SOLAR HEATING & COOLING PROGRAMME
INTERNATIONAL ENERGY AGENCY

TASK 27

Performance of Solar Facade Components

Performance, durability and sustainability

of advanced windows and solar components for building envelopes

Final Report

Subtask C: Sustainability

Project C2: Failure Mode Analysis

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Project C2: Failure Mode Analysis

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1 Introduction

This report is composed of two distinct parts:

The first part (§2) includes terminology on service life planning (from ISO 15686 standards) and technical terms on window and facade (from SZFF Switzerland).

The second part (§3 and 4) presents the durability tools:
FMEA concept, methodology and applications in order to search failure modes.
Application on:
Double Glazing Unit
Argon gas filled / Low-e coating window
Solar Collector

Service Life prediction, including Data fusion concept, methodology and application in order to assess a service life, and description of the factor metrhod.

2 Terminology

In order to facilitate the mutual understanding (and to reach a common level of knowledge in terms of SLP and FMEA), it was decided to supply participants with multilingual lists of terms.
Until now, were provided lists on :
- Service life and durability concepts,
- Multilingual technical terms.

2.1 Service life planning and durability (ISO 15686)

Ageing	Vieillissement	Degradation due to long term influence of agents related to use	Dégradation due à l'influence dans le temps des agents (environnement, utilisation).
Agents	Agents	Whatever acts on a construction or its part to reduce its performance.	Ce qui agit sur un bâtiment ou ses diverses parties et qui amenuise ses performances.
Building	Bâtiment	Construction works that has the provision of shelter for its occupants or contents as one of its main purposes and is usually enclosed and designed to stand permanently in one place.	Construction ayant principalement pour fonction d'abriter ses occupants ou son contenu ; elle est généralement fermée et conçue pour demeurer en place de façon permanente0.
Building assembly	Assemblage (de bâtiment)	Set of components used together	Ensemble de composants utilisés ensemble.
Building component	Composant (de bâtiment)	Product manufactured as a distinct unit to serve a specific function or functions	Produit fabriqué comme unité distincte pour remplir une ou plusieurs fonctions spécifiques.
Building material	Matériau (de construction)	Substance that can be used to form products or construction works	Matière servant à fabriquer des produits ou réaliser des ouvrages de construction.
Building product	Produit (de construction)	Item manufactured or processed for incorporation in construction works.	Tout élément fabriqué ou conçu pour être incorporé dans des constructions.
Building sub-component	Sous-composant (de bâtiment)	Manufactured product forming par of a component	Produit manufacturé faisant partie d'un composant.
Client	Client	Person or organisation that requires a construction to be provided, altered or extended, and is responsible for initiating and approving the brief.	Personne physique ou morale qui demande la construction, la transformation ou k'extension d'un bâtiment et responsable de l'établissement et de l'approbation du programme.
Constructor (contractor)	Entrepreneur (contractant)	Person or organisation that undertakes the construction.	Personne physique ou morale qui entreprend une construction.
Critical property	Propriété critique	Property of an assembly, component or material that must be maintained above a certain minimum level if it is to retain the ability to perform its intended function.	Propriété qui doit être maintenue au dessus d'un certain niveau pour que le bâtiment ou ses parties conservent l'aptitude à remplir leurs fonctions escomptées.
Defect	Défaut	Fault or deviation in the aimed condition of an assembly, component or material.	Défaillance ou écart par rapport à l'état prévu d'un bâtiment ou de ses parties.
Degradation	Dégradation	Reduction over time in the performance of an assembly, component or material	Modification dans le temps de la composition, de la micro-structure et des propriétés d'un composant ou d'un matériau amenuisant ses performances.
Degradation mechanism	Mécanisme de dégradation	Chemical, mechanical or physical changes that reduce the performance of an assembly, component or material.	Modifications d'ordre chimique, mécanique ou physique entraînant des changements d'une ou plusieurs propriétés critiques d'un produit de construction.

Design life	Durée de vie de conception	Period of use intended by the design, e.g. as established by agreement between the client and the designer to support specification decisions.	Durée de vie recherchée par le concepteur, par exemple celle qu'il a indiquée au maître d'ouvrage à l'appui des décisions de spécifications.
Designer Durability	Concepteur Durabilité	Person or organisation responsible for stating the form and specification of a building or parts of a building. Capability of an item to perform its required function over a period of time.	Personne physique ou morale chargée de définir la forme et la spécification d'un bâtiment ou des parties de bâtiment. Aptitude d'un bâtiment ou de ses parties à remplir sa fonction, pendant un laps de temps donné, sous l'influence d'agents prévisibles lors de son utilisation.
Effect	Effet	Result of action of an agent.	
Estimated service life	Durée de vie estimée	Reference service life multiplied by factors related to specific conditions, e.g. materials, design, environment, use and maintenance (factors method).	Durée de vie de référence multipliée par les facteurs liés aux circonstances spécifiques, par exemple matériaux, conception, environnement, utilisation et entretien (approche factorielle).
Failure	Défaillance	Termination of the ability of an item to perform a specific function.	Perte de l'aptitude du bâtiment ou de ses parties à remplir une fonction donnée.
Feed back from practice	Retour d'expérience	Inspection of buildings. Performance evaluation or assessment of residual service life of building parts used in actual buildings.	
Maintenance	Entretien / Maintenance	Combination of all technical and associated administrative activities during the service life that are meant to retain an item in a state in which it can perform its required function. Includes cleaning, repair and replacement of parts.	Recours à l'association d'actions techniques et administratives au cours de la durée de vie en vue de maintenir un bâtiment ou ses parties dans un état lui permettant de remplir ses fonctions.
Obsolescence	Obsolescence	Inability of an item to satisfy changing requirements.	Perte de l'aptitude d'un élément à satisfaire aux exigences requises suite aux diminutions de ses performances.
Performance	Performance	*Capability of a building or parts of a building to perform their required functions under the influence of expected degradation agents.*	Aptitude d'un bâtiment ou de ses parties à remplir leurs fonctions dans les conditions d'utilisation prévues.
Performance requirement	Exigence de performance	Range of acceptable performance within which a critical property is maintained.	Niveaux de performance quantitatifs et qualitatifs requis pour une propriété critique.
Performance criterion	Critère de performance	A level of a performance characteristic, below which the corresponding critical property or properties of a component no longer are maintained.	
Performance evaluation	Evaluation de performance	Evaluation of critical properties on basis of measurement or inspection.	Evaluation des performances critiques sur la base d'un mesurage ou de contrôle.
Performance over time	Performance dans le temps	Description of how a critical property varies with time under the influence of degradation	Description de la façon dont une propriété varie dans le temps, sous l'influence d'agents de

		agents.	dégradation.
Predicted service life	Durée de vie prédite	Service life predicted from recorded performance over time as found in service life models or testing.	Durée de vie évaluée à partir de performances observées antérieurement, par exemple reprise de modèles de durée de vie ou à la suite d'essais de vieillissement.
Property	Propriété	Inherent or acquired feature of an item.	Caractéristique inhérente ou reconnue pour un élément.
Reference service life	Durée de vie de référence	Service life established for a class of building or parts of a building for use as basis for estimating service life in specific items in specific conditions.	Durée de vie attendue d'un bâtiment ou de ses différentes parties, servant de base pour l'estimation de la durée de vie.
Refurbishment	Réhabilitation	Modification and improvements to an existing plant, building or civil engineering works to bring it up to an acceptable condition.	Opérations et améliorations apportées à un bâtiment existant ou à ses parties afin de le remettre dans un état acceptable.
Residual life	Durée de vie résiduelle	Time between the moment of consideration and the end of the service life.	Temps restant entre le moment considéré et la fin de vie prévisionnelle.
Restoration	Restauration	*Operations on building or parts of building that are meant to give back its original aspect or state..*	Opération ayant pour but de rendre à un élément son aspect ou son état d'origine

Service life	Durée de vie	Period of time after installation during which all essential properties of an item meet or exceed the required performance.	Période débutant avec la mise en service, pendant laquelle un bâtiment ou ses différentes parties satisfont tout juste ou largement aux exigences de performance ou font mieux.
Supplier / Manufacturer	Fournisseur / Fabricant	Person or organisation that supplies and/or manufactures buildings or parts of buildings.	Industriel : Personne qui préfabrique des bâtiments ou des parties de bâtiment. Fournisseur : Personne physique ou morale qui fournit des bâtiment ou des parties de bâtiment.
User	Utilisateur	Person who occupies, visits or operates a building.	Personne physique ou morale ou animal auquel un bâtiment est destiné (y compris le propriétaire, le gérant et les occupants du bâtiment)

2.2 Window and facade: Technical terms

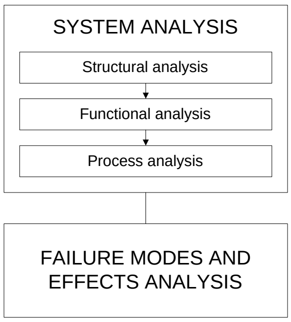
C2 participants agree on the use of Swiss document (EMPA) on window and facade terminology when leading FMEA.
SZFF-CSFF (Schweizerische Zentrallstelle für Fenster- und Fassadenbau)
Fachwörter – Verzeichnis. Fenster- und Fassadenbau
German – English – French – Italian

3 FMEA Methodology

Used from the 1960s in the aeronautical and car industries, FMEA is a convenient tool for the safety studies of industrial systems. FMEA is intended for the verification of the product ability to satisfy client's needs (reliability, maintenability, disposability, safety). Commonly used in these industrial domains, it targets and checks weak points before mass-production in order to define preventive measures.
We want to apply a similar approach for building products. With adaptations due to building specificities, CSTB has developed a “risk assessment” approach, in order to know why he has failed or how he will fail. Identify and assess risks, foresee the consequences and possibly propose solutions, are the goals of such study.

