Management of Combined Seismic and Energy Retrofitting of a Typical Swiss Building

Master's Thesis

Student

Estrella Ghielmini

Institute of Structural Engineering (IBK)

Swiss Federal Institute of Technology (ETH Zürich)

Supervisor

Prof. Dr. Božidar Stojadinović

Advisors

Dr. Yves Reuland

Safak Arslantürkoglu

Zürich

04.07.2022

ETH

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Declaration of originality

The signed declaration of originality is a component of every semester paper, Bachelor's thesis, Master's thesis and any other degree paper undertaken during the course of studies, including the respective electronic versions.

Lecturers may also require a declaration of originality for other written papers compiled for their courses.

I hereby confirm that I am the sole author of the written work here enclosed and that I have compiled it in my own words. Parts excepted are corrections of form and content by the supervisor.

Title of work (in block letters):

Management of Combined Seismic and Energy Retrofitting of a Typical Swiss Building

Authored by (in block letters):

For papers written by groups the names of all authors are required.

Name(s):	First name(s):
Ghielmini	Estrella

With my signature I confirm that

- I have committed none of the forms of plagiarism described in the 'Citation etiquette' information sheet.
- I have documented all methods, data and processes truthfully.
- I have not manipulated any data.
- I have mentioned all persons who were significant facilitators of the work.

I am aware that the work may be screened electronically for plagiarism.

Place, date	Signature(s)
Zürich, 04.07.2022	E. Ghielmini

For papers written by groups the names of all authors are required. Their signatures collectively guarantee the entire content of the written paper.

Acknowledgement

First, I would like to express my thanks to Prof. Dr. Božidar Stojadinović for giving me the opportunity to write this Master's Thesis at the Chair of Structural Dynamics and Earthquake Engineering and for his precious advice during the project. The suggested literature enabled a contextualisation in the framework of ongoing research and the very useful indications given throughout the Thesis led to a valuable discussion base.

I am particularly thankful to my supervisors Dr. Yves Reuland and Safak Arslantürkoglu, who supported me during the Thesis with their know-how and their guidance, which made the development of this work possible. Their accurate feedback and suggestions allowed me to improve the results of this project, as well as to interpret and discuss them critically. Additionally, they carefully modelled the case study building in the software 3Muri (S.T.A. DATA) and Autodesk Revit, doing all the preparatory work for the seismic and thermal analysis.

My gratefulness extends also to Elisa Ambrassa, who introduced me to building modelling in Autodesk Revit and shared useful information regarding BIM. My thanks are also directed to Alice Comune for the constructive discussion on commonly realised thermal retrofits and national Italian energy policies.

Thanks also to S.T.A. DATA and Autodesk Revit for the academic software licenses.

Summary

In this Master's Thesis, the seismic and thermal performance of the Swiss multi-family case study building is analysed and assessed to be uncompliant with the current seismic and energy code provisions (SIA 269/8: 2017 [1] and Swiss Cantonal Energy Provisions MuKEn [2]). More specifically, the minimum seismic compliance factor with respect to a new Swiss building is computed to $\alpha_{min} = 0.44$ with the software 3Muri (S.T.A. DATA). Concerning the thermal transmittance of the structure's envelope, it proves to be 64-220 % higher than the requirements for a renovated residential building [2]. The quantification of the yearly heating demand is executed with Autodesk Revit.

Consequently, synergetic retrofit alternatives are designed to meet the thermal requirements and to improve the personal safety of the building's occupants. Particular attention is paid to the CO_2 emissions of the building before, during and after the synergetic interventions.

The selected seismic retrofitting options consist of the application of carbon fiber reinforced polymer (CFRP) strips or near-surface mounted steel reinforcement on the masonry walls which are most prone to fail at low values of inter-storey drift. The energetic interventions act on the building's envelope (external walls, windows and roof) and comprise façade and roof insulation as well as window replacement.

The design and selection process of combined retrofits followed in this project is documented through a flowchart. Related to the flowchart, a decision-making diagram is developed to opt for the most appropriate combined retrofit in terms of overall CO_2 emissions, costs, interruption time of building occupancy and structural safety. Subsequently, the chosen intervention is optimised, leading to a further reduction of greenhouse gas emissions and structural safety deficit at unaltered monetary expenses.

Through this Thesis, a procedure to support professionals in the planning of low-carbon and cost-efficient, high-quality, synergetic retrofits is presented.

04.07.2022 Estrella Ghielmini

List of Contents

List of Figures

List of Tables

1 Introduction

The following report deals with the management of a combined seismic and energy retrofit of a residential building located in Switzerland.

The structure is assessed in terms of seismic and thermal performance using building models in the software 3Muri (S.T.A. DATA) and Autodesk Revit. The realisation of this project allowed the development of knowledge in the use of finite elements (FEM) programs and software used for the implementation of BIM. Moreover, insight into current seismic and thermal retrofit methods was gained through the Thesis. The application of construction management practices and tools strengthened skills which are extremely valuable also in practice.

