is corroborated by Figures 6.5 and 6.6. It clearly emerges how these aspects play a fundamental role on the cladding lifetime: service life expectancy for façades featuring a proper execution is twice that of the others.

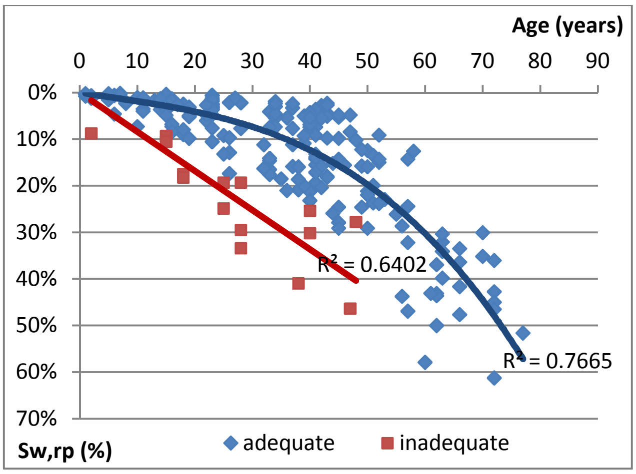


Figure 6.5 - Overall degradation curve according to the execution level

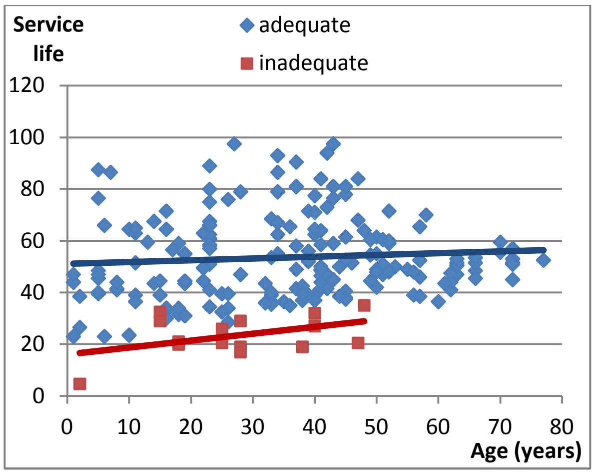


Figure 6.6 - Service life distribution over time according to the execution level

In general, these graphs proved how ceramic external cladding is a durable cladding system, only if it is accurately maintained and, above all, designed and installed. In addition to this, the models of Gaspar (2009) proved to be effective tools to describe the degradation evolution of building components

6.2.1 Factor method application

Finally, the factor method was applied to the sample.

This section consisted on two steps. At first, the Reference Service Life was evaluated; then, different weighting coefficients combinations were studied for the factors that compose the method’s formula, in order to optimize their assignment.

Because of its basic importance, RSL was calculated as the average of three values; the aim was to make it as reliable as possible. For these reasons, some preliminary operations were carried out, taking into account the variables that influence the degradation evolution of the claddings and that were the basis of the previous graphical analyses. Such variables were classified according to the multiplying factors of the factor method: Table 6.2 shows the categorization.

Table 6.2 - Variables’ categorization according to the factor method

A - material’s quality, finishing, or treatment	
A1 - surface	Glazed Not glazed
A2 - color	Light Dark White
A3 - tiles dimension	L < 20 L ≥ 20
B - characteristic of the design	
B1 - substrate	Masonry Concrete
B2 - peripheral joints	Yes No
B3 - peripheral protections	Yes No
C - characteristic of execution on site	
C1 - level of execution	Adequate Inadequate
D - indoor environmental conditions	

E - outdoor environmental conditions	
E1 - façade orientation	North East South West
E2 - wind/rain action	Mild Average Severe
E3 - distance from the sea	< 1 km > 1 and < 5 km > 5 km
E4 - humidity	High Low
F - construction’s conditions of use	
G - maintenance level	
G1 - regular maintenance	Yes No
G2 - ease of inspection	Current Unfavourable

Subsequently, a weighing value was conferred to each of them, in order to weight their influence on the claddings’ loss of performance. The coefficients assigned are 0.8, 0.9, 1, 1.1 and 1.2, according to the variable’s low or high severity: depending on whether the sub-factor indicates a condition more or less favourable, a value more or less high was conferred. The point of reference for this set consisted on the outcomes of the previous graphical analyses, concerning the degradation evolution. Once the factors were weighted, the factor method was inversely applied to each element of the sample, as shown in Equation 6.2:

$$ESL = RSL \cdot A \cdot B \cdot C \cdot D \cdot E \cdot F \cdot G \quad \rightarrow \quad RSL = \frac{ESL}{A \cdot B \cdot C \cdot D \cdot E \cdot F \cdot G} \quad \rightarrow \quad RSL = \frac{ESL}{0.8^x \cdot 0.9^y \cdot 1.1^z \cdot 1.2^k}$$

Where: Equation 6.2

ESL 50 years;

x number of occurrences of 0.8;

y number of occurrences of 0.9;

z number of occurrences of 1.1;

k number of occurrences of 1.2.

The results obtained through Equation 6.2 served to obtain the final RSL value, which was used for further application of the factor method. In fact, as mentioned, RSL was calculated as the average of three values, as follows:

- 50 years - Average expected service life given by the degradation model of Gaspar (2009);
- 51 years - Average of the RSL values obtained by Equation 6.2, concerning the elements that feature all the sub-factors equal to 1 (standard conditions);
- 53 years - Average of the RSL values obtained by Equation 6.2, concerning the elements that feature ESL/RSL ratio's standard deviation < 3%.

The Reference Service Life for ceramic wall claddings was found to equal 51 years. The three values used (50, 51 and 53 years) are hardly different; this coherence is an evidence of the validity of the findings achieved so far.

At this point, six scenarios were studied in order to improve the accuracy of the weighting multiplying factors. Each scenario is the result of a different iteration, and features a different coefficients set.

The principles that led to the assignment of the values are listed in Table 6.3. Afterwards, the factor method was applied six times to the sample's elements, each time featuring the weighting coefficients' set from a different scenario.

Statistical analyses on the ESL values obtained were performed, leading to the outcomes shown in Table 6.4. Within the various statistical indicators, the main aim was to maximize the percentage of values FM/GM close to 1.00; FM/GM is the ratio between the ESL values obtained through the Factor Method and the outcomes of the Graphical Method. The closer the ratio's value is to 1.00, the closer the outcome is to reality. These percentages can be seen in the last row of Table 6.4. The best results are highlighted in blue.