This methodology will be applied to advanced windows and solar components for building envelopes.

The proposed approach is composed of two main steps:
- the analysis of the system (including structural, functional and process analysis),
- the search of failure modes.



3.1.1 System analysis

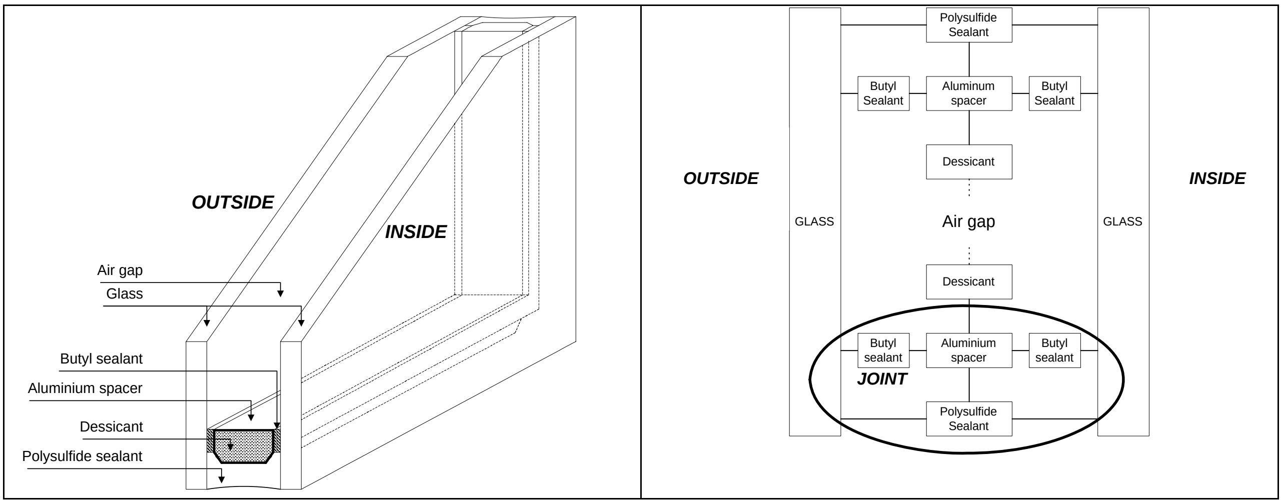
The proposed approach relies, on one hand, on the precise description of the system, the identification of its functions and the definition of its environment.
On the other hand, we also consider the building process of the product (design, manufacturing, transport, storage, setting up …).
A double glazing unit case study illustrate each step of the approach.

3.1.2 Structural analysis

This first step consists in identifying all the components, their characteristics as well as the environment in which they could be located in.
The structure of the studied product is described with:
- morphology (geometrical shape, dimensions …),
- topology of relations with other objects,
- physico-chemical composition of its constitutive elements and their own description.

Example:

The figure represents a double glazing unit (left part) and its structural representation (right part).



OUTSIDE	INSIDE
Water (rain, snow)	Water (condensation)
UV and solar radiations	
High or low temperatures	High or low temperatures
Air and pollutants: O_2, CO_2, CO, Ozone, NO_x, SO_x, HCl, …	Air and pollutants: O2, CO2, CO, Ozone, NOx, SOx, HCl, …
Cleaning agents	Cleaning agents
Hot vapour	Hot vapour
Dust	Dust
Shocks	Shocks
Wind stresses	
Action of frames	
Movements of wall	

Note:
Combined environmental stresses (successive or concomitant stresses) should be taken into account:
- water AND low temperature is Freezing,
- high temperatures AND Rain fall is Thermal shocks,

3.1.3 Functional analysis

This second step consists in identifying all the functions of the product and its components (role of each component in the global functioning):
- either needs as regards the user (The product is designed to fulfil user's needs, these needs are expressed in terms of functions: thermal insulation, …),

- either functions stemming from constructive choice (seals to prevent water entry in a glazing unit).

For building domain, “The product fulfils a function” could be generally expressed as “The building product transforms climatic factors”. For envelope products, it acts as a filter between two environments, filtering heat flows between outdoor and indoor environments (thermal insulation), stopping water from outdoor (watertightness of a roofing system), …
But, these same climatic factors can have an impact on its constitutive elements and could involve: modification of the materials properties, degradation and even failure…

Example:

Function		Elements
Needs	Landscape vision	Glass $^{(1)}$ + Air gap + Glass $^{(2)}$ (Transparency)
	Light transmission	Glass $^{(1)}$ + Air gap + Glass $^{(2)}$ (Transparency)
	Thermal insulation	Glass $^{(1)}$ + Air gap + Glass $^{(2)}$ (Emptiness)
	Acoustical insulation	Glass $^{(1)}$ + Air gap + Glass $^{(2)}$ (Emptiness)
Technical functions	Water resistance of joint	Joint
	Resistance to environment	Glass + Butyl sealant + Polysulfide sealant + Glass/sealant interface + spacer/sealant interface
	Water absorption	Desiccant

3.1.4 Process analysis

This third step consists in identifying the various steps of the construction process. On the contrary of a classical approach (we first define the specifications of the product in order that it fulfils the functions for which it was designed, and then check if the manufacturing process leads in reaching the defined specifications), we will first define the characteristics of the product according to the workmanship process (manufacturing and setting up stages) and then identify the product ability to fulfil the functions for which it was designed, given the workmanship quality.

Example:

Design → Manufacturing → Transportation → Handling and Storage → Installation → Use

1 – Design Nature and rigidity of frames *2 – Manufacturing* Squareness and rigidity Planeness Quality of joint (Water and air permeability) Adhesion (surface quality, cleanness) Materials (Butyl, Polysulfide) Desiccant quality and quantity Quality of desiccated air	*3 – Transportation* Deformations Degradation of joint *4 – Handling and Storage* Deformations Degradation of joint *5 – Installation* Plumb and level Blocking Problems in adhesion (joint breaking)

3.1.5 Conclusion

With structural functional and process analysis, we know why and how the product works (functions ensured by the product, and elements involved in the “success” of each function).
With FMEA, we will now identify why and how it could fail in fulfilling the functions.

3.2 Failure modes and effects analysis

FMEA consists in the identification of all failure modes for each function, the search for causes, and finally the identification of effects. We want to imagine, forecast and write the potential futures of the product.

The novelty of the approach concerns the search of causes and effects. The behaviour towards solicitations of an element, its degradation or failure can change the environment of neighbouring elements. For example, the cracking of the seal of a double glazing unit under UV and temperature stresses could involve stresses in generally protected elements (low-emissive layer towards humidity or pollutants).
We propose to search direct effects (influence of the degradation or failure on the considered element) as well as indirect effects (influence on other elements or on system).

The principle of the failure modes analysis is a multi-step approach, that lead to the following table:

Functions	Elements	Modes	Causes	Direct effects	Indirect effects

Step 1:
Thanks to structural and functional analysis, the first two columns are filled.

Functions	Elements	Modes	Causes	Direct effects	Indirect effects
Landscape vision	Extern. glass				
	Air gap				
	Intern. glass				
Resistance to environment	Glass				
	Polysulfide sealant				
	Butyl sealant				
	…				

Once filled these columns, we have to search modes and causes.
Three types of causes could then be identified :
① classical cause as the action of an environmental agent on an element,

② an unexpected behaviour due to a defect in building process,
③ the influence of the behaviour of a neighbouring element on the considered element.
The type 1 causes are deducted from the following table which draws up the potential initial stresses for each element.

	External glass	Air gap	Polysulfide sealant	Butyl sealant	Aluminium spacer	Dessicant	Internal glass	
Water (rain, snow)	x		x					
UV and solar radiations	x	x			x		x	
High or low temperatures	x	x	x	x	x	x	x	
Air and pollutants: O_2, CO_2, CO, Ozone, NO_x, SO_x, HCl, …	x		x					
Cleaning agents	x		x					
Hot vapour	x		x					
Dust	x		x					
Shocks	x							
Wind stresses	x	x	x	x	x	x	x	
Action of frames	x	x	x	x	x	x	x	
Movements of wall	x	x	x	x	x	x	x	
							x	Water (condensation)
	x	x	x	x	x	x	x	High or low temperatures
			x				x	Air and pollutants: O2, CO2, CO, Ozone, NOx, SOx, HCl, …
			x				x	Cleaning agents
			x				x	Hot vapour
			x				x	Dust
							x	Shocks

Step 1 – Initial stresses condition.

The type 2 causes are stated by experts. They include potential defects, negligence, errors due to materials (quality, homogeneity of concrete), mean (inefficient mixing or vibrating of concrete), method (surface cleanness,…), middle (temperature, humidity for concrete casting), manpower.
Then, direct effects as well as indirect effects are identified.

This leads to the updating of environmental stresses conditions.