A new approach for decision-making to select the most appropriate synergetic intervention is developed in this Thesis. The suggested framework combines multiple criteria, reaching further than the usual factors considered in the conventional design of seismic retrofit measures. Typically, structural safety and the decisive cost variable are the leading components. In addition to those criteria, the innovative decision-making framework includes also CO_2 emissions and carbon savings related to the interventions as well as it takes into account occupancy interruption for tenants entailed by the retrofits. Although the conceived decision-making procedure is based on a specific Swiss building, the followed methodology can be utilised for any other retrofit with just minor adjustments. Furthermore, the presented process not only provides a valuable base for objective and standardised decision-making and optimisation of retrofit measures but also helps in the evaluation of interventions' usefulness for buildings. Thus, it prevents needless retrofittings already before they are designed in detail.

The developed procedure is accompanied by a substantial societal impact. In fact, through the extensive commissioning of combined retrofit measures, multiple aspects of relevant importance are enhanced: society's safety and resilience are empowered, as well as the carbon footprint is decreased.

Currently, the design, evaluation and optimisation of multiple retrofit alternatives and the exploration of possible synergies are labour-intensive. This process can be significantly accelerated by leveraging new technologies. Amongst them, the creation of digital twins of buildings, used from the design phase throughout the whole operation until dismantling, would reduce the workload of structural and energy engineers. In fact, they ideally can be used directly for thermal and (possibly) seismic analysis. Furthermore, visual programming tools [3] and generative design [4] can automate the process related to parametric [5], set-based [6] design and can thus significantly foster optimisation procedures.

1.1 Motivation of the Thesis

Switzerland's building stock is ageing: 50.7 % of all residential buildings were built before 1970 [7]. Since the renovation of structures would be much more sustainable from an economic and ecologic point of view compared to the erection of new buildings, the assessment of interventions and performance upgrades of buildings is a relevant subject in the present situation and, even more, it will be in the future.

Furthermore, the seismic performance of Swiss buildings must be improved because the majority of structures was built before the introduction of modern code provisions and is therefore uncompliant with the actual requirements [8]. The safety level of a structure in Switzerland is evaluated according to SIA 269/8: 2017 [1] through an effective compliance factor α_{eff}, which is linked to the personal risk factor of the occupants related to earthquake events [9]. In case the calculated compliance factor results lower than the minimum admissible value $\alpha_{\min}$ defined by SIA 269/8: 2017, table 1 [1], the structure must be seismically retrofitted [9]. On the other hand, if $\alpha_{\min} < \alpha_{eff} < 1$, seismic upgrade is conducted based on commensurability criteria [10]. Oftentimes, seismic retrofit of existing structures lacks commensurability, as the expected costs for the interventions are disproportionate in relation to the achievable seismic risk reduction [8]. As the vast majority of the Swiss building stock has an uncompliant seismic performance, the seismic risk is not negligible [10], even though the seismicity in Switzerland is considerably lower compared to countries in Southern Europe.

Moreover, the energy consumption of Swiss buildings must be reduced to meet the goal of the energy strategy 2050 [11] and the correlated net-zero CO_2 emissions [12]. Currently, around 60.1 % of the heating is ensured through oil and gas combustion [13], which are non-renewable energy sources. In Switzerland, about 1/4 of the total energy use (230 TWh) [14] is employed for heating (> 55 TWh) [15]. Additionally, the building stock causes approximately 1/3 of the total CO_2 emissions in Switzerland [12].

A promising solution that acts on the three mentioned aspects is represented by synergetic retrofits. According to the approach of sustainable life cycle assessment, an upgrade of seismic performance has the potential to limit damages to the possibly executed thermal interventions in case of an earthquake event [16], [17]. Combined retrofits may be effective for many European countries [18]. In fact, case studies of integrated seismic and energy interventions around Europe have been conducted in different seismic zones and climatic conditions: upgrades of unreinforced masonry buildings have already been performed and documented in Italy, Romania, Greece, Portugal, Spain, Slovakia, Poland, the Netherlands and Switzerland [19]. As a result, it was stated that synergetic retrofits are most effective in moderate to high seismicity regions and at locations characterised by tendentially cooler climatic conditions [19]. Applying those insights to Switzerland, a further, detailed investigation shows promise, despite the country lies in a zone of relatively low seismicity [20]. Switzerland's climate is rather cool: in Zurich, there are averagely more than 3000 heating degree days per year, while in Sion there are slightly less than 3000 [21]. According to the Swiss definition, heating degree days are computed as the temperature difference of the outside air temperature to the aimed inside air temperature of 20° C during the days with a mean daily temperature below 12° C [21].

Combining seismic retrofit with thermal renovation works proved to have the potential for reduced resource employment [22] compared to separate interventions since for instance construction site installations and construction processes can be shared for both types of interventions. Furthermore, the barrier for a thermal retrofit is usually much lower than for seismic interventions, as energy interventions are primarily carried out from the exterior of a building, while seismic retrofit usually must be executed from the interior, discomforting the occupants and stoking fears of high expenditures [18].

In the literature, combined seismic and energy interventions on reinforced concrete structures and unreinforced masonry buildings are described and analysed [19]. In this Master's Thesis a four-storey residential building with unreinforced masonry walls assumed to be located in Sion, Switzerland, is analysed to explore the potential of synergetic retrofits. The gained knowledge is used to develop a tool that can be applied by engineers in any retrofitting project.

