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INDOOR RADON AND AIR QUALITY INVESTIGATIONS IN NEW OR RENOVATED ENERGY-EFFICIENT SWISS SINGLE-FAMILY DWELLINGS

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DESIGN SAFE, COMFORTABLE AND HEALTHY ENVIRONMENT; TOOLS DEVELOPMENT (GUIDELINES, SOFTWARE, ETC)

Research summary

The perspectives of a new energy crisis subsequent to the depletion of natural resources along with the increase of energy costs make, more than forty years after the first oil crisis, energy savings a priority. This lead to rethink building practices so as to make it more sustainable and economical in terms of energy consumption by ensuring the air tightness and a good thermal insulation. Indeed, the less we ventilate such sealed houses, the more moisture, number and level of pollutants increase in the indoor environment. The deterioration of the indoor air quality and the appearance of occupants non-specific health disorders are the consequences. Preliminary results indicate the attention to pay to energy-efficient buildings. On the one hand, the concentration of indoor radon has a clear tendency to increase after an energy saving action. On the other hand, it appears that even though the new Swiss energy efficient houses seem less affected by this problem than the traditional renovated houses, or even transformed according to these label requirements, unexpected situations may still arise. People living in energy saving buildings need to be well informed about the risks and about "what-to-do and not-to-do" living in such "high tech" houses. Maintenance of technical installation can also be troublesome.

Keywords: Energy-efficient single family dwellings, radon concentration, indoor air quality

1. Introduction

Results reported in this paper come from a research project termed Mesqualair led by the School of Engineering and Architecture of Fribourg in Switzerland, which aimed at evaluating indoor air quality over a large sample of new, or refurbished, energy-efficient single-family dwellings. Air quality is assessed by analysing individuals' exposure to radon, VOCs (volatile organic compounds) and molds. This paper is focusing on radon gas concentration in dwellings located in the six French Cantons of Switzerland. Some of the results are compared with few others coming from a similar project done in the Italian part of Switzerland.
Radon is a radioactive and inert gas found naturally under the ground. It is part of the decay chain of uranium. Radon gas atoms can in turn disintegrate, producing polonium, bismuth and lead. These radioactive decay products combine to airborne particles and tend to concentrate in confined spaces. When inhaled, they can be deposited in the lungs and irradiate lung tissue, possibly leading to cancer (Federal office of public health, FOPH, 2015). Radon gas can easily come up to the surface through permeable grounds. Therefore, spatial gradients of radon concentration may be significant. In Switzerland, areas with significant radon concentrations are mainly found in the Alps and the Jura mountains. In some cases, however, high concentrations have also been measured in buildings on the Central Plateau. Thus, radon may be found anywhere.

2. Research objectives

The research question is to determine if energy-efficient buildings practices have an impact on indoor air quality. In these buildings a particular attention should have been paid to the envelope's air tightness as well as to the ventilation. Unfortunately, this is not always true.
Already in 2003, a study established the correlations between ventilation and radon levels in family dwellings (Janssen, 2003) showing that indoor radon levels are well correlated with airtightness and occupants' behaviour regarding ventilation. The author was confident that future energy-efficient dwellings with improved airtightness would suffer from increased indoor radon concentrations.
Several studies suggested that situations that overrun recommended values for radon or more generally for indoor air quality in energy-efficient dwellings are not isolated (Guhr 2004 in Austria and Kirchner et al., 2011 in France and Poffijn et al., 2012 in Belgium). Milner et al. (2014) demonstrated that mean indoor radon concentrations are enhanced by approx. 56.6% in dwellings presenting an increasing airtightness without compensation by ventilation. High radon levels are observed in low-energy and passive houses due to the enhanced pressure difference resulting from the interaction of mechanical ventilation and high air tightness (Arvela et al., 2014).
In Ticino, CH, a research was conducted by Gambato et al. (2014) in order to measure indoor radon levels in 225 family houses as well as to evaluate the ventilation system efficiency. Among them 146 were new and 26 renovated buildings. These buildings were then compared to the 4216 measurements made between 2005 and 2010 in traditional houses. Globally the averaged radon concentration in Minergie labelled dwellings was not as high as in traditional ones and the difference was even shown to be statistically significant ($p<0.001$). Another study from Pampuri et al. (2012) over 160 traditional family dwellings for which a radon level was known before energy

retrofitting highlighted that in 25% of the houses radon levels were higher than before renovation. They also noted that 50% of the buildings reached over 300 Bq/m^3, reference value recommended by the FOPH. The same has been observed by Yarmoshenko et al. (2014) in Russia in energy-efficient multi-storey buildings.