Functions	Elements	Modes	Causes	Direct effects	Indirect effects
Landscape vision	Extern. glass	Scratching Cracking	Cleaning method	Bad vision	
	Air gap				
	Intern. glass	Scratching Cracking	Cleaning method	Bad vision	
Resistance to environment	Glass	Cracking	Shocks Wind stresses	Air and water permeability	
		Deformation	Shocks Wind stresses	-	Stress on joint
	Polysulfide sealant	Cracking	Process problem, Pollutants, Cleaning agents, Temperature, Thermal shocks, Water	Air and water permeability	Hydric stress on butyl sealant
	Butyl sealant	Craking	Process problem, Temperature	Permeability	-
	…				

Step 1 – FMEA table (Extract)

	External glass	Air gap	Polysulfide sealant	Butyl sealant	Aluminium spacer	Dessicant	Internal glass	
Water (rain, snow)	x		x	**x**				
UV and solar radiations	x	x			x		x	
High or low temperatures	x	x	x	x	x	x	x	
Air and pollutants: O_2, CO_2, CO, Ozone, NO_x, SO_x, HCl, …	x		x	**x**				
Cleaning agents	x		x	**x**				
Hot vapour	x		x					
Dust	x		x	**x**				
Shocks	x							
Wind stresses	x	x	x	x	x	x	x	
Action of frames	x	x	x	x	x	x	x	
Movements of wall	x	x	x	x	x	x	x	
				x			x	Water (condensation)
	x	x	x	x	x	x	x	High or low temperatures
			x	**x**			x	Air and pollutants: O2, CO2, CO, Ozone, NOx, SOx, HCl, …
			x	**x**			x	Cleaning agents
			x				x	Hot vapour
			x	**x**			x	Dust
							x	Shocks

Step 1 – Updated stresses condition

Step 2:
With the updated environmental stresses condition table and the column indirect effect, new failures (modes, causes and the consequences) are identified.

Functions	Elements	Modes	Causes	Direct effects	Indirect effects
Landscape vision	External glass	Scratching Cracking	Cleaning method	Bad vision	
	Air gap				
	Internal glass	Scratching Cracking	Cleaning method	Bad vision	
Resistance to environment	Glass	Cracking	Shocks Wind stresses	Air and water permeability	
		Deformation	Shocks Wind stresses	-	Stress on joint
	Polysulfide sealant	Cracking	Process problem, Pollutants, Cleaning agents, Temperature, Thermal shocks, Water	Air and water permeability	Hydric stress on butyl sealant
	Butyl sealant	Craking	Process problem, Temperature, Water*, Pollutants*, Cleaning agents*, Dust*	Permeability	Water, dust penetration in air gap
	…				

Step 2 – FMEA table (Extract)

And so on …

Functions	Elements	Modes	Causes	Direct effects	Indirect effects
Landscape vision	External glass	Scratching Cracking	Cleaning method	Bad vision	
	Air gap	Condensation Dust deposit	Joint breaking	Bad vision	
	Internal glass	Scratching Cracking	Cleaning method	Bad vision	
Resistance to environment	Glass	Cracking	Shocks Wind stresses	Air and water permeability	
		Deformation	Shocks Wind stresses	-	Stress on joint
	Polysulfide sealant	Cracking	Process problem, Pollutants, Cleaning agents, Temperature, Thermal shocks, Water	Air and water permeability	Hydric stress on butyl sealant
	Butyl sealant	Craking	Process problem, Temperature, Water*, Pollutants*, Cleaning agents*, Dust*	Permeability	Water, dust penetration in air gap

Step 3 – FMEA table (Extract)

3.3 Interest and perspectives

Though it is seldom used in construction, FMEA is a promising method that could be used efficiently in our context. It gives guidelines to improve the reliability and the quality of innovative products.

From the Project C2 discussions raised several aspects concerning FMEA use :
- FMEA is then a familiar tool (modelling expert reasoning),
- FMEA is a relevant and useful tool during design stage, intended to identify weak points of products; weak points means either problems, neglecting, errors during manufacturing process,… or problems of materials behaviour (degradation or failure) facing to environmental stresses or behaviour of neighbouring materials.
- FMEA is a useful tool first for experience and know-how gathering, second because it allows a rigorous and exhaustive analysis of product behaviour.
- FMEA is used in order to identify and rank potential failure modes (thanks to criticality analysis), to determine their causes and effects, and thus to suggest relevant test procedure to characterise their durability.

3.4 Additional information

A FMEA analysis is generally supplement with a criticality analysis (FMEC̲A).
It consists in assessing, based on some criteria (occurrence probability, detectability, financial and human consequences gravity…) a criticality indicator for all identified failure modes.
The ranking or selection of failure modes is then possible. It directly influences the choice of the needed actions intended to increase the reliability and safety of the studied systems.

3.5 Application: FMEA of a Double Glazing Unit

Function	Element	Mode	Cause	Direct effect	Indirect effet
Resistance to environment	Glass	Cracking	Shocks	Integrity	Permeability, Transparency
			Wind stresses	Integrity	Permeability, Transparency
			Wind, shocks and T°C ... Action of frames	Integrity	Permeability, Transparency
		Deformation	Temperature	Integrity	Stress on joint
			Shocks	Integrity	Stress on joint
			Thermal shocks (cleaning hot vapour)	Integrity	Stress on joint
	Polysulfide sealant	Cracking	Process problem	Permeability (air&water)	Stress on butyl sealant
			Wind, shocks and T°C ... Action of frames	Permeability (air&water)	Stress on butyl sealant
			Wind, shocks and T°C ... Action of glass	Permeability (air&water)	Stress on butyl sealant
			Wind, shocks and T°C ... Action of spacer	Permeability (air&water)	Stress on butyl sealant
			Pollutants	Permeability (air&water)	Stress on butyl sealant
			Cleaning agents (Acid, base)	Permeability (air&water)	Stress on butyl sealant
			Temperature	Permeability (air&water)	Stress on butyl sealant
			Thermal shocks (cleaning hot steam)	Permeability (air&water)	Stress on butyl sealant
			Water	Permeability (air&water)	Stress on butyl sealant
	Butyl sealant	Cracking	Process problem	Permeability (air&water)	Failure of joint
			Wind, shocks and T°C ... Action of frames	Permeability (air&water)	Failure of joint
			Wind, shocks and T°C ... Action of glass	Permeability (air&water)	Failure of joint
			Wind, shocks and T°C ... Action of spacer	Permeability (air&water)	Failure of joint
			Thermal shocks (cleaning hot steam)	Permeability (air&water)	Failure of joint
			Temperature	Permeability (air&water)	Failure of joint
			Polysulfide failure … Pollutants	Permeability (air&water)	Failure of joint
			Polysulfide failure … Cleaning agents	Permeability (air&water)	Failure of joint
			Polysulfide failure … Water	Permeability (air&water)	Failure of joint
	Aluminium	Expansion	Temperature	Movements	Stress on joint
		Corrosion	Polysulfide failure …Water	Loss of material	Weak points (mechanical resistance)
			pollutants or Acid/base	Loss of material	Dust
				Expansion	Stress on joint
	Glass/sealant or spacer/sealant interfaces	Breaking	Process problem	Integrity	Permeability (air and water)
			Wind, shocks and T°C ... Action of frames	Integrity	Permeability (air and water)
			Wind, shocks and T°C ... Action of glass	Integrity	Permeability (air and water)
			Aluminium … Action of aluminium (T°C)	Integrity	Permeability (air and water)
			Incompatibility of materials	Integrity	Permeability (air and water)
			Temperature	Integrity	Permeability (air and water)
			Pollutants	Integrity	Permeability (air and water)
			Cleaning agents (Acid, base)	Integrity	Permeability (air and water)
			UV	Integrity	Permeability (air and water)
			Thermal shocks (cleaning hot steam)	Integrity	Permeability (air and water)
	Dessicant	Loss of absorption ability	? (Temperature, time, …)	Integrity	Increasing of humidity in cavity
Landscape vision	Glass (1&2)	Scratching	Cleaning method	Bad vision	-
		Cracking	Resistance to environment	Bad vision	-
	Air gap	Condensation	Water and air permeability (joint)	Bad vision	-
			Dessicant … Condensation	Bad vision	-
		Dust deposit	Water and air permeability (joint)	Bad vision	-
			Corrosion aluminium … deposit	Bad vision	-
Light transmission	Idem landscape vision				
Thermal insulation	Glass	Decreasing of insulating property	Cracking (resistance to environment)	Bad thermal insulation	-
	Air gap	Decreasing of insulating property	Water and air permeability (joint)	Bad thermal insulation	-
Acoustical insulation	Glass	Decreasing of acoustic property	Cracking (resistance to environment)	Bad acoustic insulation	-
	Air gap	Decreasing of acoustic property	Water and air permeability (joint)	Bad acoustic insulation	-