Table 6.3 - Scenarios' characterization

Scenario 1	It takes into account the average service life value obtained from Figure 6.2 (53 years). A difference of 0.05 from 1.00 has been assigned for every year of difference between the service life of each variable and the average
Scenario 2	It takes into account the average service life value obtained from Figure 6.1 (50 years). A difference of 0.05 from 1.00 has been assigned for every year of difference between the service life of each variable and the average
Scenario 3	A weighting value equal to 1.00 has been conferred to all the sub-factors
Scenario 4	The values conferred are 0.80, 1, and 1.20, based on ISO 15686; the age differences evaluated in scenarios 1 and 2 have been used as a point of reference
Scenario 5	The values conferred are 0.90, 1, and 1.10; the age differences evaluated in scenarios 1 and 2 have been used as a point of reference
Scenario 6	It consists on an optimized manual assignment of the values to the various sub-factors

Table 6.4 - Statistical analysis of the scenarios results

Scenarios		**1**	**2**	**3**	**4**	**5**	**6**
FM/GM average (< 1.05)		0.737	0.747	1.039	0.978	1.033	**1.003**
Standard deviation FM/GM		0.524	0.315	0.313	**0.287**	0.289	0.291
Amplitude of results	FM (years) (< GM)	148.13	69.14	0.00	56.78	37.89	58.32
	GM (years)	74.50	93.00	74.50	74.50	74.50	74.50
Extremes values FM	Max. (< 106 years)	156.22	83.65	51.00	88.08	74.70	89.70
	Min. (> 13.25 years)	8.09	14.51	51.00	31.30	36.81	31.38
FM/GM ≥ 0.85 (> 50%)		33.33%	33.85%	66.67%	64.10%	**69.23%**	**69.23%**
FM/GM ≥ 1.50 (< 10%)		8.21%	**1.54%**	5.13%	5.64%	7.18%	5.64%
0.85 ≤ FM/GM ≤ 1.15		14.87%	22.05%	36.41%	45.64%	41.54%	**47.69%**

In general, Scenarios 1 and 2 obtained the worst results in terms of percentage; the reason is that many sub-factors feature a wide difference between their expected service life and the average value. This leads to assigning too scattered weighting coefficients (until 1.55), which lead to unrealistic ESL values.

Surprisingly, scenario 3 showed better outcomes, confirming that the optimised coefficients set should be closer to the standard conditions (1.00).

Instead, scenarios 4, 5 and 6 gave the best results in terms of statistical percentages. In particular, the manual iteration of Scenario 6 (Table 6.5) led to the highest percentage of ratios FM/GM within the range 0.85-1.15. It can be noticed that the optimised assignment of weighting coefficients yielded 47.69% ESL values which are fairly close to reality, representing for this reason a rather satisfactory outcome.

Furthermore, another significant outcome was achieved using the coefficients proposed by ISO standard (scenario 4): these led to the second highest percentage (45.64%). In this way, factor method proved to be a practical and, above all, effective tool to estimate the service life of a building component in specific conditions.

Table 6.5 - Values obtained in scenario 6

Factors	Sub-factors	Final value	Factors	Sub-factors	Final value
A1 - surface	Glazed Not glazed	1.050 0.850	E1 - façade orientation	North East South West	0.950 1.000 1.050 1.050
A2 - color	Light Dark White	1.000 1.000 1.025	E2 - wind/rain action	Mild Average Severe	1.125 1.000 0.975
A3 - tiles dimension	L < 20 L ≥ 20	1.000 0.800	E3 - distance from the sea	< 1 km > 1 and < 5 km > 5 km	0.925 0.950 1.050
B1 - substrate	Masonry Concrete	1.000 1.000			
B2 - peripherical joints	Yes No	1.025 1.000	E4 - humidity	High Low	0.900 1.050
B3 - peripherical protection	Yes No	1.000 1.000	G1 - regular mantainance	Yes No	1.350 1.000
C1 - level of execution	Adequate Inadequate	1.000 0.500	G2 - easie of inspection	Current Unfavourable	1.000 0.950

6.3 Future developments

After reviewing the dissertation stages and discussed the results achieved, a review of the possible future development about this subject has been carried out. In fact, this work constitutes the first application of the factor method to the prediction of service life of direct adhered ceramic façades. Therefore, it is definitely possible to make improvements and progresses to this line of research. Among those that seemed more interesting and applicable in the short and medium term, some suggestions have been listed. They concern all the steps of the study, from data gathering to degradation evolution assessment; instead, factor method will be discussed separately.

- Despite being sufficiently complete and having resulted in significant outcomes for a fair number of variables, the sample collected may be enhanced. In fact, regarding some factors (e.g. façade orientation), results have been rather inconclusive. This leads to the need of further researches concerning such characteristics, in order to draw more statistically significant conclusions. In addition to this, more old façades may be added, in order to make the plotting of the degradation curve more reliable;
- The development of further studies on the influence of design and installation on the durability of ceramic claddings would be interesting. In fact, outcomes have clearly shown how these aspects considerably affect the service life of the building component. For this reason, a separate research

concerning façades characterized by execution errors and inadequate design may be made, for a better comprehension of the mechanisms that lead the component to a premature degradation;

- The study should be extended to other building components. In this way, models and methodologies applied in the current work may be validated and improved;
- It would be useful to identify the anomalies *in situ* with the aid of more advanced technologies. For instance, thermographic analyses may lead to a more reliable detection of some defects, adhesive failure above all;
- In the long term, it is important to create a database that provides information regarding design, maintenance and durability of building components. In this way, access to knowledge would be easier and more effective, as mentioned in the introduction. Something similar has been developed by CSTB and Politecnico of Milano: a database concerning the reference service life values for construction materials and components. This idea should be carried forward and completed with the addition of more information.
- It would be interesting to assign to each degradation mechanism an intervention strategy, and identify the associated repair costs, thus allowing a more objective and practical development of maintenance plans;
- Further studies may be performed on the type of ownership of the building. This would allow correlating the minimum requirements set (service life limit) with the different maintenance policies implemented. As done by Shohet and Paciuk (2004), the sample could be separated according to the use (e.g., residential and corporative buildings), in order to identify the reasons of the decision for intervention and determine more realistic requirements.