1.2 Description of the Case Study Building

The case study building analysed in this Master's Thesis deals with a residential building complex situated in Zurich Affoltern. The general site plan is shown in Figure 1. To induce the building to be uncompliant with the seismic code provisions, for the purpose of this Thesis it is ideally relocated from Zurich to Sion, where the seismicity is higher.

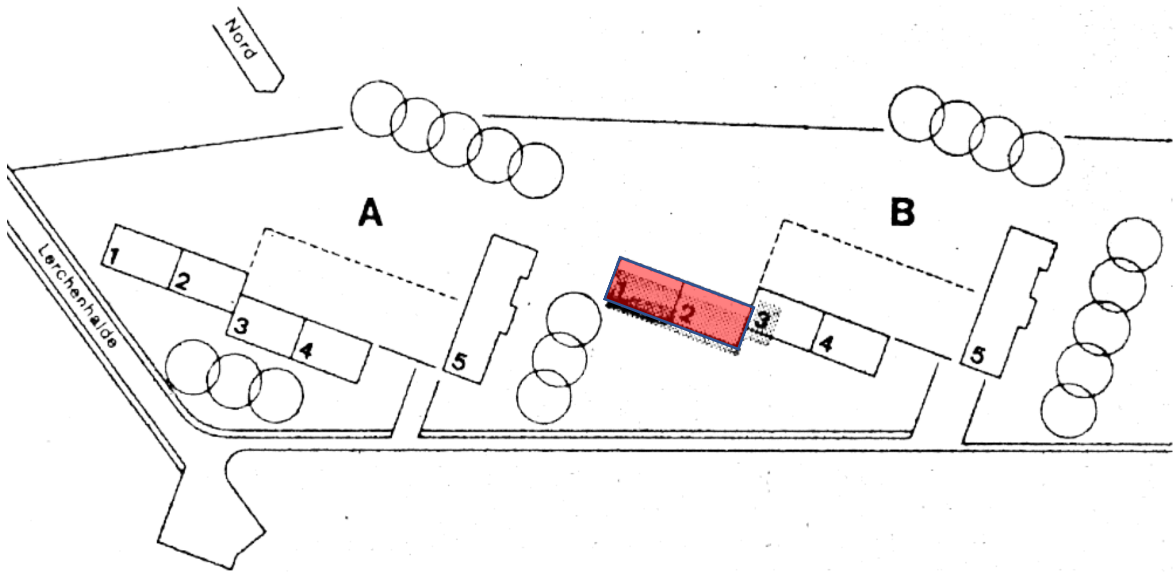


Figure 1: Site plan (red: case study building)

The complex was built in the early 1970s and the façades underwent a renovation in 1986. A general impression of the building can be gained from Figure 2.

Figure 2: Eastern façade (left), western façade with balconies (right)

The structure is characterised by a basement and an underground garage, a ground floor and three upper floors (Figure 3). The total height over terrain amounts to 12.17 m.

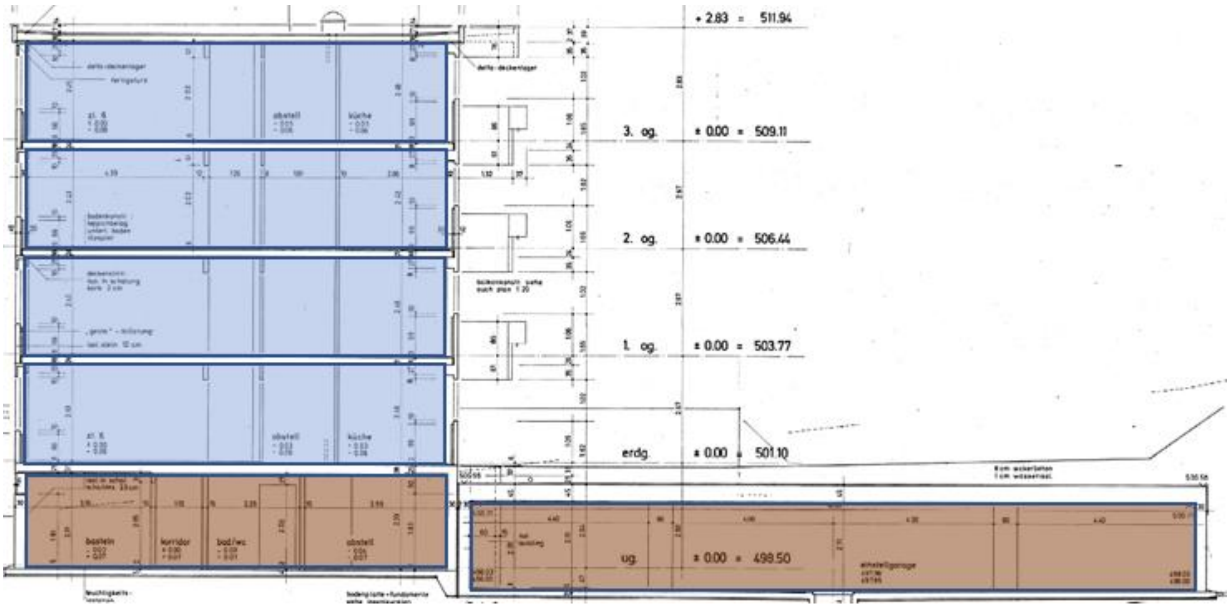


Figure 3: Transversal section

The layout dimensions are 18.25 m in length and 11.06 m in width. Each overground floor is identical and is subdivided into two residential units, each one of them comprising three rooms, a kitchen, a restroom and a balcony (Figure 4).