3.6 Application: Argon gas filled / Low-e coating window

Function	*Element*	*Mode*	*Cause*	*Direct effect*	*Indirect effet*
Resistance to environment	Glass	Cracking	Shocks	Integrity	Permeability, Transparency
			Wind stresses	Integrity	Permeability, Transparency
			Wind, shocks and T°C ... Action of frames	Integrity	Permeability, Transparency
		Deformation	Temperature	Integrity	Stress on joint
			Shocks	Integrity	Stress on joint
			Thermal shocks (cleaning hot vapour)	Integrity	Stress on joint
		Loss of performance	Flaw (Stone, scratch, …)	Reduce strength	-
	Polysulfide sealant (Sec. sealant)	Cracking	Process problem	Permeability (air&water)	Stress on butyl sealant
			Wind, shocks and T°C ... Action of frames	Permeability (air&water)	Stress on butyl sealant
			Wind, shocks and T°C ... Action of glass	Permeability (air&water)	Stress on butyl sealant
			Wind, shocks and T°C ... Action of spacer	Permeability (air&water)	Stress on butyl sealant
			Cyclic stresses	Permeability (air&water)	Stress on butyl sealant
			Pollutants	Permeability (air&water)	Stress on butyl sealant
			Cleaning agents (Acid, base)	Permeability (air&water)	Stress on butyl sealant
			Temperature	Permeability (air&water)	Stress on butyl sealant
			Thermal shocks (cleaning hot steam)	Permeability (air&water)	Stress on butyl sealant
			Water absorption	Permeability (air&water)	Stress on butyl sealant
	Butyl sealant (Prim. sealant)	Cracking	Process problem	Permeability (air&water)	Failure of joint / Condensation
			Wind, shocks and T°C ... Action of frames	Permeability (air&water)	Failure of joint / Condensation
			Wind, shocks and T°C ... Action of glass	Permeability (air&water)	Failure of joint / Condensation
			Wind, shocks and T°C ... Action of spacer	Permeability (air&water)	Failure of joint / Condensation
			Thermal shocks (cleaning hot steam)	Permeability (air&water)	Failure of joint / Condensation
			Cyclic stresses	Permeability (air&water)	Failure of joint / Condensation
			UV radiation	Permeability (air&water)	Failure of joint / Condensation
			Temperature	Permeability (air&water)	Failure of joint / Condensation
			Polysulfide failure … Pollutants	Permeability (air&water)	Failure of joint / Condensation
			Polysulfide failure … Cleaning agents	Permeability (air&water)	Failure of joint / Condensation
			Polysulfide failure … Water absorption	Permeability (air&water)	Failure of joint / Condensation
	Composite spacer	Expansion	Temperature	Movements	Stress on joint
		Breaking	lysulfide failure …Water, pollutants or Acid/ba	Loss of material	Weak points (mechanical resistance)
				Loss of material	Dust
				Expansion	Stress on joint

	Glass/sealant or spacer/sealant interfaces	Breaking	Process problem Wind, shocks and T°C ... Action of frames Wind, shocks and T°C ... Action of glass Aluminium … Action of aluminium (T°C) Incompatibility of materials Temperature Pollutants Cleaning agents (Acid, base) UV Thermal shocks (cleaning hot steam)	Integrity Integrity Integrity Integrity Integrity Integrity Integrity Integrity Integrity Integrity	Permeability (air and water) Permeability (air and water) Permeability (air and water) Permeability (air and water) Permeability (air and water) Permeability (air and water) Permeability (air and water) Permeability (air and water) Permeability (air and water) Permeability (air and water)
	Low-e coating				
	Dessicant	Loss of absorption ability	? (Temperature, time, …) Process problem (water absorption before manufacturing) Not enough amount used	Integrity	Increasing of humidity in cavity Increasing of humidity in cavity Increasing of humidity in cavity
Landscape vision	Glass (1&2)	Scratching	Cleaning method Collision or friction Accumulation of dirt	Bad vision Bad vision Bad vision	- - -
		Cracking	Resistance to environment	Bad vision	-
	Low-e coating				
	Air gap (Argon)	Condensation	Water and air permeability (joint) Dessicant … Condensation	Bad vision Bad vision	- -
		Dust deposit	Water and air permeability (joint) Corrosion aluminium … deposit	Bad vision Bad vision	- -
Light transmission	Idem landscape vision				
Thermal insulation	Glass	Decreasing of insulating property	Cracking (resistance to environment)	Bad thermal insulation	-
	Low-e coating				
	Air gap (Argon)	Decreasing of insulating property	Water and air permeability (joint)	Bad thermal insulation	-
Acoustical insulation	Glass	Decreasing of acoustic property	Cracking (resistance to environment)	Bad acoustic insulation	-
	Air gap (Argon)	Decreasing of acoustic property	Water and air permeability (joint)	Bad acoustic insulation	-

3.7 Application: Solar Collector

Function	Components	Mode	Cause	Direct effect
Resistance to environment	Box	Corrosion	Humidity + pollution	
	Fixings (on roof)	Corrosion	Humidity + pollution	Ruin
	Seal	Cracking	UV + Temperature Pollutants or cleaning agents	Loss of watertightness
		Creep	Dimensional variations of box (T°C) Wind, shocks, …	Loss of watertightness
	Glazing	Scratching	Cleaning	Decreasing of transmission
		Cracking	Shocks	Loss of watertightness
	Low emissive coating	Loss of performance	UV Humidity + Pollutants, Cleaning agents	Decreasing in thermal efficiency
	Absorber (Selective coating)	Loss of efficiency	Corrosion Humidity + Pollutants, Cleaning agents Excessive heating	Blistering, unsticking
	Absorber ("Plate")	Corrosion	Humidity + Pollutants, Cleaning agents	
	Absorber (Heat-conveying pipes)	Dissociation (Bad contact)	Corrosion (humidity, pollutants) Expansion / contracting cycles Design / manufacturing problem	Decreasing in thermal efficiency
		Breaking	Damages due to freeze	Ruin
		Obstruction	Sludge due to corrosion Chemical incompatibility in hydraulic circuit Corrosive action of heat-conveying fluid	Decreasing of flow
		Flow problems	Decreasing - Air trapping Excessive - Controller	Decreasing in thermal efficiency
	Fixing absorber / box	Corrosion	Corrosion (Humidity + pollutants)	Loss of performance
		Rupture	Corrosion (Humidity + pollutants) Wear (dimensional variations of absorber)	Ruin
	Connectors	Leakage	Wear of seal Corrosion (Humidity + pollutants)	Loss of watertightness
	Pipes	Corrosion	Humidity + pollution	
		Breaking	Damages due to freeze	Ruin
		Obstruction	Sludge due to corrosion Chemical incompatibility in hydraulic circuit Corrosive action of heat-conveying fluid	Decreasing of flow
		Flow problems	Decreasing - Air trapping Excessive - Controler	Decreasing in thermal efficiency
	Insulation	Ageing	High temeratures Water	Binder "departure" Water absorption

Function	Components	Mode	Cause	Direct effect
Confinement	Glazing	Cracking	Shocks Differences in thermal expansion	Loss of watertightness
	Glazing / seals	Dissociation	Incompatibility seal and glazing Design / manufacturing problem Movements of glazing	Loss of watertightness
	Seals	Cracking	UV + Temperature Pollutants or cleaning agents	Loss of watertightness
		Creep	Dimensional variations of box (T°C) Wind, shocks, …	Loss of watertightness
	Seals / Box	Dissociation	Incompatibility seal and box Design / manufacturing problem Movements of box (temperature...)	Loss of watertightness
	Box	Corrosion	Humidity + pollution	Loss of watertightness
	Box / pipes	Dissociation	Corrosion Design / manufacturing problem Movements of pipes Movements of box (wind, temperature...) Movements of box (problem in fixings)	Loss of watertightness
Energy collection	Glazing	Scratching	Cleaning	Decreasing of transmission
		Cracking	Shocks	Decreasing of transmission
		Dirt	External deposit dust, vegetation, pollutants Internal deposit (condensation) Internal deposit (binder of insulation)	Decreasing of transmission
	Insulation	Loss of efficiency	Confinement problem … Water absorption Manufacturing problem	Output heat flow (through the box)
	Low emissive coating	Loss of efficiency	UV, temperature Confinement … Humidity, Pollutants, Cleaning agents	Output heat flow (through glazing)
Energy transformation	Coating	Loss of efficiency	Corrosion Confinement … Humidity + Pollutants, Cleaning agents Excessive heating	Loss of thermal efficiency
	Absorber	Corrosion	Confinement … Humidity, Pollutants, Cleaning agents	Decreasing in thermal efficiency
	Absorber / HC pipes	Dissociation (Bad contact)	Corrosion (humidity, pollutants) Expansion / contracting cycles (excessive temperature) Design / manufacturing problem	Decreasing in thermal efficiency
	Heat-conveying pipes	Breaking	Damages due to freeze	Ruin
		Obstruction	Sludge due to corrosion Chemical incompatibility in hydraulic circuit Corrosive action of heat-conveying fluid	Decreasing of flow
		Flow problems	Decreasing - Air trapping Excessive - Controller	Inefficiency of heat exchanges
Heat transport	Pipes	Breaking	Damages due to freeze	Ruin
		Obstruction	Sludge due to corrosion Chemical incompatibility in hydraulic circuit Corrosive action of heat-conveying fluid	Decreasing of flow
		Flow problems	Decreasing - Air trapping Excessive - Controller	Inefficiency of heat exchanges
	Connector	Leakage	Corrosion	Decreasing in thermal efficiency