According to Hamilton et al. (2015) energy retrofits in buildings can improve indoor air quality as well as energy consumption if air renewal is warranted by an efficient ventilation system. To improve indoor air quality, it is necessary to be aware of the indoor air pollutants balance as well as being informed of the need for good air exchange.

In the Mesqualair project, one third of the buildings are labelled Minergie (183 are new ones and 30 are renovated) and the two other third are traditional energy rehabilitation. The first point of interest is to get a global overview of the situation of indoor air quality in single family dwellings. Then we want to determine if new efficient houses offer better indoor conditions than renovated ones. In the first case, everything should have been planned to ensure airtightness and good air renewal. In doing so, new energy-efficient building should be less problematic than refurbished ones. According to this assumption, Minergie building should normally offer more favourable health conditions. Finally recommendations will be addressed to architects and construction companies in order to help them anticipating the problem.

3. Statistical description and method

Three types of houses have been selected for this study. One group is composed by newly

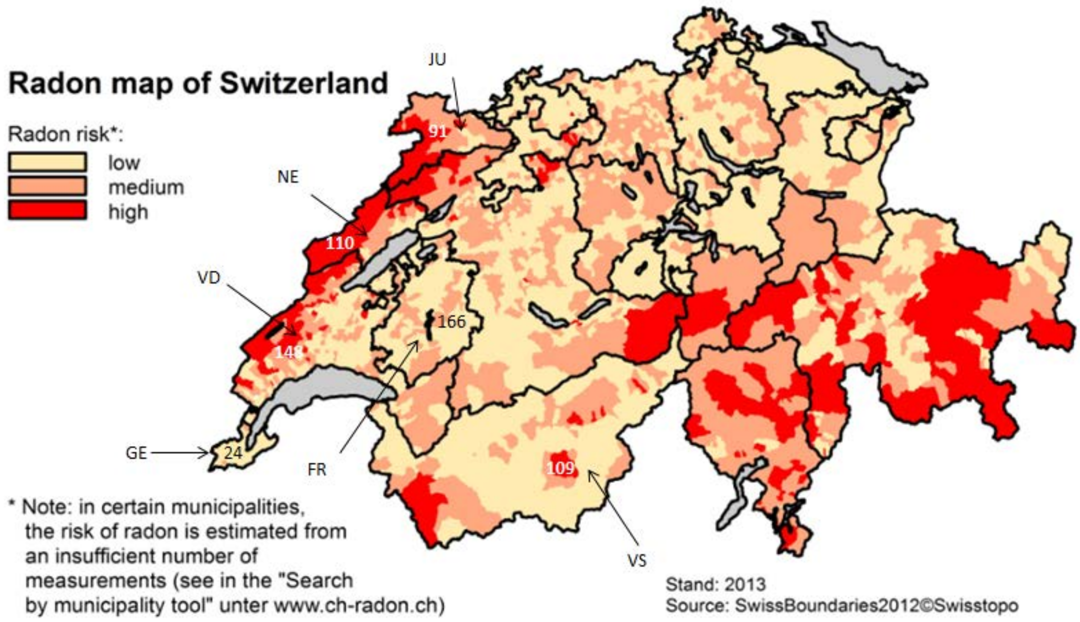

Fig 1: Radon risk in Switzerland (FOPH, 2013). French part of Switzerland is composed by 6 regions: FR – Fribourg, VS – Valais, GE – Genève, VD – Vaud, Ne – Neuchâtel and JU – Jura. Numbers indicate how many single family dwellings have been measured during Mesqualair study.

built efficient energy houses, labelled Minergie (NM). Another smaller group gathers traditional dwellings that have been refurbished and are also labelled Minergie

(RM). Finally, the third and larger one, contains traditional houses that have been totally or partially renovated (RT). A questionnaire has been addressed to all these dwellings. Radon level was measured using dosimeters exposed during at least three months during winters of 2013 and 2014 in a living room of the house close to the ground level. The distribution of measurements across Swiss regions is shown in Fig 2. Colours refer to those of the radon map of Switzerland (Fig 1).
More than the regions, the risk area seems to be more interesting. Tab 1 provides statistics of dwellings population according to radon risk area. We notice that half of the population is living in medium zone and one fourth in each extreme area. We should also notice that we have globally twice RT than M houses.