6.2.1 Factor method

The main suggestion concerning the factor method concerns the sub-factors: the set of the variables could be improved. This need comes from the fact that in some cases the multiplication of the coefficients results in values that overly increase or decrease RSL. This issue had been debated also by Emídio (2012). For example, taking into account the environmental outdoor conditions, four variables have been individualized: distance from the sea, façade orientation, humidity exposure and atmospheric agents' action. In the case of all favourable factors, the value of RSL would be 106 years (51*1.2*1.2*1.2*1.2), which is rather far from reality. The same would happen if all values were unfavourable.

The author suggested the development of a different approach to the sub-factors' correlation, determining weighting coefficients for each of them. In other words, a sort of variables rating based on the effectiveness of their influence on claddings deterioration.

In addition to this, an accurate review of the factors considered could also be useful. In fact, some of them have led to inconclusive results and may be excluded from the categorization. One example is peripheral joints and protection; the current survey has proved how they do not significantly affect the degradation evolution of the façade as a whole. For this reason, these factors may be excluded from the calculation.

Instead, other variables should be analysed; an example is materials, which may be inserted in the sub-factors classification. In fact, an incorrect choice of materials is one of the most common causes of degradation (Chapter 3). But, as mentioned, it is clearly difficult to obtain precise information. For this reason, such data may be supported by laboratory studies concerning performance and compatibility of tiles, bedding materials and joints grout. This would allow introducing the influence of materials' choice in the factor method application; together with others variables' analysis, this may lead to more significant outcomes.

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ANNEX 1 - INSPECTION SHEET

Inspection sheet nº: ______________________ Inspection date: ______________

Address: ____

Façade characterization

Orientation: N / S / W / E Year of conclusion: ______________

Façade type: Main Side Ceramic wall cladding area:

Material

Tiles dimension: ______________ Surface: ______________

Tiles colour:

Design

Substrate: ______________ Existence of joints: Peripheral Splitting Structural

Peripheral protections: Y / N Corner protections: Y / N

Environmental conditions

Pollution exposition: Y / N Wind/rain action: Severe Moderate Mild

Humidity exposition: High Low Sea distance: < 1 km > 1 km / < 5 km > 5 km

Maintenance level

Regular maintenance: Y / N Ease of inspection: Y / N

Anomalies

		Degradation level				% Area+	Localization*				Infiltrations	Causes / notes
		1	2	3	4		c	e	c	j		
Aesthetic defects	Superficial dirt											
	Degradation (scratches)											
	Edge crushing											
	Small spots on the surface											
	Humidity stains											
	Biological growth											
	Change in brightness and/or colour											
	Efflorescence											
Cracking	Glazing cracking											
	Cracking without predominant direction											
	Crack with marked direction											
Joint deterioration	Staining or change in colour											
	Without loss of material in joints											
	With loss of material in joints											
Adhesion failure	Adhesive failure											
	Arching											
	Detachment											

+ - width for cracks with marked direction

* - (p) centre; (e) edge; (c) corners; (j) adjoining the quartering joints or the structural joints

Notes:

ANNEX 2 - INSPECTION SHEET OF A CASE STUDY

Inspection sheet nº: 95 | Inspection date: 04 / 12 / 2012

Address: Rua Presidente Arriaga, 120-124

Façade characterization

Orientation: ~~N~~ / S ~~/ W / E~~ | Year of conclusion: 1956

Façade type: Main ~~Side~~ | Ceramic wall cladding area: 40 mq

Material

Tiles dimension: 13,5 x 13,5 | Surface: Glazed

Tiles colour: White & Colours

Design

Substrate: Masonry | Existence of joints: ~~Peripheral~~ ~~Splitting~~ ~~Structural~~

Peripheral protections: ~~Y /~~ N | Corner protections: ~~Y /~~ N

Environmental conditions

Pollution exposition: Y ~~/ N~~ | Wind/rain action: Severe ~~Moderate~~ ~~Mild~~

Humidity exposition: High ~~Low~~ | Sea distance: < 1 km ~~> 1 km / < 5 km~~ ~~> 5 km~~

Maintenance level

Regular maintenance: ~~Y /~~ N | Ease of inspection: Y ~~/ N~~

Anomalies

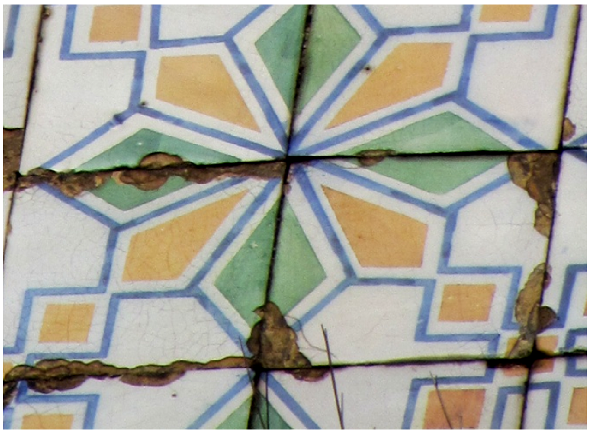
		Degradation level				% Area+	Localization*				Infiltrations	Causes / notes
		1	2	3	4		c	e	c	j		
Aesthetic defects	Superficial dirt	x				100%	x	x				
	Degradation (scratches)											
	Edge crushing		x			40%	x	e				
	Small spots on the surface			x		80%	x					
	Humidity stains											
	Biological growth											
	Change in brightness and/or colour											
	Efflorescence											
Cracking	Glazing cracking	x				75%	x					
	Cracking without predominant direction		x			1%	X					
	Crack with marked direction											
Joint deterioration	Staining or change in colour											
	Without loss of material in joints				x	50%	X					Fungus and biological growth
	With loss of material in joints				x	40%	X					
Adhesion failure	Adhesive failure		x			10%	x	x				
	Arching											
	Detachment											