3.8 Comparison between IFMA and FMEA

IFMA **Initial Failure Modes Analysis**	**FMEA** **Failure Modes and Effects Analysis**
Objectives:	***Objectives:***
To identify relevant durability tests for components	To identify: - weak points (from design stage), - potential problems in construction process, - future in service behaviour.
Component approach	***Product approach*** ***(product behaviour deducted from material knowledge)***
Functional and general requirements (User's point of view) ↓ In use conditions definition ↓ Critical functional property (Required value and test methods) ↓ Failure / Damage / Degradation identification (Expert opinion / Field tracking studies) ↓ Degradation indicator and critical degradation factors ↓ Risk assessment (S, P_0, P_D) ↓ Ranking of failure modes: → relevant tests selection	Identification of functions (Product functions, role of components) ↓ Identification of in use conditions and construction process ↓ Modelling of product behaviour ↓ Degradation and failure modes, causes and effects ↓ Criticality analysis ↓ Ranking of failure modes: → durability information / relevant actions
Observation:	***Observation:***
- Reasoning based on the study of consequences (non ability to fulfil the functions). - Choice of the relevant test. - Quantitative approach (environmental stresses and required performance).	- Reasoning based on the modelling of product behaviour from materials behaviour. We take into account events chaining (normal behaviour or degradation of components) leading to product failure. - Decision elements for the choice of the relevant actions, i.e. product modification (risk analysis at design stage), maintenance planning or diagnosis (exploitation stage). - Qualitative approach.
Durability characterisation of a component towards environmental stresses (for the most probable and hazardous failure modes)	**Improvement of design, construction, use of product by identification of all failure modes and selection of the most probable and hazardous one.**

4 Service Life Prediction

4.1 Principle: From data to decision

Confronted with a complex problem (meteorology, toxicology, traffic management,…), an expert adopts the following approach:

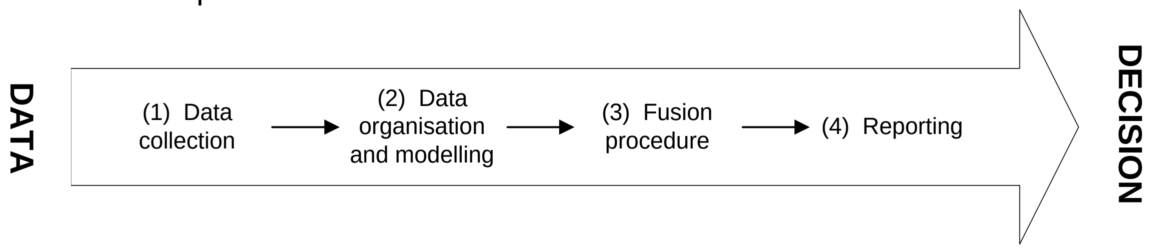
- first, he collects all data concerning the system (definition of the product, its environment,…) ;
- then he tries to understand and model all involved phenomena ;
- finally, from this modelling, he extracts decision elements (recommendations, elements for comparison of alternatives, assessment parameters to be used in other models, …).

In this context and especially in service life assessment problem, one of the major obstacles to decision-making is to be able to handle these both uncertain and heterogeneous information.

Experts need tools and procedure intended to extract the decision elements from all the available information, often with management of uncertainty and ignorance. The solution is data co-exploitation, that is to say “Simultaneous exploitation of several points of view on a data or on a method to process it.”
Such approach enriches the analysis (complementary information, analysis and exploitation of conflict) and leads to synthesised and consensual information. Furthermore, managing uncertainty and ignorance increases the credibility of the results.

4.2 Proposed approach

The four main steps are:



The two steps (1) and (2) lead to several models (several points of view) allowing service life assessment of building products.
Data fusion procedure (3) then extracts consensual information, which is presented as a useable format (4).
We will not detail each step, but briefly present the main aspect and key information.

4.3 Data collection

Several tools and methods for durability assessment currently exist (field tracking studies, expert opinion, accelerated testing, natural weathering, modelling (reliability models…), materials science, …
But their use implies some problems: non reproducibility and tracability of field tracking studies, subjectivity of expert opinion, length of accelerated tests and natural weathering, relevance of torture test, required quality and quantity of knowledge for

modelling (these studies are only available for simple and well-known materials or products, for one or two degradation phenomena).
Data collection consists in the collection of every available durability data on the product or one of its components, in its predicted environment or one of its parts.
Indeed, two types of service life data could be collected :
- Data wholly representing the system in its predicted environment;
- Data only representing a part of the system (component), and/or a part of the predicted environment (one degradation phenomena).

All this information is dispersed (multitude of sources and studies), dissimilar (scale, uncertainty formalism) and of various quality (strength of hypothesis...).

Example:
Let us illustrate this concept with a basic example.
We want to assess the service life of an external painted reinforced concrete wall.
Data collection is the search for:
- data on the system (RC wall),
- data on the system but in a specific environment (RC wall with respect to cracking under mechanical loads),
- data on RC wall components (concrete, paint and steel),
- data on degradation phenomena of these components (carbonation of concrete, corrosion of steel bars, …).

We have to keep all information that will be used for the quality assessment of data (see next paragraph “Model quality assessment”). We then provide the participant with a data collection sheet.,

4.4 Data Organisation and Modelling

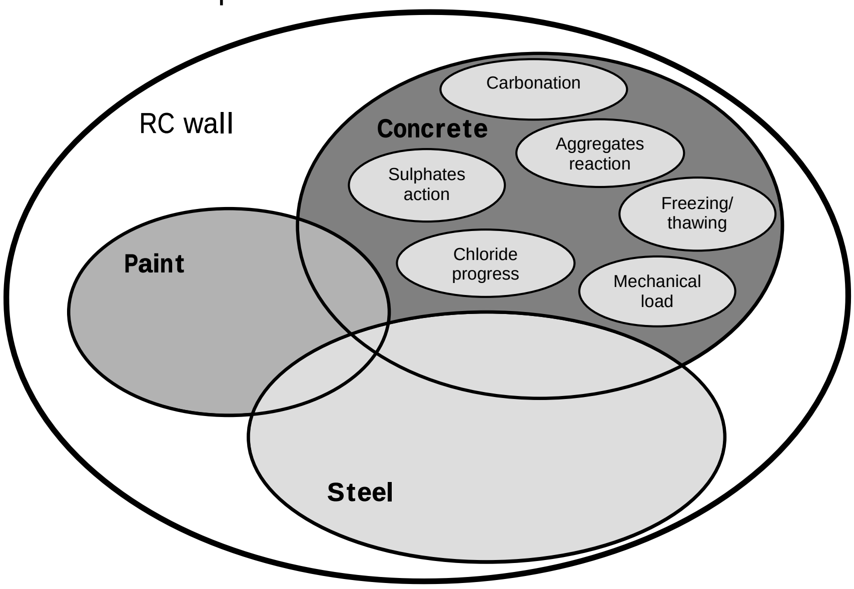
We want to assess the service life of the product in its predicted environment, but we have either global answer (type 1), or part of the answer (type 2). This problem could be explained in terms of **granularity**, that is to say the “fineness of the modelling grain”. Each data represents the system more or less finely, according to the “power of the zoom”.
This fineness is characterised by three dimensions of granularity.
- We define Geometrical granularity G_G and Phenomenological granularity G_P on a qualitative scale. G_G scale is “Materials, components, product”; and G_P scale is expressed according to the number of agents : “One, several and all agents”.
- Temporal granularity G_T (“raw” service lives SL = 60 years or precise modelling of degradation state, with regular time intervals).

An organisation step is needed in order to built models allowing a global answer from these partial answers. Data of similar granularities are simply placed on a same level.
For each level, a system behaviour model is built (let’s remind that it have to allow the assessment of product service life).
According to the level, various cases could be seen:
- If $G_G = G_P = 1$, datum represents completely the system (Service life of a reinforced concrete wall for instance).

- If $G_G < 1$ and $G_P = 1$, data represent partially the system, we have to geometrically aggregate these data (Degradation model of concrete, aggregated with degradation models of steel).
- If $G_G < 1$ and $G_P < 1$, then we have to do a double aggregation (Carbonation model, freeze/thawing model… and all degradation models of concrete phenomenologically aggregated to obtain a degradation model of concrete, then geometrically aggregated to obtain a system degradation model).

It implies that a good knowledge of the product and its behaviours is required, at a macro level (product, environment) as well as a micro level (materials, degradation agents).

Example:
RC wall behaviour could be represented knowing concrete, steel, paint behaviours and their interrelation.
Each component could be represented by sub-components or phenomena. Fig. 25 gives Concrete example.



Multi-model aspect of RC wall

4.5 Model quality assessment

We then associate with each service life assessment, a quantitative attribute *m* called “belief mass”. *m* belongs to [0, 1] (0 represents “no confidence” and 1 represents “certainty”). It represents the confidence we could have in an assessment and then should express the strength of hypothesis, uncertainties … of models, methods.

As an operational method, we proposed a simple multicriteria analysis, based on the Pedigree concept approach (developed by Funtowicz et Ravetz). Pedigree reflects the quality of information, and thus allows the characterisation of data production process with relevant pedigree criteria.
We have:
- chosen the relevant criteria which characterise the quality of an information,

- defined the assessment method for each criterion,
- proposed an aggregation method.

The chosen criteria C_i characterise according to us the three aspects of information quality : the way the service life data is produced (Granularity level, Theoretical structure, Input parameters, Reference), its format (Credibility), and the relevance of its use in our study (Geographical correlation, Temporal correlation, …[1]).
Each criteria is defined on a 5-levels qualitative scale [0, 1, 2, 3, 4], with a lexicographical correspondence. Aggregation method is simply a normalised average mean in order to obtain a [0, 1] mass.

We thus have a set of couples (SL, m) resulting from modelling step

4.6 Fusion procedure

4.6.1 Definitions

Each model giving a service life (SL) is called *evidence* (answer to the question: "what is the service life of this product ?").