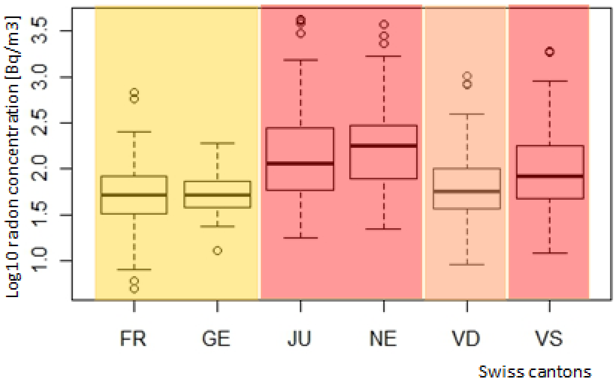

Fig 2: Radon distributions across Swiss regions.

Number of dwellings	Minergie (M)		Renovated	All types
Risk area	NM	RM	RT	
All	181 (28%)	32 (5%)	436 (67%)	649
High	30 (14%)		128 (29%)	158 (23%)
Medium	109 (51%)		236 (54%)	345 (53%)
low	74 (35%)		72 (17%)	158 (24%)

Tab 1: Number of dwellings according to radon risk area.
Taking into account all the new and refurbished single dwellings, indoor radon concentrations are on average higher in the high radon risk area, according to the FOPH standards. Geologic factor also seems to be a determinant.

A total number of 649 houses have been radon tested and, among them, 615 did return the questionnaire. About 125 questions have been asked to the occupants. They cover about 11 specific topics from construction considerations to building materials, equipment and use, organization in the house, damages, life customs, comfort perception as well as energy consumption. Half of the samples is located in medium risk area and approximately one fourth in each are located in high and low risk areas. Descriptive statistics of the population show a huge dispersion of radon level from 6 Bq/m^3 to 4284 Bq/m^3 (Table 2). Radon concentration is rather higher in traditional houses than in Minergie ones.
According to FOPH, radon mean concentration in Switzerland dwellings is around 75 Bq/m^3. We have monitored some high concentrations even in Minergie houses. Radon probability density function is lognormal (Fig 3) (Daraktchieva et al., 2014).

Radon concentration [Bq/m³ of air]	All types of dwellings	Minergie dwellings	Traditional dwellings
Minimum	6	6	16
1st quartile	43	31	50
Median	72	48	90
Mean	183.8	87.3	229.3
3rd quartile	149.5	89.5	191
Maximum	4284	1594	4284

Tab 2 : Descriptive statistic of Mesqualair population.

It was then decided to test the effect of different variables on radon concentrations using ANCOVA tests taking into account covariables such as *risk area* and *Traditional/ Minergie* when applicable, after applying a logarithmic transformation to normalise the distribution.

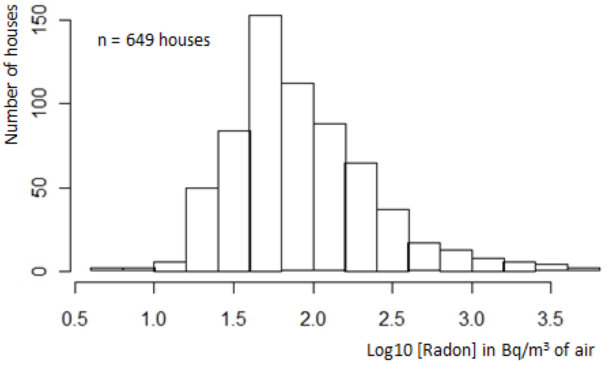

Fig 3: Log10 radon concentration probability density function.

4. Results

Many variables have been tested in order to describe the sample and also to understand radon behaviour in different environments and conditions.

4.1 Effect of type of dwellings

Looking at radon behaviour in the two main types of dwellings, it is found that radon level difference is statistically significant ($p<0.01$) between these types (Fig 4). Radon levels are significantly higher in traditional houses. The tendency is the same among Minergie dwellings comparing new and refurbished ones (Fig 5). These results are similar as those found in Ticino (Pampuri et al., 2012).