+ - width for cracks with marked direction

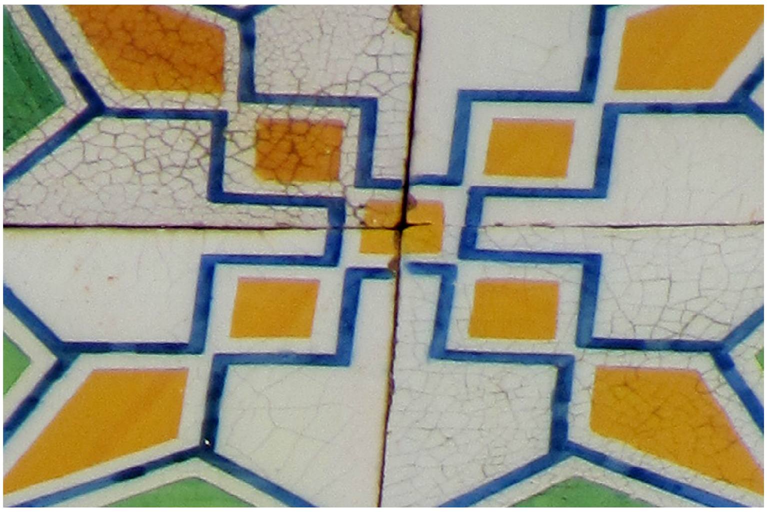
* - (p) centre; (e) edge; (c) corners; (j) adjoining the quartering joints or the structural joints

Notes:

PHOTOGRAPHIC RECORD


Edge crushing


Small spots on the surface


Glazing cracking


Cracking without predominant direction


Joint deterioration without loss of material


Joint deterioration with loss of material

ANNEX 3 - CHARACTERIZATION OF THE CLADDINGS STUDIED

Building identification								Facade characterization						Joints			Design		Ambiental conditions			
Code	Address	Freguesia	Year of conclusion	Age	Repaired	Regular mant.	Structure	Facade orient.	Facade type	CWT area	Tiles dimension	Surface	Tiles color	Periph.	Splitting	Struct.	Periph. protection	Corner protection	Pollution exposition	Wind action	Humidity exp.	Sea distance
Ed. 1	Rua Antonio Maria Cardoso, 3	Mártires	1998	14	N	N	Concrete	S	Side	205	14x14	Glazed	Grey	Y	N	N	N	N	Y	Severe	High	< 1 km
Ed. 2	Rua Presidente Arriaga, 29	Prazeres	1898	41	Y	N	Masonry	N	Main	70	14x14	Glazed	Colorful	N	N	N	Y	N	Y	Severe	High	< 1 km
Ed. 3	Calçada Ribeiro Santos, 1-5	Santos-o-Velho	1918	26	Y	N	Masonry	N	Main	300	14x14	Not glazed	Colorful	N	N	N	Y	N	Y	Severe	High	< 1 km
Ed. 4	Av. Estados Unidos da America, 50-54	Alvalade	1957	55	N	Y	Concrete	W	Side	135	15x15	Glazed	Colorful	N	N	N	Y	N	Y	Moderate	Low	> 5 km
Ed. 5	Rua Antonio Taborda, 30-34	Prazeres	1928	26	Y	N	Masonry	W	Main	70	14x14	Glazed	White&Color	N	N	N	Y	N	Y	Moderate	High	< 1 km
Ed. 6	Avenida Gomes Pereira, 61	Benfica	1965	47	N	N	Concrete	W	Main	78	10x15	Glazed	Orange	N	N	N	Y	N	Y	Moderate	Low	> 5 km
Ed. 7	Rua Abade Faria, 16	Alto da Pina	1921	46	Y	N	Masonry	W	Main	8.5	14x14	Glazed	Colorful	Y	N	N	Y	N	Y	Moderate	Low	> 1 e < 5 km
Ed. 8	Rua Sabino de Sousa, 39	São João	1907	10	Y	N	Masonry	E	Main	40	15x15	Not glazed	White&Color	N	N	N	Y	N	Y	Mild	Low	> 1 e < 5 km
Ed. 9	Rua Sabino de Sousa, 67	São João	1908	18	Y	N	Masonry	E	Main	37	14x14	Glazed	White&Color	N	N	N	Y	N	Y	Mild	Low	> 1 e < 5 km
Ed. 10	Rua Sabino de Sousa, 112	São João	1911	27	Y	N	Masonry	W	Main	60	15x15	Glazed	White&Color	N	N	N	Y	N	Y	Mild	Low	> 1 e < 5 km
Ed. 11	Rua Luis Pastor de Macedo, 28	Lumiar	1978	34	N	Y	Concrete	N	Side	9.5	25x25	Glazed	White&Color	N	N	N	N	N	N	Mild	Low	> 5 km
Ed. 12	Rua Luis Pastor de Macedo, 28	Lumiar	1978	34	N	N	Concrete	W	Main	11.5	15x15	Glazed	Green	N	N	N	N	N	N	Moderate	Low	> 5 km
Ed. 13	Rua Luis Pastor de Macedo, 30	Lumiar	1978	34	N	Y	Concrete	N	Side	9.5	25x25	Glazed	White&Color	N	N	N	N	N	N	Mild	Low	> 5 km
Ed. 14	Rua Luis Pastor de Macedo, 30	Lumiar	1978	34	N	N	Concrete	W	Main	11.5	15x15	Glazed	Green	N	N	N	N	N	N	Moderate	Low	> 5 km
Ed. 15	Rua Luis Pastor de Macedo, 32	Lumiar	1978	34	N	Y	Concrete	N	Side	9.5	25x25	Glazed	White&Color	N	N	N	N	N	N	Mild	Low	> 5 km
Ed. 16	Rua Luis Pastor de Macedo, 32	Lumiar	1978	34	N	N	Concrete	W	Main	11.5	15x15	Glazed	Green	N	N	N	N	N	N	Moderate	Low	> 5 km
Ed. 17	Rua Luis Pastor de Macedo, 5	Lumiar	1971	41	N	N	Concrete	W	Main	125	15x15	Glazed	Green	N	N	N	Y	N	N	Moderate	Low	> 5 km