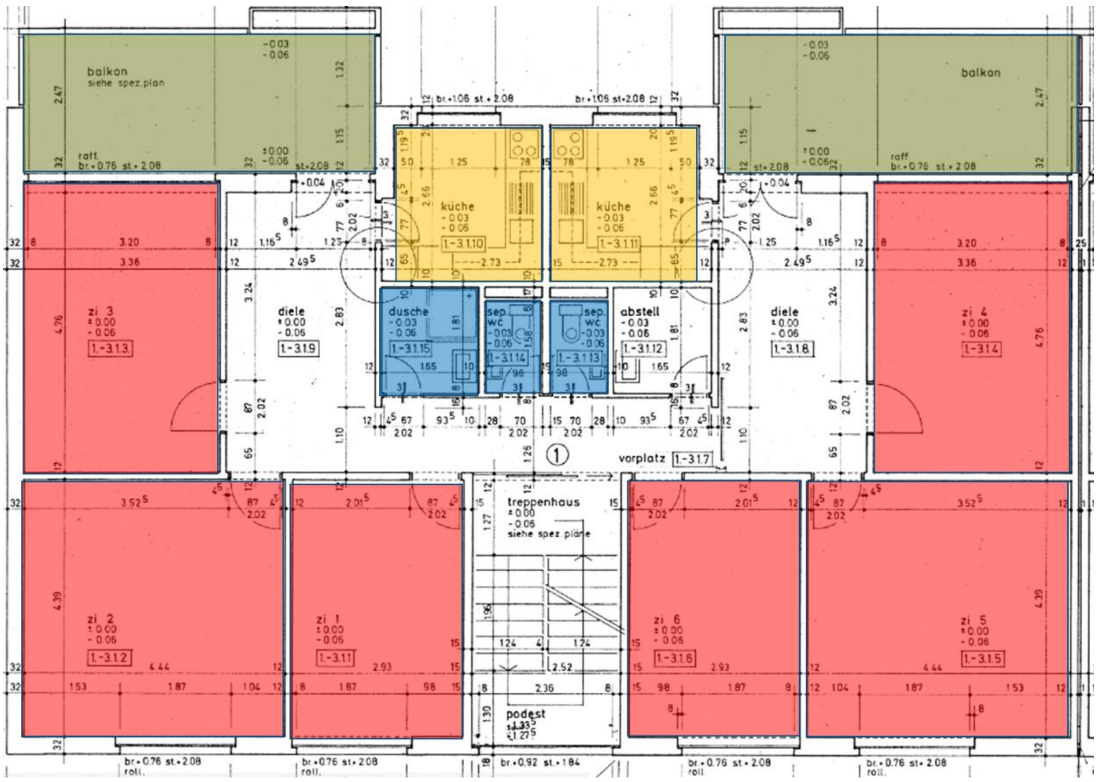


Figure 4: Layout of the upper floors

All walls, except the ones on the basement floor, are made of unreinforced masonry. Most external masonry walls are 32 cm thick, except for the ones adjacent to an adjoining building, which have a thickness of 12 cm. The internal walls are mainly 12 cm thick, while some minor, separatory walls only show an 8-10 cm thickness.

On the western façade, there are many large window openings on every floor, including the ground floor, extending from the building's edges over approximately 1/3 of the façade length each. In the middle part of the west façade, an unreinforced masonry wall with smaller windows is present.

On the eastern side of the building, narrower windows are distributed over the entire façade surface.

2 Building Analysis: Is-State

2.1 Seismic Analysis

Within the scope of this Thesis, only the in-plane seismic compliance of the building's walls is examined. The out-of-plane failure of the walls is evaluated as not critical since the rigid reinforced concrete floor slabs are considered as firmly connected to the walls, restraining them and preventing overturning. The quality of the masonry walls is assumed to be sufficient to avoid cohesion-related issues between the bricks and the mortar in the joints.

2.1.1 Modelling in 3Muri

The software 3Muri (version 13.2.0.14) is used for the seismic analysis of the case study building. The 3Muri building model was kindly prepared and shared by Safak Arslantürkoglu [23].

All walls thinner than 12 cm are ignored in the modelling since they are regarded as non-structural, being disconnected from the ceilings by a 1 cm thick polystyrene layer. The reinforced concrete slabs (thickness 18 cm) are modelled as stiff horizontal diaphragms, rigidly connected to the structural walls.

The chosen control node 114 (see Figure 5) is located on the top level of the model (ceiling), near the mass centre but not close to the centre of stiffness of the analysed building, according to the specifications given by [24]. The choice of the control node is based on the criterion of representative displacement behaviour. Namely, the displacements should not be excessively sensitive to the choice of the node and lie in the same range as the average displacement of the whole floor, since the floors move as rigid bodies.