4.2 Effect of the radon risk area

The comparison of radon levels according to risk area in all buildings shows that radon concentrations are significantly higher ($p<0.01$) in high risk zone than in medium or low areas (Fig 6). Presumably, the type of dwelling and its location according to the radon map is having an important impact on the indoor radon level. Renovated building located in high risk area seems to have a greater risk to experience high radon levels (Fig 7). Globally a renovated house is having higher risk of presenting higher indoor radon level than a new energy efficient house.

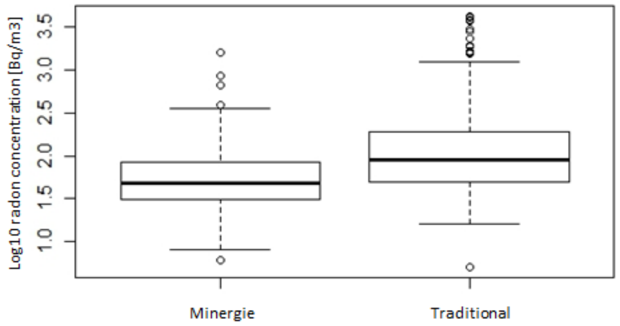

Fig 4: Radon concentration in the two main types of dwellings included in Mesqualair study.

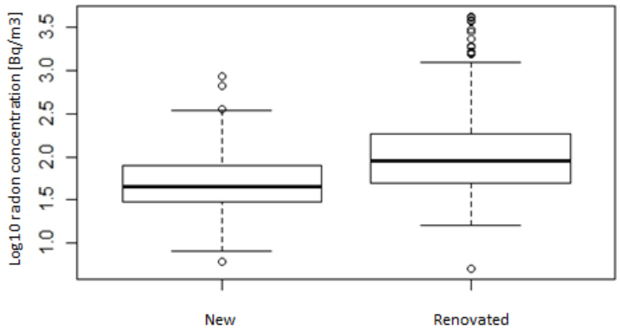

Fig 5: Radon concentrations in new or renovated dwellings.

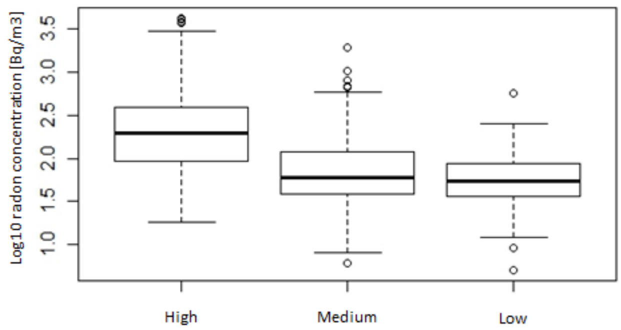

Fig 6: Radon level according to radon risk area.

4.3 Effect of natural ground inside the house

Among the studied houses, 40% have bare and natural ground including 60 Minergie dwellings and 205 traditional ones. Does inside natural ground enhance the risk of indoor high radon level specifically in radon high risk area? The answer is "yes", radon levels are significantly higher when natural ground is found at the basement ($p<0.004$).

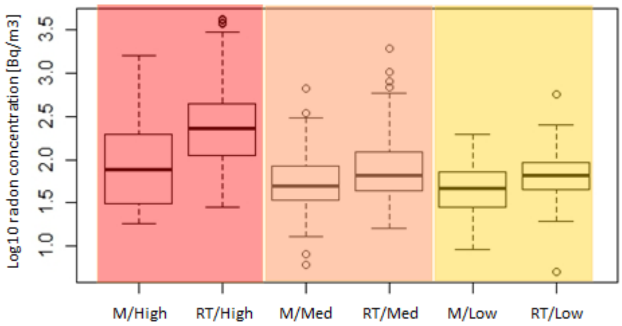

Fig 7: Radon level according to the type of house and the radon risk area.

Comparing RT and M dwellings, with or without bare ground, radon levels are globally higher in RT houses (Fig 4) and even slightly higher in both types when dwellings have natural ground in the basement (Fig 8).
Is this effect reinforced in area prone to radon? As can be seen at Fig 9, the effect in RT dwellings is not so different as previously described. Nevertheless, high risk area is responsible of higher radon levels and even more with natural ground inside.
In M houses the effect is well much marked in high radon risk area when having natural ground in the basement than without.