Ed. 18	Avenida da Igreja, 60	Campo Grande	1961	6	Y	N	Concrete	S	Main	35	8x24	Not glazed	Brown	N	N	N	Y	N	Y	Moderate	High	> 5 km
Ed. 19	Avenida do Brasil, 122	São João de Brito	1958	39	Y	Y	Concrete	N	Main	80	14x14	Glazed	Yellow	N	Y	N	N	N	Y	Severe	Low	> 1 e < 5 km
Ed. 20	Avenida do Brasil, 122	São João de Brito	1958	39	Y	Y	Concrete	S	Main	80	14x14	Glazed	Yellow	N	Y	N	N	N	Y	Severe	Low	> 1 e < 5 km
Ed. 21	Avenida do Brasil, 120	São João de Brito	1958	43	Y	Y	Concrete	E	Side	295	14x14	Glazed	Yellow	N	Y	N	N	N	Y	Severe	Low	> 1 e < 5 km
Ed. 22	Avenida do Brasil, 120	São João de Brito	1958	43	Y	Y	Concrete	W	Side	295	14x14	Glazed	Yellow	N	Y	N	N	N	Y	Severe	Low	> 1 e < 5 km
Ed. 23	Rua Inocêncio Francisco da Silva, 24	São Domingos de Benfica	1993	19	N	N	Concrete	S	Main	125	7.5x23	Not glazed	Brown	N	N	N	N	N	Y	Moderate	Low	> 5 km
Ed. 24	Rua Inocêncio Francisco da Silva, 24	São Domingos de Benfica	1993	19	N	N	Concrete	N	Main	30	7.5x23	Not glazed	Brown	N	N	Y	N	N	Y	Mild	Low	> 5 km
Ed. 25	Rua das Chagas 1-3	São Paulo	1887	66	Y	N	Masonry	S	Side	50	13.5x13.5	Glazed	White&Color	Y	N	N	N	N	N	Severe	High	< 1 km
Ed. 26	Rua das Chagas 1-3	São Paulo	1887	66	Y	N	Masonry	N	Side	47.5	13.5x13.5	Glazed	White&Color	Y	N	N	N	N	N	Severe	High	< 1 km
Ed. 27	Rua das Chagas 1-3	São Paulo	1887	66	Y	N	Masonry	E	Main	100	13.5x13.5	Glazed	White&Color	Y	N	N	N	N	Y	Severe	High	< 1 km
Ed. 28	Rua Prof. Fernando da Fonseca, 23	Lumiar	1996	16	N	N	Concrete	N	Main	15	8x24	Not glazed	Beige	Y	N	N	Y	N	Y	Moderate	Low	> 5 km
Ed. 29	Rua Prof. Fernando da Fonseca, 23	Lumiar	1996	16	N	N	Concrete	W	Side	4.5	8x24	Not glazed	Beige	Y	N	N	Y	N	Y	Moderate	Low	> 5 km
Ed. 30	Rua Prof. Fernando da Fonseca, 23	Lumiar	1996	16	N	N	Concrete	E	Side	4.5	8x24	Not glazed	Beige	Y	N	N	Y	N	Y	Moderate	Low	> 5 km
Ed. 31	Calçada São Vicente, 87	São Vicente de Fora	unav.	19	Y	N	Masonry	E	Main	17.5	15x15	Glazed	White&Color	Y	N	N	Y	N	Y	Moderate	High	< 1 km
Ed. 32	Calçada São Vicente, 41-43	São Vicente de Fora	1910	11	Y	N	Masonry	E	Main	40	15x15	Glazed	White&Color	Y	N	N	Y	N	Y	Moderate	High	< 1 km
Ed. 33	Rua das Escolas Gerais, 61	São Miguel	1903	50	Y	N	Masonry	N	Main	14	13.5x13.5	Glazed	White&Color	N	N	N	N	N	Y	Severe	High	< 1 km
Ed. 34	Rua das Escolas Gerais, 57-59	São Miguel	1878	49	Y	N	Masonry	N	Main	25	13.5x13.5	Glazed	White&Color	N	N	N	Y	N	Y	Severe	High	< 1 km
Ed. 35	Rua de Saudade, 43	Santiago	1885	45	Y	N	Masonry	E	Main	12.5	16x16	Glazed	White&Color	N	N	N	Y	N	Y	Severe	High	< 1 km
Ed. 36	Rua de Saudade, 45	Santiago	1885	45	Y	N	Masonry	E	Main	10.5	15x15	Glazed	White&Color	Y	N	N	Y	N	Y	Severe	High	< 1 km
Ed. 37	Rua de Saudade, 45	Santiago	1885	45	Y	N	Masonry	N	Main	20	15x15	Glazed	White&Color	Y	N	N	Y	N	Y	Severe	High	< 1 km
Ed. 38	Rua de Saudade, 3	Sé	1889	16	Y	Y	Masonry	N	Side	105	15x15	Glazed	White&Color	N	N	N	Y	N	Y	Severe	High	< 1 km
Ed. 39	Rua de Saudade, 1	Sé	1889	16	Y	N	Masonry	E	Main	12	15x15	Glazed	White&Color	N	N	N	Y	N	Y	Severe	High	< 1 km
Ed. 40	Rua Augusto Rosa, 2-12	Sé	1889	45	Y	N	Masonry	S	Main	55	15x15	Glazed	White&Color	N	N	N	Y	N	Y	Severe	High	< 1 km
Ed. 41	Rua São Mamede, 11	Sé	1938	66	Y	N	Masonry	N	Main	25	13x13	Glazed	White&Color	N	N	N	Y	N	Y	Severe	High	< 1 km