2.1.1.1 Geometrical Properties

Figure 5 shows the simplified ground view inputted in the 3Muri software. As described in Section 2.1.1, all non-structural walls are neglected in the model to create a model as simple as reasonably possible for the sake of reducing the computational effort. The in-plane load transfer on the reinforced concrete floor slabs is subdivided into 60 % in the main X-direction and 40 % in the Y-direction. All walls are built in unreinforced masonry and are modelled accordingly.

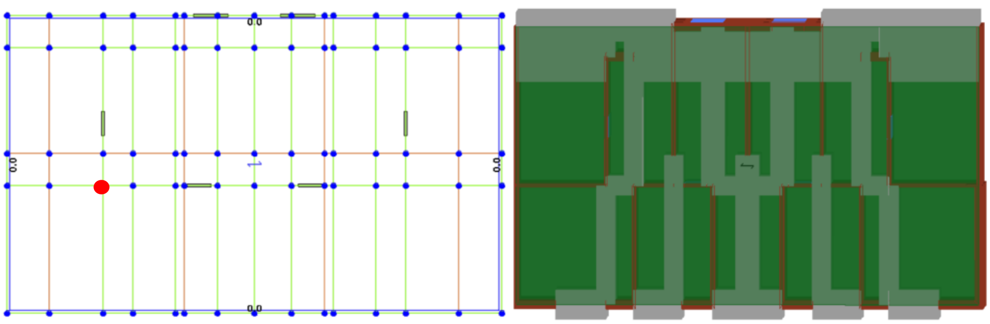


Figure 5: Ground view of the 3Muri model (left: alignments and control node 114 on level 4 (red), right: top view of the 3D model)

2.1.1.2 Material Properties

The structural elements of the building are featured according to the standard material properties filed in the 3Muri database and material parameters suggested by different publications [25], [26], [27] (Table 1).

Table 1. Material properties used in the 3Muri model

	E [N/mm²]	G [N/mm²]	w [kN/m³]	f_m, f_{cm}, f_{ym} [N/mm²]	f_k, f_{ck}, f_{yk} [N/mm²]	f_{vm0} [N/mm²]	f_{vlim} [N/mm²]	γ [-]
Masonry (clay bricks)	3'850[1]	963[2]	13	7	4.90	0.29[3]	2.2	2.00
Concrete C20/25	29'000	12'083	25	0.28	0.20	-	-	1.50
Steel rebars B500A	205'000	85'416	79	5.38	5.00	-	-	1.15

2.1.1.3 Actions and Applied Loads

The seismic actions used for the analysis in 3Muri are determined through SIA 261: 2020 [20]. As explained in Section 1.2, to induce the building to be uncompliant with the seismic code provisions, it is shifted from its real location in Zurich to Sion, where the seismicity is higher: Sion lies in the seismic zone Z3b with a horizontal design ground acceleration $a_{gd} = 1.6 \text{ m/s}^2$ (SIA 261: 2020 [20], 16.2.1.2). The soil is assumed to be of type E (loose rock, most conservative acceleration spectrum for the vibration period of the building, determined through modal analysis). Accordingly, the acceleration spectrum parameters given by SIA 261: 2020, table 24 [20] are inserted in 3Muri.

The self-weights of floors and walls are computed automatically by the 3Muri software with the assigned geometrical and material properties, as well as the dead and live loads. According to SIA 260: 2013, table 2, [28] for the calculation of the applied loads on design level, 30 % of the live loads are added to the self-weight of the structural elements and to the dead loads (permanent load case, with $\psi_2 = 0.3$ for residential purposes).

These loads are applied horizontally in correspondence to the floor levels of the building in different load patterns (uniformly distributed forces or static forces matching the first eigenmode of the building). Additionally, the forces act in different senses and directions:

[1] $E = 550f_m$ [25]
[2] $G = 0.25E$ [26]
[3] In accordance with [27]

positive or negative sense (+/-) in the principal axes of the structure (X/Y). Furthermore, they are characterised by different accidental eccentricities of the resulting force with respect to the centre of stiffness (SIA 261:2020, 16.5.2.7 [20]).

2.1.2 Results: Seismic Compliance

The seismic compliance is evaluated through the effective compliance factor $\alpha_{eff} = \frac{A_R}{A_d}$ [1], which indicates the ratio between the seismic capacity of an existing building and the demand required for a new structure [9]. For the displacement-based analysis in 3Muri, the compliance factor is computed as the ratio of the displacement capacity d_m and the displacement demand d_t, namely $\alpha_{eff} = \frac{d_m}{d_t}$.

The displacement capacity d_m is reached at the failure of the first structurally relevant element, which leads to a partial or total collapse of the structure. Once the collapse point on the pushover curve is selected, a new bilinearization according to the N2 method is carried out.

The displacement demand d_t is evaluated by means of the N2 method [29], [30], more precisely it is the value of the displacement at the intersection of the bilinearised curve and the pushover curve. The aforementioned intersection point is defined by a shear force $V_{intersection} = 0.7 \cdot V_{max}$, where V_{max} is the maximal reached shear force in the pushover curve [9].