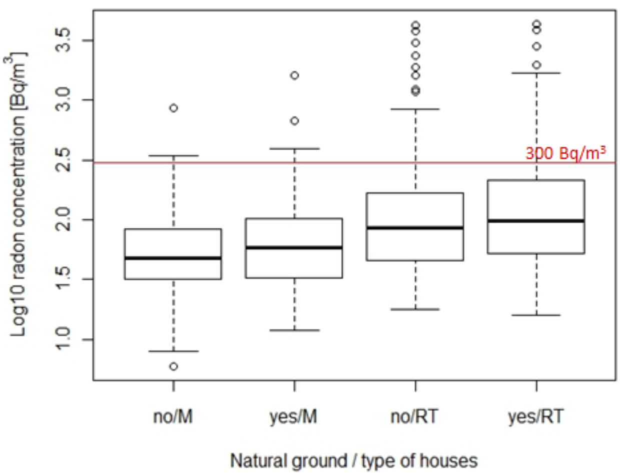

Fig 8: Boxplots of M and RT houses experiencing or not natural ground in the basement.

The only 8 houses composing this group are experiencing globally much higher radon levels compared to other M dwellings but however smaller than the highest RT radon levels.

So, in area prone to radon, it is always desirable to undertake preventive measures whatever the type of renovation (M or RT) in order to take into account the radon risk in the dwelling.

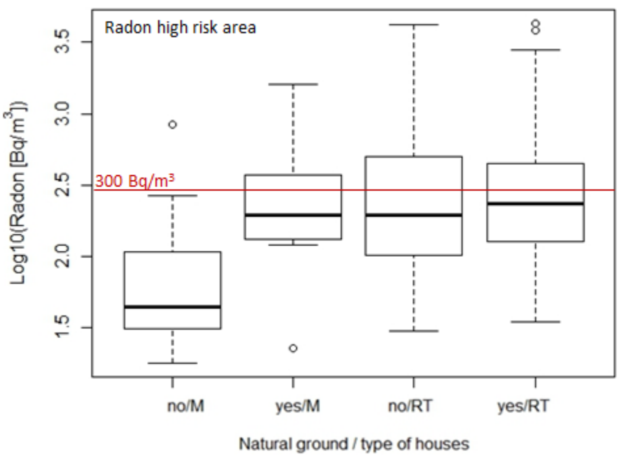

Fig 9: Boxplots of dwellings experiencing or not natural ground in the basement in high risk area.

4.4 Effect of energy retrofitting

Some owners undertook a global and some others a partial energy retrofitting of their dwelling a few years ago. To determine the consequences of such interventions, we tested these separately. As shown on Table 3, targeted intervention doesn't seem to have great impacts on indoor radon level. Interestingly enough, as long as when the building envelope is concerned by the energy remediation, the response is immediate and significant. As soon as external walls, floors, windows and roof are improved from the viewpoint of energy efficiency, radon levels turn out to be higher compared to the other cases (Fig 10). In fact, when the building underwent global energy sanitation, indoor health conditions are worse than before.
The next point to be investigated is whether or not the occurrence of a CVS (controlled ventilation system) is beneficial to lower radon levels and ultimately for people's health.

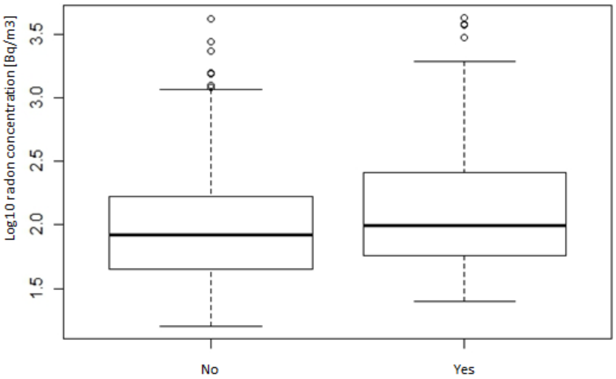

Fig 10: Effect of global energy retrofitting.