Building identification								Facade characterization						Joints			Design		Ambiental conditions			
Code	Address	Freguesia	Year of conclusion	Age	Repaired	Regular mant.	Structure	Facade orient.	Facade type	CWT area	Tiles dimension	Surface	Tiles color	Periph.	Splitting	Struct.	Periph. protection	Corner protection	Pollution exposition	Wind action	Humidity exp.	Sea distance
Ed. 42	Rua Regedor, 5	Madalena	1905	18	Y	N	Masonry	W	Main	28	13x13	Glazed	Black&Blue	N	N	N	Y	N	Y	Moderate	High	< 1 km
Ed. 43	Rua Regedor, 11	Madalena	unav.	42	Y	N	Masonry	W	Main	4.5	15x15	Glazed	White&Color	N	N	N	Y	N	Y	Moderate	High	< 1 km
Ed. 44	Avenida Rui Nogueira Simões, 2	São Domingos de Benfica	1998	14	N	N	Concrete	W	Main	170	10x20	Not glazed	White&Color	N	N	N	N	N	Y	Moderate	Low	> 5 km
Ed. 45	Avenida Rui Nogueira Simões, 6	São Domingos de Benfica	1998	14	N	N	Concrete	W	Main	170	10x20	Not glazed	White&Color	N	N	N	N	N	Y	Moderate	Low	> 5 km
Ed. 46	Rua dos Ferreiros a Estrela, 2	Lapa	1915	22	Y	N	Masonry	W	Side	105	13,5x13,5	Glazed	White&Color	Y	N	N	Y	N	Y	Moderate	High	< 1 km
Ed. 47	Calçada da Estrela, 60	Lapa	1915	22	Y	N	Masonry	S	Main	11.5	13,5x13,5	Glazed	White&Color	Y	N	N	Y	N	Y	Moderate	High	< 1 km
Ed. 48	Calçada da Estrela, 72	Lapa	1890	40	Y	N	Masonry	S	Main	32	13,5x13,5	Glazed	White&Color	N	N	N	Y	N	Y	Moderate	High	< 1 km
Ed. 49	Calçada da Estrela, 183-191	Lapa	1887	38	Y	N	Masonry	N	Main	6.5	14x14	Glazed	Colorful	N	N	N	Y	N	Y	Moderate	High	< 1 km
Ed. 50	Rua Bela Vista à Lapa, 1-5	Lapa	1887	38	Y	N	Masonry	W	Main	18.5	14x14	Glazed	Colorful	N	N	N	Y	N	Y	Moderate	High	< 1 km
Ed. 51	Rua Bela Vista à Lapa, 30-42	Lapa	1916	62	Y	N	Masonry	S	Side	55	14x14	Glazed	White&Color	N	N	N	Y	N	Y	Moderate	High	< 1 km
Ed. 52	Rua Bela Vista à Lapa, 88-96	Lapa	unav.	25	Y	N	Masonry	E	Main	48.5	14x14	Glazed	White&Color	N	N	N	Y	N	Y	Moderate	High	< 1 km
Ed. 53	Rua Borges Carneiro, 47-55	Lapa	unav.	19	Y	N	Masonry	S	Main	35	15x15	Glazed	White&Color	N	N	N	Y	N	Y	Moderate	High	< 1 km
Ed. 54	Rua dos Navigantes, 4-6	Lapa	1884	53	Y	N	Masonry	S	Main	18	15x15	Glazed	White&Color	N	N	N	Y	N	Y	Moderate	High	< 1 km
Ed. 55	Rua Lapa, 14-18	Lapa	1881	26	Y	N	Masonry	S	Main	6	13,5x13,5	Glazed	Colorful	N	N	N	Y	N	Y	Moderate	High	< 1 km
Ed. 56	Rua Lapa, 14-18	Lapa	1881	16	Y	N	Masonry	S	Main	22.5	15x15	Glazed	White&Color	N	N	N	Y	N	Y	Moderate	High	< 1 km
Ed. 57	Rua Lapa, 108-112	Lapa	1900	25	Y	N	Masonry	S	Main	45	14x14	Glazed	White&Color	N	N	N	Y	N	Y	Moderate	High	< 1 km
Ed. 58	Rua Buenos Aires, 31	Lapa	unav.	22	Y	N	Masonry	W	Main	6.5	13,5x13,5	Glazed	Green	N	N	N	Y	N	Y	Moderate	High	< 1 km
Ed. 59	Rua Do Possolo, 47-51	Prazeres	unav.	51	Y	N	Masonry	E	Main	7	7,5x15,5	Glazed	Brown	N	N	N	Y	N	Y	Moderate	High	< 1 km
Ed. 60	Avenida Infante Santo, 57	Lapa	1955	57	N	N	Concrete	E	Main	66	7,5x15,5	Glazed	Brown	Y	N	N	Y	N	Y	Severe	High	< 1 km
Ed. 61	Avenida Infante Santo, 57	Lapa	1955	57	N	N	Concrete	N	Side	40	7,5x15,5	Glazed	Brown	Y	N	N	Y	N	Y	Moderate	High	< 1 km
Ed. 62	Avenida Infante Santo, 63	Lapa	1955	26	Y	N	Concrete	E	Main	40.5	7,5x15,5	Glazed	Brown	Y	N	N	Y	N	Y	Severe	High	< 1 km
Ed. 63	Rua Caminhos de Ferro, 82-86	São Vicente de Fora	unav.	17	Y	N	Masonry	E	Main	10.5	14x14	Glazed	Grey	Y	N	N	N	N	Y	Severe	High	< 1 km
Ed. 64	Rua Caminhos de Ferro, 30-32	São Vicente de Fora	unav.	11	Y	N	Masonry	E	Main	50	13,5x13,5	Glazed	Colorful	N	N	N	N	N	Y	Severe	High	< 1 km
Ed. 65	Rua Caminhos de Ferro, 26-28	São Vicente de Fora	1913	45	Y	N	Masonry	E	Main	5	14x14	Glazed	Brown	N	N	N	N	N	Y	Severe	High	< 1 km
Ed. 66	Rua Caminhos de Ferro, 26-28	São Vicente de Fora	1913	45	Y	N	Masonry	E	Main	17.5	14x14	Glazed	White&Color	N	N	N	N	N	Y	Severe	High	< 1 km
Ed. 67	Calçada do Cardeal, 15	São Vicente de Fora	1913	39	Y	Y	Masonry	W	Main	6	13,5x13,5	Glazed	White&Color	N	N	N	N	N	Y	Severe	High	< 1 km
Ed. 68	Calçada do Cardeal, 17	São Vicente de Fora	unav.	11	Y	N	Masonry	W	Main	17.5	14x14	Glazed	Colorful	N	N	N	N	N	Y	Severe	High	< 1 km
Ed. 69	Calçada Santa Apolónia, 32	Santa Engrácia	unav.	33	Y	N	Masonry	S	Main	12	15x15	Glazed	Colorful	N	N	N	N	N	Y	Severe	High	< 1 km
Ed. 70	Rua Lapa, 101	Lapa	1914	50	Y	N	Masonry	N	Main	20	8x16	Glazed	Green	N	N	N	Y	N	Y	Moderate	High	< 1 km
Ed. 71	Rua Cruz de Santa Apolónia, 21	Santa Engrácia	unav.	36	Y	N	Masonry	N	Main	10.5	13,5x13,5	Glazed	White&Color	N	N	N	N	N	Y	Severe	High	< 1 km
Ed. 72	Rua Vale de Santo António, 69	Santa Engrácia	2011	1	N	N	Concrete	E	Main	95	14,5x14,5	Glazed	Blue	N	N	N	N	N	Y	Moderate	High	< 1 km
Ed. 73	Rua Vale de Santo António, 69	Santa Engrácia	2011	1	N	N	Concrete	N	Main	75	14,5x14,5	Glazed	Blue	N	N	N	N	N	Y	Moderate	High	< 1 km
Ed. 74	Rua 4 de Infantaria, 22	Santo Condestável	1894	10	Y	N	Masonry	W	Main	26	14x14	Glazed	Colorful	N	N	N	Y	N	Y	Moderate	High	> 1 e < 5 km
Ed. 75	Rua do Salitre, 132	São Mamede	1948	2	Y	N	Concrete	N	Main	105	15x15	Glazed	Green	N	N	N	Y	N	Y	Moderate	Low	> 1 e < 5 km
Ed. 76	Rua do Salitre, 149	São Mamede	unav.	1	Y	N	Concrete	N	Main	50	14x14	Glazed	White&Color	Y	N	N	Y	N	Y	Moderate	Low	> 1 e < 5 km
Ed. 77	Rua do Salitre, 151-157	São Mamede	unav.	2	Y	N	Concrete	N	Main	12.5	14x14	Glazed	Brown	Y	N	N	Y	N	Y	Moderate	Low	> 1 e < 5 km
Ed. 78	Rua do Salitre, 151-157	São Mamede	unav.	2	Y	N	Concrete	N	Main	15	14x14	Glazed	White&Color	Y	N	N	Y	N	Y	Moderate	Low	> 1 e < 5 km
Ed. 79	Calçada do Carmo, 48-52	Sacramento	1883	48	Y	N	Masonry	E	Main	50	16x16	Glazed	Colorful	N	N	N	Y	N	Y	Moderate	High	< 1 km