The displacement demand d_t of a building can also be represented by the capacity spectrum method, in which the capacity of the building, derived from pushover analyses, is transformed into spectral accelerations and displacements, and plotted together with the demand spectrum in an Acceleration-Displacement Response Spectrum diagram [30]. The displacement demand d_t is quantified as the intersection point between the seismic demand required by the earthquake event and the capacity spectrum curves [30].

The outputs of 3Muri are cross-checked for plausibility purposes: a comparison of field measurements of the vibration period and the period computed by the software (T_x = 0.3 s, T_y = 0.2 s) for the vibration modes with the highest mass contribution is done.

The software generates 24 analyses, corresponding to the different load applications described in Section 2.1.1.3. In the following Table 2, the results of the seismic analysis done in 3Muri are represented.

Table 2: Results of the seismic analysis executed in 3Muri

Analysis	Seismic direction	Seismic load	Eccentricity [cm]	Capacity d_m [cm]	Demand d_t [cm]	Compliance factor α
1	X +	Uniform	0	1.60	3.50	0.46
2	X +	Static forces	0	2.16	4.13	0.52
3	X -	Uniform	0	1.52	3.46	0.44
4	X -	Static forces	0	2.56	3.97	0.64
5	Y +	Uniform	0	1.28	1.35	0.95
6	Y +	Static forces	0	1.99	1.66	1.20
7	Y -	Uniform	0	1.20	1.20	1.00
8	Y -	Static forces	0	2.73	1.50	1.82
9	X +	Uniform	53.8	1.52	3.41	0.45
10	X +	Uniform	-53.8	1.68	3.50	0.48
11	X +	Static forces	53.8	2.32	4.13	0.56
12	X +	Static forces	-53.8	2.32	4.11	0.56
13	X -	Uniform	53.8	1.52	3.46	0.44
14	X -	Uniform	-53.8	1.60	3.45	0.46
15	X -	Static forces	53.8	2.32	4.09	0.57
16	X -	Static forces	-53.8	2.40	4.06	0.59
17	Y +	Uniform	89.6	0.72	1.25	0.58
18	Y +	Uniform	-89.6	1.36	1.52	0.89
19	Y +	Static forces	89.6	1.28	1.53	0.84
20	Y +	Static forces	-89.6	2.15	1.86	1.16
21	Y -	Uniform	89.6	0.56	1.12	0.50
22	Y -	Uniform	-89.6	1.28	1.37	0.93
23	Y -	Static forces	89.6	1.12	1.37	0.82
24	Y -	Static forces	-89.6	2.09	1.71	1.22

As it can be noticed from Table 2, the lowest compliance factor is 0.44 (analysis 3 and analysis 13). Since analysis 3 entails more damaged/failed walls than analysis 13, it is identified as the most critical one.

2.1.2.1 Commensurability

The comparison of costs caused by seismic retrofits with the therewith achieved risk reduction provides the base to assess commensurability defined by SIA 269/8: 2017 [1]. The lowest compliance factor α_{min} determined in Section 2.1.2 is used to quantify the personal risk factor (PRF) with the aid of Figure 6. Subsequently, the difference in PRF between the initial value of $\alpha_{min} = 0.44$ and a compliance factor $\alpha = 1$ required for new buildings is calculated.

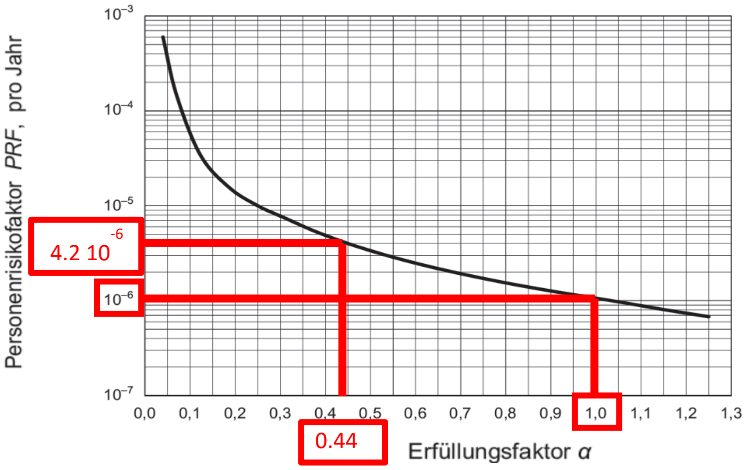


Figure 6: Personal risk factor (PRF) as a function of the compliance factor α (SIA 269/8: 2017 [1], figure 7)

The occupancy (PB) of the structure is evaluated through SIA 269/8: 2017 [1], table 2 for a residential building: the specific occupancy in persons per room is 0.2-0.6. Therefore, a mean value of 0.4 persons/room is chosen. Including bathrooms and kitchens, 10 rooms are present per floor, which leads to an occupancy of 4 people/floor and hence 16 people for the entire building. Life safety costs (GK) are assumed to be 10 million CHF referring to SIA 269/8: 2017 [1], 10.3.9. Based on SIA 269/8: 2017 [1], 10.7.2, a discount rate of 2 % over 50 years of remaining building service life is embraced. Following the methodology described by SIA 269/8: 2017 [1], 10.7.2, the proportional safety costs are computed to 16'000 CHF (Table 3).