An *evidence* is:
- focusing on a subset (of service lives) A of time scale [0, T], the set of possible answers (called "*frame of discernment*"). Let's remark that we will work on a continuous and orderly frame of discernment,
- characterised by a confidence attribute m. m(A) is the probability we only know "that", that is to say $SL \in A$.

An *evidence* is translated in belief function : a mass m is associated with A (probability to know only A), and its complement (1-m) is associated with the frame of discernment (probability to know only [0, T], that is to say to know nothing). The whole mass is thus distributed on time scale : $\Sigma = 1$ (i.e. certainty).
It's a mean to represent the knowledge contained in this considered model.

4.6.2 Principle

Let 1 and 2 be two evidences, respectively focusing on service lives subset $A_1, \ldots, A_n$ and $B_1, \ldots, B_m$, with belief masses m_1 and m_2.
Data fusion, which consists in the search of the resulting mass distribution grouping the knowledge of evidences 1 and 2 (see example) is done with Dempster rule:

$$m(\theta) = k \sum_{\substack{i,j \\ A_i \cap B_j = \theta}} m_1(A_i).m_2(B_j) \qquad \textbf{[1]}$$

Because of associativity, this rule is easily generalised to the fusion of several data (data fusion result is equal whatever the fusion order is).

Example

For example, if we fusion the two following data :
1 – A = [20, 40] with $m_1(A) = 0,6$
2 – B = [30, 60] with $m_2(B) = 0,7$

[1] The service life of a window in Sweden in 1960 is different of a window in France in 2000

then the resulting distribution of masses m_r is:$m_r(A) = m_r([20,40]) = 0,6.(1–0,7) = 0,18$
$m_r(B) = m_r([30,60]) = (1–0,6).0,7 = 0,28$
$m_r(A \cap B) = m_r([30, 40]) = 0,6.0,7 = 0,42$
$m_r(T) = (1–0,6).(1–0,7) = 0,12$

The sum of the four resulting masses is of course 1. It's a new evidence, grouping the knowledge contained in evidences 1 and 2, now focusing on three subsets and the frame of discernment.
That is to say: service life is probably [30, 40] (belief 0,42), without forgetting the sets [20, 40] et [30, 60] (respective belief values 0,6 and 0,7). Perhaps we are totally wrong and the result will be in any case "somewhere else" (Frame of discernment).

4.6.3 Limits

The existence of "**conflict"** (two conflictual data $A \cap B = \emptyset$) limit the validity of Dempster rule. A part of the resulting mass ($m_1.m_2$) is associated with empty set : it is called conflicting mass m_c.
Adaptations to Dempster rule are proposed in bibliography, association of m_c mass:
- to the union set, that is to say supposing one of the source is exact (Dubois),
- to the set "ignorance", representing indecision between the two sources (Yager),

The second problem is **"weak coherence"** ($A \cap B \approx \emptyset$). A weak coherence is the intermediate case between coherence and conflict. It leads to counter-intuitive results (the major part of the mass is associated with a small interval $A \cap B$). We then propose a rule in case of weak coherence. From a given overlapping limit *lim*. the mass is not associated with $A \cap B$ but with $A \cup B$ (when in doubt, we prefer indecision to uncertain choice).
But these rules involve either the loss of associative aspect, or the loss of informativity (SL = 60 yrs is informative, SL $\in$ [0, 200] yrs is non informative).
Given these various problems, a universal rule, suitable for any set of data, can't be found.

4.6.4 Solution

We have to define decision rules allowing the choice of the most relevant rule for the initial set of data: to define a **fusion strategy**.

4.7 Reporting

After fusion, the resulting mass distribution on T subsets is obtained.

4.7.1 Failure distribution

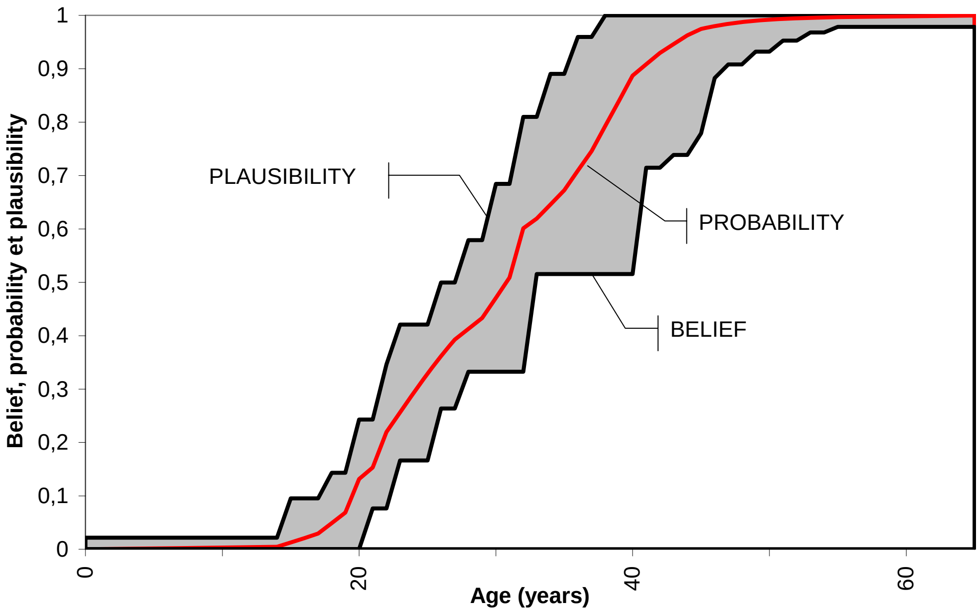
The result presentation generally used in durability domain is failure probability distribution. Adapted to our approach, the a priori probability (pignistic probability of Smets) we could observe a failure before t, is given with the following formula, $[x_i, y_i]$ is the interval n°i resulting of fusion :

$$P([0,t]) = \sum_{x_i < t} \frac{m([x_i, y_i])}{\left|[x_i, y_i]\right|} \qquad \textbf{[2]}$$

With Evidence Theory, two curves called belief (BEL) and plausibility (PL) curves are associated with the cumulative probability distribution, from the same information.
Bel ([0, t]), the belief at t, is the measure of the belief we have to observe a failure before t.
Pl([0, t]), the plausibility at t, is a measure of how much we can believe in a failure before t, assuming all unknown parameters are supportive of a failure after t.

$$\mathrm{Bel}([0,t]) = \sum_{[x_i,y_i]\subseteq[0,t]} m([x_i,y_i]) \quad \& \quad \mathrm{Pl}([0,t]) = \sum_{x_i<t} m([x_i,y_i]) \qquad \textbf{[3]}$$

These curves surround probability curve, it's in some way optimistic and pessimistic values of P. They draw a zone, which we call "uncertainty zone" (Fig. 24).



Failure distributions

4.7.2 Characteristic service lives

From this graph, characteristic service lives ***SL_k*** are assessed as follows, for an acceptable risk ***k*** (depending on gravity and cost of consequences, impact on system and environment, human and goods…):

$$SL_k \;/\; P(SL \le SL_k) \le k \qquad \textbf{[4]}$$

It is the service life SL_k for which the probability of observing a lower real service life SL than the characteristic service life SL_k, is lower than the considered k.
On this example, $SL_{10\%}$ = 20 years, with the interval [15, 26] years.

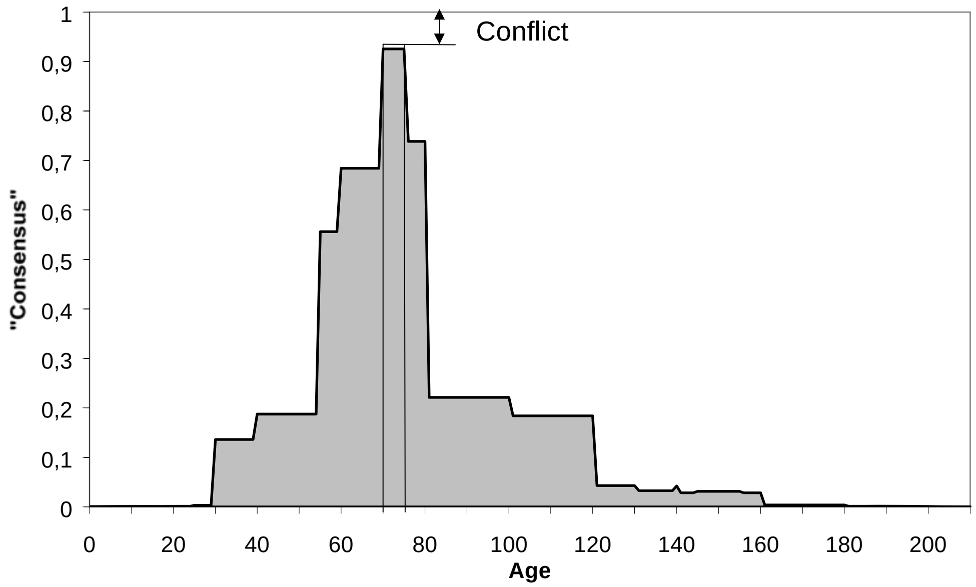
4.7.3 Consensual curve

The consensual service life or "contour function" is the distribution of masses on the frame of discernment.
for a given service life t is consequently the sum of the masses of all resulting sets t belongs, that is to say :

$$C_f(\{t\}) = \pi(t) = \sum_{t\in R_i} m_i \qquad [$$

C_f verifies $0 \leq C_f \leq 1$ since $\sum_{R_i} m_i = 1$.