Building identification								Facade characterization						Joints			Design		Ambiental conditions			
Code	Address	Freguesia	Year of conclusion	Age	Repaired	Regular mant.	Structure	Facade orient.	Facade type	CWT area	Tiles dimension	Surface	Tiles color	Periph.	Splitting	Struct.	Periph. protection	Corner protection	Pollution exposition	Wind action	Humidity exp.	Sea distance
Ed. 80	Rua Da Junqueira, 317	Santa Maria de Belém	1918	72	Y	N	Masonry	N	Main	39	14x14	Glazed	White&Color	N	N	N	N	N	Y	Severe	High	< 1 km
Ed. 81	Rua Campo de Ourique, 180-184	Santa Isabel	1892	72	Y	N	Masonry	S	Main	7.5	12,5x12,5	Glazed	White&Color	N	N	N	Y	N	Y	Moderate	Low	> 1 e < 5 km
Ed. 82	Rua Campo de Ourique, 180-184	Santa Isabel	1892	72	Y	N	Masonry	E	Side	19	12,5x12,5	Glazed	White&Color	N	N	N	Y	N	Y	Moderate	Low	> 1 e < 5 km
Ed. 83	Rua Sociedade Farmacêutica 43-45	Coração de Jesus	1913	50	Y	N	Masonry	E	Main	19.5	8x16	Glazed	Green	N	N	N	Y	N	Y	Mild	Low	> 1 e < 5 km
Ed. 84	Rua Bernardo Lima, 9-11	Coração de Jesus	1909	58	Y	N	Masonry	E	Main	34	16x16	Glazed	White&Color	N	N	N	N	N	Y	Mild	Low	> 1 e < 5 km
Ed. 85	Rua Passos Manuel, 30-36	São Jorge de Arroios	1888	39	Y	N	Masonry	W	Main	9.5	14x14	Glazed	White&Color	N	N	N	Y	N	Y	Mild	Low	> 1 e < 5 km
Ed. 86	Largo de Santa Barbara, 9	São Jorge de Arroios	1895	70	Y	N	Masonry	W	Main	30	14x14	Glazed	Colorful	Y	N	N	N	N	Y	Mild	Low	> 1 e < 5 km
Ed. 87	Largo de Santa Barbara, 9	São Jorge de Arroios	1895	70	Y	N	Masonry	N	Side	76	14x14	Glazed	Colorful	Y	N	N	N	N	Y	Mild	Low	> 1 e < 5 km
Ed. 88	Rua Arroios, 36-42	São Jorge de Arroios	1915	47	Y	N	Masonry	W	Side	9	7,5x15,5	Glazed	Brown	N	N	N	Y	N	Y	Mild	Low	> 1 e < 5 km
Ed. 89	Rua Da Junqueira, 337-339	Santa Maria de Belém	unav.	51	Y	N	Masonry	N	Main	18	13,5x13,5	Glazed	White&Color	Y	N	N	N	N	Y	Severe	High	< 1 km
Ed. 90	Rua Da Junqueira, 376-384	Santa Maria de Belém	1892	72	Y	N	Masonry	S	Main	17.5	13,5x13,5	Glazed	Blue	N	N	N	N	N	Y	Severe	High	< 1 km
Ed. 91	Rua Da Junqueira, 376-384	Santa Maria de Belém	1892	72	Y	N	Masonry	S	Main	56	13,5x13,5	Glazed	White&Color	N	N	N	N	N	Y	Severe	High	< 1 km
Ed. 92	Rua Da Junqueira, 223	Santa Maria de Belém	1907	52	Y	N	Masonry	N	Main	57.5	16x16	Glazed	White&Color	N	N	N	Y	N	Y	Severe	High	< 1 km
Ed. 93	Rua Da Junqueira, 207	Santa Maria de Belém	1908	57	Y	N	Masonry	N	Main	25	15,5x15,5	Glazed	White&Color	N	N	N	N	N	Y	Severe	High	< 1 km
Ed. 94	Rua Presidente Arriaga, 56-58	Prazeres	1900	60	Y	N	Masonry	N	Main	15	13,5x13,5	Glazed	White&Color	N	N	N	N	N	Y	Severe	High	< 1 km
Ed. 95	Rua Presidente Arriaga, 120-124	Prazeres	1916	56	Y	N	Masonry	S	Main	38	13,5x13,5	Glazed	White&Color	N	N	N	N	N	Y	Severe	High	< 1 km
Ed. 96	Rua Joaquim Casimiro, 9-11	Prazeres	1931	38	Y	N	Masonry	E	Main	30	7,5x15,5	Glazed	White	N	N	N	Y	N	Y	Severe	High	< 1 km
Ed. 97	Rua do Prior, 3	Prazeres	1896	33	Y	N	Masonry	N	Main	19	14x14	Glazed	White&Color	Y	N	N	Y	N	Y	Moderate	High	< 1 km
Ed. 98	Rua Santos-O-Velho, 26-32	Santos-o-Velho	unav.	77	Y	N	Masonry	S	Main	40	14x14	Glazed	Green	N	N	N	Y	N	Y	Severe	High	< 1 km
Ed. 99	Rua Vítor Cordon, 34-40	Mártires	1911	50	Y	N	Masonry	S	Main	54	15,5x15,5	Glazed	White&Color	N	N	N	N	N	Y	Severe	High	< 1 km
Ed. 100	Rua Vítor Cordon, 34-40	Mártires	1911	50	Y	N	Masonry	W	Side	39.5	15,5x15,5	Glazed	White&Color	N	N	N	N	N	Y	Severe	High	< 1 km
Ed. 101	Travessa Alcaide, 15	Santa Catarina	unav.	32	Y	N	Masonry	W	Main	21	14x14	Glazed	White&Color	N	N	N	Y	N	Y	Severe	High	< 1 km
Ed. 102	Rua Fernandes Tomás, 25	São Paulo	1884	51	Y	N	Masonry	N	Main	12.5	8x16	Glazed	White&Color	N	N	N	Y	N	Y	Severe	High	< 1 km
Ed. 103	Rua Fernandes Tomás, 66	São Paulo	1888	57	Y	N	Masonry	N	Main	110	15,5x15,5	Glazed	White&Color	N	N	N	N	N	Y	Severe	High	< 1 km
Ed. 104	Rua Poço dos Negros, 119	São Paulo	1899	52	Y	N	Masonry	N	Main	16	14x14	Not glazed	Colorful	N	N	N	Y	N	Y	Severe	High	< 1 km
Ed. 105	Rua Gaivotas, 25-27	São Paulo	1899	52	Y	N	Masonry	E	Side	18	14x14	Not glazed	Colorful	N	N	N	Y	N	Y	Severe	High	< 1 km
Ed. 106	Rua Poiais de São Bento, 37	Mercês	1920	56	Y	N	Masonry	N	Main	5	13,5x13,5	Glazed	Colorful	N	N	N	N	N	Y	Severe	High	< 1 km
Ed. 107	Rua 4 de Infantaria, 15	Santo Condestável	unav.	47	Y	N	Masonry	E	Main	15.5	15,5x15,5	Glazed	Brown	N	N	N	Y	N	Y	Moderate	Low	> 1 e < 5 km
Ed. 108	Rua Pereira e Sousa, 14	Santo Condestável	1885	61	Y	N	Masonry	S	Main	18	13,5x13,5	Glazed	Colorful	N	N	N	Y	N	Y	Moderate	Low	> 1 e < 5 km
Ed. 109	Rua Correia Teles, 53	Santo Condestável	1917	49	Y	N	Masonry	N	Main	13	15,5x15,5	Glazed	White&Color	Y	N	N	Y	N	Y	Moderate	Low	> 1 e < 5 km
Ed. 110	Rua Correia Teles, 51	Santo Condestável	1914	49	Y	N	Masonry	N	Main	108	15,5x15,5	Glazed	White&Color	Y	N	N	Y	N	Y	Moderate	Low	> 1 e < 5 km
Ed. 111	Rua Almeida e Sousa, 27	Santo Condestável	1904	44	Y	N	Masonry	N	Main	70	13,5x13,5	Glazed	Blue	N	N	N	Y	N	Y	Moderate	Low	> 1 e < 5 km
Ed. 112	Rua Coelho da Rocha, 5	Santo Condestável	1916	52	Y	N	Masonry	N	Main	11.5	8x16	Glazed	Green	N	N	N	N	N	Y	Moderate	Low	> 1 e < 5 km
Ed. 113	Calçada da Estrela, 177-181	Lapa	1888	41	Y	N	Masonry	N	Main	11	8x16	Glazed	Green	N	N	N	Y	N	Y	Moderate	High	< 1 km
Ed. 114	Calçada da Estrela, 177-181	Lapa	1888	41	Y	N	Masonry	N	Main	17	14x14	Glazed	White&Color	N	N	N	Y	N	Y	Moderate	High	< 1 km
Ed. 115	Rua Do Possolo, 41	Prazeres	1927	44	Y	N	Masonry	E	Main	36.5	13,5x13,5	Glazed	White&Color	N	N	N	Y	N	Y	Moderate	High	< 1 km
Ed. 116	Av. Estados Unidos da America, 52	Alvalade	1957	40	N	Y	Concrete	N	Side	7	15x15	Glazed	Colorful	N	N	N	Y	N	Y	Mild	Low	> 1 e < 5 km