Table 3: Parameters for calculation of commensurable costs

Eff. compliance factor $\boldsymbol{\alpha_{min}}$	[-]	0.44
PRF_M before the seismic retrofit	[1/year]	$4.2 \cdot 10^{-6}$
PRF_M after the seismic retrofit	[1/year]	$1.0 \cdot 10^{-6}$
Occupancy per room	[people]	0.4
Number of rooms	[-]	40
Life safety costs	[CHF]	10'000'000
Discount rate per year for 50 years and 2 % discount rate	[-]	0.032
Total building occupancy	[people]	16
Δ PRF_M	[1/year]	0.0000032
Δ RP_M	[CHF/year]	512
Commensurable costs in 50 years SIC_M	**[CHF]**	**16'000**

2.1.2.2 Embodied CO_2 Emissions from Repair Works

For the estimation of the embodied carbon emissions caused by probable repair works after a seismic event, the analysis with the minimum compliance factor $\alpha_{min} = 0.44$ (analysis 3, X-direction, see Table 2) is considered.

The condition (damaged or failed) of all structural walls is assessed for several displacements on the most critical pushover curve. Some of the chosen points correspond to specific degrees of structural damage (slight, moderate and extensive damage), defined by linear combinations of the yield displacement d_y and the displacement of the control node at ultimate strength d_u. These equations are shown in Table 4.

Table 4: Assessment points on the pushover curve for different degrees of structural damage [31]

Degrees of structural damage	Displacement
Slight damage	$0.75\ d_y$
Moderate damage	$0.5d_y + 0.33d_u$
Extensive damage	$0.25d_y + 0.67\ d_u$

In addition to the described damage states, further points on the pushover curve are evaluated: the condition of the walls at displacements close to slight damage, at the point of maximal shear force, at the failure of the first vertical elements and beyond their failure is considered (Figure 7).

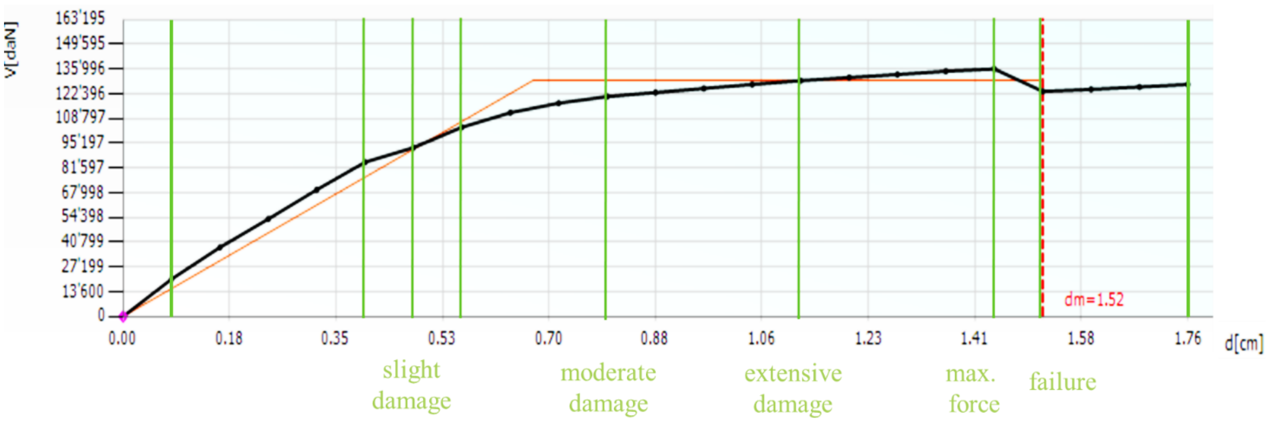


Figure 7: Points of damage assessments on the critical pushover curve computed by 3Muri (analysis 3)

The loss in terms of CO_2 emissions caused by an earthquake event is evaluated with the Performance Assessment Calculation Tool (PACT) powered by the software SimaPro. The PACT is based on FEMA P-58 Seismic Performance Assessment of Buildings, Volume 1 – Methodology [32]. Software version 3.2.1 (March 2018) is used in this project. The emissions are estimated by means of life cycle assessment (LCA) procedures [32]. Amongst other functionalities, the tool includes a database of consequence functions related to different damage states. These consequence functions provide a quantification of carbon emissions (CO_2-equivalents) due to the repair or the replacement of damaged or, respectively, failed walls.

The CO_2 emissions are described by a lognormal distribution. For the purpose of this Thesis, the median value is taken into account, without considering the statistical dispersion of the data. The most appropriate types of structural elements comprised in the PACT database matching the masonry walls of the building are shown in Table 5 together with the related CO_2 emissions.