4.5 Effect of the occurrence of a controlled ventilation system

Houses without controlled ventilation system experience higher indoor radon level than the others (Fig 12). This result is not so surprising. M dwellings need to accommodate at least a ventilation concept to get the label. In that case, it is no surprising to see RT dwellings presenting higher indoor radon concentrations. Finally the radon high risk area is still the more problematic location even when the house is equipped with a ventilation system (Fig 13).

Type of energy retrofitting	No	yes	
Windows replacement	91 (21%)	341 (79%)	No significant effect
Roof renovation	198 (46%)	234 (54%)	No significant effect
External walls and floors	244 (56%)	188 (44%)	Significant effect (p<0.001)
Walls and interior ceilings	300 (69%)	132 (31%)	No effect
Windows and roof	---	180 (42%)	No interaction effect
External windows and walls	---	160 (37%)	No interaction effect
Roofing and exterior walls	---	120 (28%)	No interaction effect
Windows , roof and exterior walls	328 (76%)	104 (24%)	Significant effect (p=0.002)

Tab 3: Types of energy retrofitting and statistical effect on radon level.

5. Outlooks and conclusive remarks

Energy retrofitting measures have an impact on indoor radon concentrations. Radon levels are significantly lower in Minergie labelled buildings than in traditional ones. However some Minergie buildings show high concentrations.

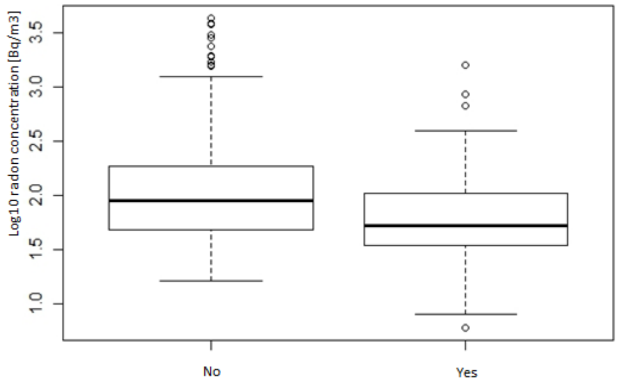

Fig 12: Effect of the occurrence of CVS on indoor radon levels.

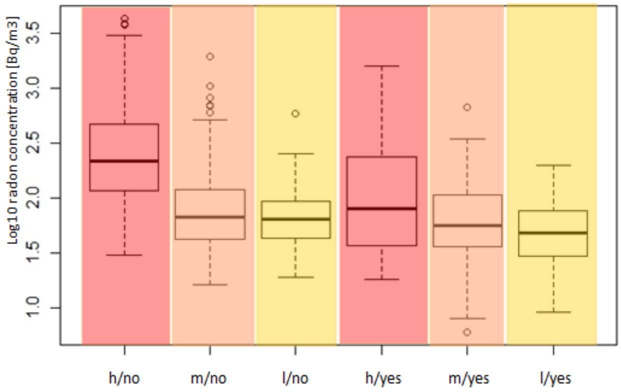

Fig 13: Cross effect of the CVS occurrence and radon risk area.

The same observation applies to Romandie and Ticino. In Romandie, individual actions like windows replacement, building envelope's insulation do not impact specifically on indoor radon levels. A tendency to concentrate more indoor radon may be noticed when these actions are combined together, especially when the building envelope is refurbished. Looking inside energy efficient dwellings, geology may be a genuine source of problems in high radon level risk areas if there is natural ground in the basement and if the indoor air renewal is not adequate.

Energy renovation of the Swiss building stock is a great challenge for the near future. It comprises 1.64 million buildings among which 83% are devoted for housing. Less than 1% has already been energy refurbished. Preliminary results of this study open a wide field of expertise that should ultimately enable us to provide recommendations to the building and energy sectors. Studying the impact of energy retrofitting measures on indoor radon as well as on indoor air quality, implies to cross lots of building parameters as well as human factors. It is thus crucial to enhance the building professional training in order to implement these new energy retrofitting measures in buildings while avoiding public health problems as much as possible. At the moment, we might expect a deterioration of the quality of life inside energy renovated building with medium and long-term significant effects on the comfort and health of the population as a whole. These effects will presumably increase the health costs and will impact the economic sector (Monn, 2012).

The label MINERGIE®, partner of this project, will practically adapt building practices in order to warrant and maintain their registered quality standards and transferable solutions should be brought to the building professionals as well as to people living in to help them adjusting their behaviours

7. Acknowledgments

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