These curves give the service life which groups the majority of consensus, [70, 75] (Fig. 25). That is to say: "[70, 75]years groups most of the vote".
For this value, the complement to 1 indicates the existence of conflict (some data don't predict this service life).



Consensual curve

4.7.4 Results qualification

We wished results qualification. In this purpose, two indicators are defined:

- Q_A = quality and relevance of the used fusion rule, according to quoted parameters (conflicting mass which govern the validity of Dempster rule, loss of information due to non relevant fusion strategy),
- Q_I = information contained in the result (surface of the uncertainty zone).

It's very important to remember that we could obtain a result even in case of poor quality data ("Garbage in, garbage out"), but it involves:

- a bad Q_I (wide uncertainty zone) synonymous of bad knowledge,
- a bad Q_A which means conflicting data or loss of information (not credible and not usable results).

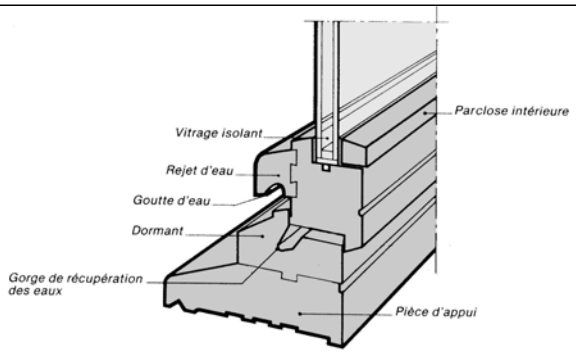
The solution is obviously an improvement of input data, increasing the accuracy and the confidence in the first case, increasing the coherence in the second case.

The other interesting advantage of this method is to point out a lack of data. Then we focus data research or production (products or degradation phenomenon seldom studied).

4.8 Example: Wooden window

4.8.1 Case study

As an example, we will study a basic wooden window with a double glazing unit.



4.8.2 Data collection, Data organisation and modelling

Data n°	Level	Sources & service life		1	2	3	4	5	6	Masses
1	**1**	[OCF,85]	{25 ; 30 ; 35} yrs	4	0	1	1	0	1,80	***0,33***
2	**1**	[EPFL,95]	30-70 yrs	4	1	4	2	2	3,14	***0,67***
3	**1**	EPFL-LESO (1)	30-50 yrs	4	1	1	1	2	2,55	***0,48***
4	**1**	EPFL-LESO (2)	40-60 yrs	4	1	1	1	2	2,55	***0,48***
5	**1**	EPFL-LESO (3)	{30 ; 50 ; 70} yrs	4	1	1	1	2	2,97	***0,50***
6	**1**	[GUMPERTZ,96]	25-50 yrs	4	0	2	1	1	2,74	***0,45***
7	**1**	[AMMAR,80]	{30 ; 45 ; 60} yrs	4	1	1	1	1	2,73	***0,45***
8	**2**	Model	Distribution	2	2	3	3	2	3,56	***0,65***

– DDV (Wooden window) = 30 yrs
– DDV (Wooden window) = 30-70 yrs (80 % degradation)
– DDV (Pine window) = 30-50 yrs
– DDV (Pine window) = 40-60 yrs
5 – DDV (Wooden window) = 50 yrs
6 – DDV (Window) = 25-50 yrs
7 – DDV (Window) = 45 yrs (mean) but minimum 30 yrs
8 – DDV (Statistical study wooden window) = distribution.

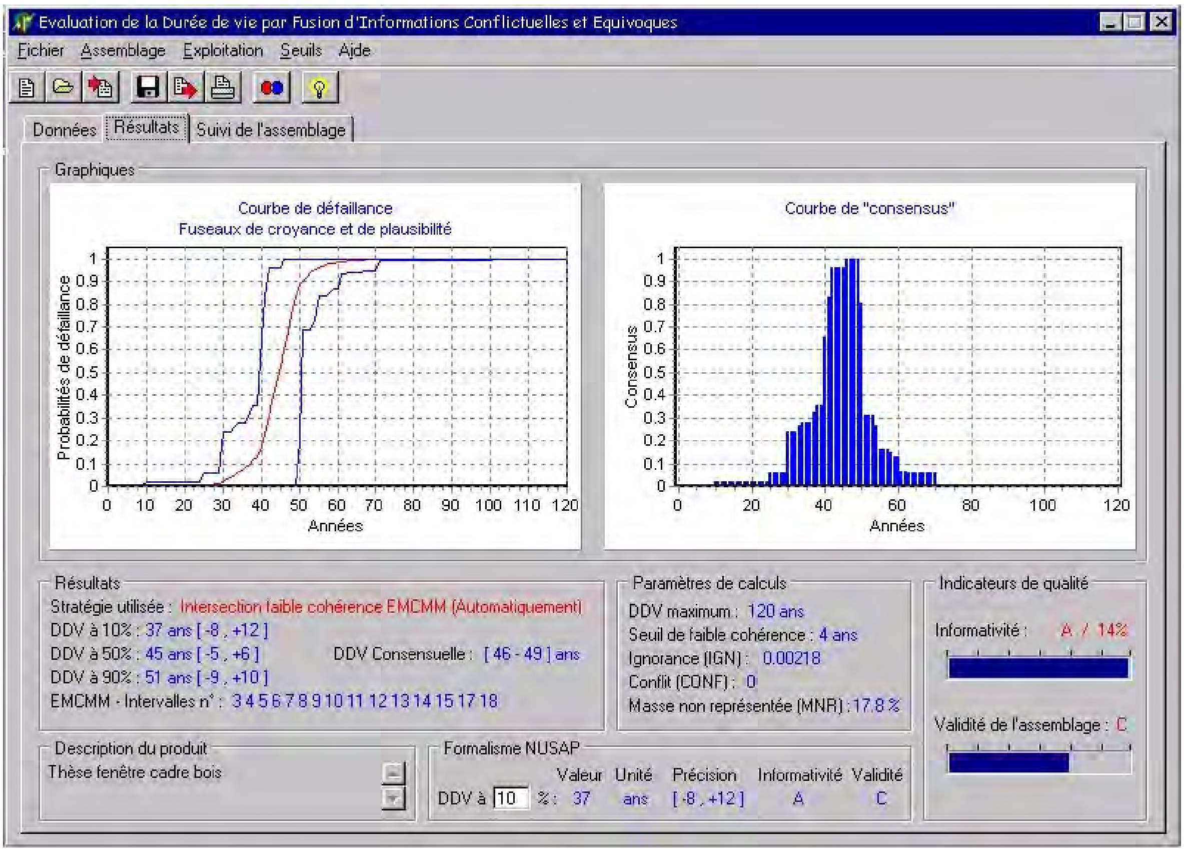
Data n°8 stems from a complete statistical study of failures.
We have the distribution of probability according to the failure mode and the corresponding service life.

Failure	Component	Cause	Probability	Service life
Water tightness	Assembly	Wood contraction	7.5	20-35
		Faulty glueing	2.8	1-10
		Others	2.6	30-70
	Opening / fixed pieces	Faulty draught-proofing	2.9	< 10
		Others	0.4	30-70
	Opening piece / windowsill		17.2	20-35
	Opening / Opening pieces		2.9	20-35
	Glazing unit / Wood	Glass rebate failure	3.1	30-70
		Glazing bead failure	0.5	1-10
		Others	0.3	30-70
	Wood / Wall	Faulty draught-proofing	17.6	10
		Faulty sealing	10.5	15-20
		Others	1.3	30-70
Air tightness		Wood contraction	3.4	20-35
		Faulty sealing	1.3	15-20
		Gap between opening	1.2	20-30
		Others	0.9	30-70
Materials degradation		Wood rotting	4.8	10-100
		Insect	0.4	10-100
		Glazing	1.8	15-20
Deformation		Wood contraction	2.2	20-35
		Glazing blocking	0.5	7
Fittings		Alloy weathering, wear of mechanisms	2.0	15

Wooden window model

4.8.3 Fusion procedure and reporting

Fusion procedure is done with the software developed in CSTB.
The screen copy of the results includes:



Service life assessment of a wooden window (Reporting)

probability distribution of failure and its uncertainty zone (upper left part of the graph),
- consensual curve (upper right part),
- characteristic service lives (lower left part),
- quality assessment (lower right part).

The result is:
- $SL_{10\%}$ = 37 years [-8, +12],
- SL_C = [46, 49] years.

Result is medium-quality; they are informative (quality A) but don't take into account some conflicting data (nearly 18%)

4.9 The Factor method ISO 15686

4.9.1 History

The Factor method is described in the standard ISO 15686-Part 1, published in 2000 by ISO (ISO, 2000), which is the first part of a series of standard dealing with service life planning of building and constructed assets.
The method is presented as a simple and deterministic approach. It is based on similar factorial methods which have been developed in Japan, and has been under discussion and evaluation for several years within the international committee CIB W80 / RILEM 175-SLM "Service life methodologies".
On one hand, the ISO factor method represents a simplification compared to the Japanese methods. On the other hand, this simplification gives less opportunity to take care of important issues as material used, special climatic conditions and other circumstances.