Building identification								Facade characterization						Joints			Design		Ambiental conditions			
Code	Address	Freguesia	Year of conclusion	Age	Repaired	Regular mant.	Structure	Facade orient.	Facade type	CWT area	Tiles dimension	Surface	Tiles color	Periph.	Splitting	Struct.	Periph. protection	Corner protection	Pollution exposition	Wind action	Humidity exp.	Sea distance
Ed. 117	Av. Estados Unidos da America, 52	Alvalade	1957	40	N	Y	Concrete	E	Main	16.5	15x15	Glazed	Colorful	N	N	N	Y	N	Y	Mild	Low	> 1 e < 5 km
Ed. 118	Av. Estados Unidos da America, 52	Alvalade	1957	40	N	Y	Concrete	S	Side	9.5	15x15	Glazed	Colorful	N	N	N	Y	N	Y	Mild	Low	> 1 e < 5 km
Ed. 119	Rua António Lopes Ribeiro	Lumiar	2001	11	N	N	Concrete	W	Main	72	10x10	Glazed	Orange	N	N	N	N	N	Y	Moderate	Low	> 5 km
Ed. 120	Rua António Lopes Ribeiro	Lumiar	2001	11	N	N	Concrete	N	Main	72	10x10	Glazed	Orange	N	N	N	N	N	Y	Moderate	Low	> 5 km
Ed. 121	Avenida Dom João II (ed. 1.16.04)	Santa Maria dos Olivais	2007	5	N	N	Concrete	N	Side	900	5x24	Glazed	Pink	N	Y	Y	N	N	Y	Severe	High	< 1 km
Ed. 122	Avenida Dom João II (ed. 1.16.04)	Santa Maria dos Olivais	2007	5	N	N	Concrete	S	Side	1000	5x24	Glazed	Pink	N	Y	Y	N	N	Y	Severe	High	< 1 km

Claddings removed from the sample