4.9.2 Factor method (ISO 15686-1)

The factor method described in (ISO, 2000) allows an estimate of the service life to be made for a particular component or assembly in specific conditions. It is based on a reference service life (normally the expected service life in a well-defined of in-use conditions that apply to that type of component or assembly) and a series of modifying factors that relate to the specific conditions of the case.

The various modifying factors are:
- A (quality of the components),
- B (design level),
- C (work execution level),
- D (indoor environment),
- E (outdoor environment),
- F (in-use conditions),
- G (maintenance level).

They can be detailed as follow:

Factors		1.1.1.1 Relevant conditions (examples)	
Agent related to the inherent quality characteristics	A	Quality of the components	Manufacturing, storage, transport, materials, protective coatings, …
	B	Design level	Incorporation, sheltering by rest of the structure
	C	Work execution level	Site management, level of workmanship, climatic conditions during the work execution
Environment	D	Indoor environment	Aggressiveness of the environment, ventilation, condensation
	E	Outdoor environment	Elevation of the building, micro-environment conditions, traffic emissions, weathering factors
Operating conditions	F	In-use conditions	Mechanical impact, category of users, wear and tear
	G	Maintenance level	Quality and frequency of maintenance

Table H.1 — Detailed factors for steel lintels

			RELEVANT CONDITIONS			
			To include:	POOR (0.8)	ASSUMED (1)	GOOD (1.2)
Inherent quality characteristics	A	Performance of Materials	Material type and/or grade	Not to BS 5977.	Mild steel sheet, pressed and welded as BS 5977.	Stainless steel or heavy duty mild steel.
			Durability features e.g., protection system	Less than G275 galvanising + BS 5977 paint/coating.	Pre-galvanised (G275), and coated with BS 3416 bitumen or 25 micron BS 5493 HF paint or Pre-Pre-galvanised (G600).	Post-galvanised to BS 729 (920 or 1420 g/m^2).
	B	Design level	Details of construction e.g., joints, fixings	Inadequate weatherproofing (joints not fully filled, inadequate cavity tray provision, no cladding over lightweight blocks).	Embedded in cavity wall with either brick outer skin or cladding over lightweight blocks. All joints fully filled.	Additional DPC tray and/or bitumen coating provided during installation.
	C	Work execution level	Site work e.g., not to BS 8000, with specific e.g's.,	No repair to site alterations and/or damage.	No repair of damage associated with storage or installation, but no site alterations.	All site damage fully repaired.
Environment	D	Indoor environment conditions	Special features, e.g., condensation	Browning plaster to inner skin with condensation risk.	Browning plaster to inner skin with no condensation risk.	Sand/cement or Browning or metal lathing plaster.
	E	Outdoor environment conditions	Special features e.g., marine or polluted	Polluted industrial or marine environment.	Urban, inland environment but not particularly polluted.	Rural, inland and unpolluted environment
Operation conditions	F	In-use conditions	Special features e.g., vandalism	Not applicable.	Not applicable.	Not applicable
	G	Maintenance	Cyclical, inc. quality	Not applicable.	Not applicable.	Not applicable

Assessment of factors (example)

"Any one (or any combination) of these variables can affect the service life. The factor method can therefore be expressed as a formula:

The Estimated Service Life of a Component (ESLC) is defined with:
ESLC = RSLC x Factor A x Factor B x Factor C x Factor D x Factor E x Factor F x Factor G"

The Reference Service Life of a Component (RSLC) is defined as the "service life that a building or parts of a building would expect (or is predicted to have) in a certain set (reference set) of in-use conditions."

"The factor method is a way of bringing together consideration of each of the variables that are likely to affect service life. It can be used to make a systematic assessment even when little or no reliable test data is available. Its use can bring together the experience of designers, observations, intentions of managers and manufacturers assurances as well as some data from test houses

4.9.3 Evaluation, Practical use and Further developments

Most of the discussion and evaluation has been on a theoretical basis (Architectural Institute of Japan, Jonathan W. Martin, Kathryn Bourke, Klaus Rudbeck, Per J. Hövde, Konrad Moser) and so far there has been limited experience using the method in practice.

Several applications are quoted by P.J. Hövde:
- D.P. Wyatt and A. Lucchini (1998, 1999),
- E. Vesikari (2000) on concrete facades,
- G. Hed (2000) on several components and products,
- B. Marteinsson (2001) on wooden window (biological deterioration).

Improvements are suggested in several studies: individual statistical treatment of each factors, range of service life instead of deterministic value, refinement in the definition of the factors (sub-factors).

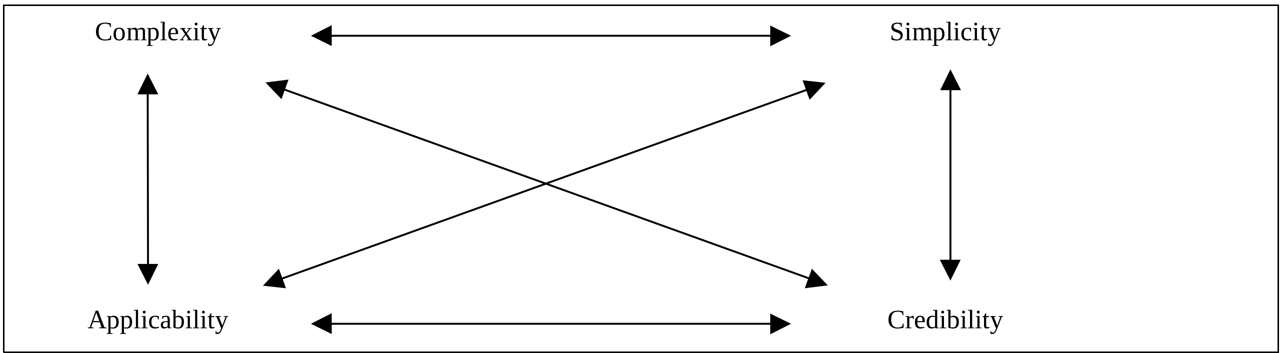
For instance, some authors propose variances (formula, factors, …), so that the method is adapted to the product studied. They can be expressed on a generic way with the following formula: $\mathrm{ESL} = \sum_j \left(\mathrm{RSL}_j \times \prod_i \mathrm{F}_{j,i} \right) + \sum_k \mathrm{F}_k$.

Example: Wooden building in the case of biological deterioration
The estimated service life is given by $y = y_s \times B \times C \times D + M$ *, where*

y_s is the standard durability value of structural members
B the coefficient of the design level,
C the coefficient of the work execution level
D the coefficient of the site, environment and building conditions
M the coefficient of the maintenance level.

Others have tried to include a probabilistic approach in the selection of the factors value, to use probabilistic distribution for each factors.

The objective of these further developments (refer to (HOVDE, 2000)) is always to give a more reliable and credible service life estimation (given the uncertainty on the collected data), without increasing the complexity (which leads to non applicable methods).



Service life prediction methodologies – Constraints (Hövde, 2000)

We can at least use the “basic” factor method proposed in the ISO standard, or develop a more accurate factor method that take into account the expertise:

- refining factors in order to focus on the most probable degradation phenomena,
- using probabilistic distribution (based on field tracking studies) for the definition of factors.

By means of a Failure Modes and Effects Analysis, we are able to define more accurately the factors (parameters influencing the service life) and thus estimate the parameters that affect the service life.

FMEA results as a justification of factors

Factors		**1.1.1.2 Relevant conditions (examples)**	
Agent related to the inherent quality characteristics	A	Quality of the components	Quality of the frame (material, assemblies, …) Quality of the protection (coating, paint, …) Quality of the DGU (sealant, spacer, …)
	B	Design level	Water evacuation (glazing bed) Stresses on the DGU sealant …
	C	Work execution level	Quality Assurance Plan of the supply chain (geometrical tolerances, oil deposit on glass, …) Incorporation in the building (air pressure, wall geometry, …) …
Environment	D	Indoor environment	Temperature Humidity Mechanical stresses …
	E	Outdoor environment	Temperature Humidity Mechanical stresses Pollutants …
Operating conditions	F	In-use conditions	Aggressiveness of Opening/Closing stresses …
	G	Maintenance level	Quality and frequency of maintenance actions (protection, water evacuation, …)

5 Conclusion

The main effort during the C2 project has been put on FMEA: presentation and explanation of the methodology, development of case studies on DGU's and solar collector, opportunity of a common work between CSTB and ASPEN. The resulting documents would have benefited from a wider review from all the participants, while only one or two contributors provided inputs and comments.

FMEA is known as the tool for predicting failure modes out of the confrontation of a functional diagram on one hand, and on the other hand the compilation of possible degradations.
It can be seen also as a design tool. "Andersen windows" company in USA use currently FMEA when designing new products, putting around the table the relevant experts. But how a small company, with a limited group of experts, can use FMEA? The solution could be to build up a core FMEA table for generic products, gathering the existing expertise, so that the users may start from a basic knowledge. So FMEA may appear as a knowledge management tool for design assistance.

The need for service life assumption appears as an objective for several product oriented projects. It is a growing concern in the construction sector:

- More precise figure for service life expected
- International standardisation in progress
- Task group on durability within the CEN CSN (Construction sector network)
- Demand for a better implementation of the durability in the EU CPD (construction product directive)
- Setting up of national durability assessment groups (France, Sweden, …)

This report present data fusion procedure and the factor method. These tools associated to FMEA can be interesting to fulfil the need of service life prediction.