Table 5: Carbon emissions from repair works/replacement of damaged/failed masonry walls

	Carbon emissions median	
Wall type	**damaged**	**failed**
Ordinary reinforced masonry walls with partially grouted cells, shear/flexure dominated, 4" to 6" (= 0.10-0.15 m) thick, up to 12" (=3.66 m) tall	501 kg CO_2/wall 32.9 kg CO_2/m'	1289 kg CO_2/wall 92.5 kg CO_2/m^2
Ordinary reinforced masonry walls with partially grouted cells, shear/flexure dominated, 8" to 12" (=0.20-0.30 m) thick, up to 12" (=3.66 m) tall	562 kg CO_2/wall 36.9 kg CO_2/m'	3124 kg CO_2/wall 224.2 kg CO_2/m^2

The walls displayed in the ground view (Figure 8) are subdivided according to the building element categories introduced in Table 5.

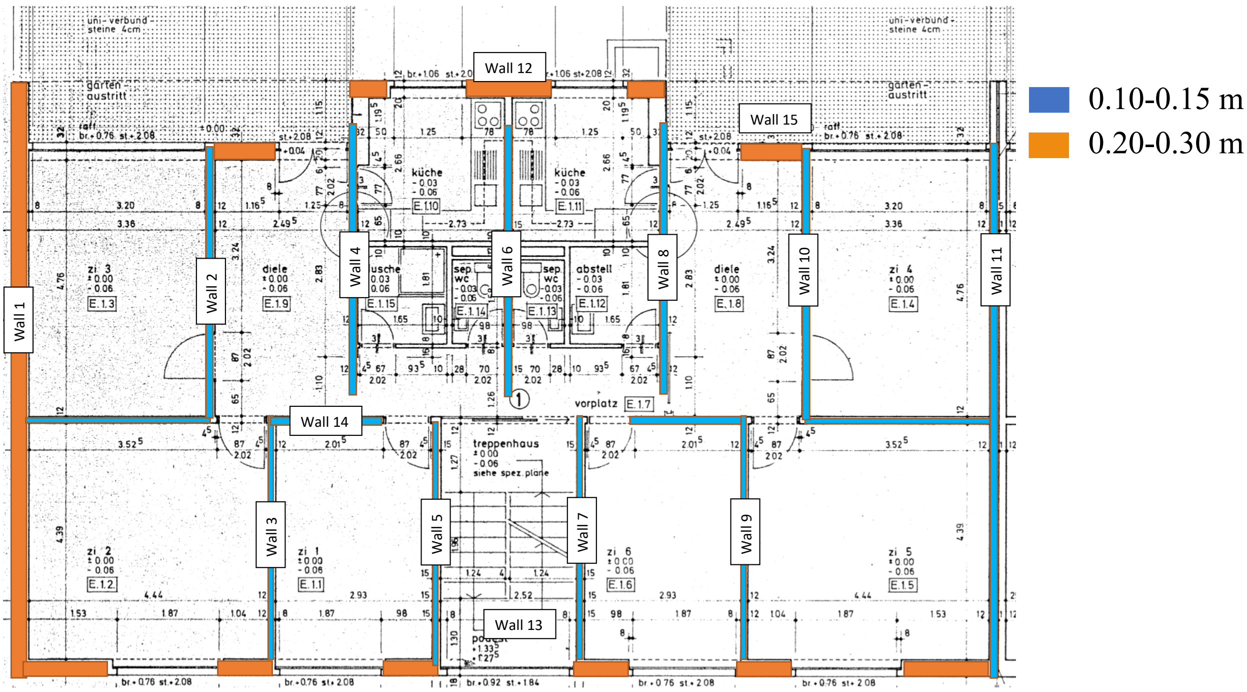


Figure 8: Layout with walls subdivided per thickness (0.10-0.15 m and 0.20-0.30 m)

Referring to [33], the values of CO_2 emission due to repair/replacement works (Table 5) are valid for a reference wall of 25" x 15" (=7.62 m x 4.57 m). Being this wall size unmatching the conditions in the case study building, where the walls are in general considerably smaller, the reference dimension is reduced to 15" x 10" (=4.57 m x 3.05 m).

Since the damages caused by an earthquake event are not uniformly distributed over the walls' area but are concentrated at the edges [33], for damaged walls their perimeter is taken as the basis for the size comparison to the standard reference wall. This way, an equivalent number of standard walls is computed and then multiplied by the CO_2 emissions in Table 5, getting the carbon footprint of repair works as a consequence of an earthquake event. This procedure is repeated for every displacement value marked on the pushover curve (Figure 7).

For failed walls, their area is taken as a quantification measure. The reason behind this choice is that a complete replacement must be executed for failed elements, thus the surface area is the decisive dimension.

The detailed calculation of the perimeters and areas of the damaged or failed walls is given in Appendix A (Table 39), while a summary of the CO_2 emissions caused by repair/replacement works is shown in Table 6.

It should be noticed that the calculated emissions due to repair/replacement works strongly vary depending on the used normalisation method (normalisation by perimeter or area of different reference wall sizes, see Table 41 in Appendix A). For illustration purposes, the computed CO_2 emissions are converted into equivalent car kilometres, presuming an average new Swiss car in 2020. The carbon emissions are quantified to 123.6 g CO_2/km [34].

Table 6: CO_2 emissions and related corresponding car-km for different displacements (and damage states) on the pushover curve

Displacement; base shear force	**Total CO_2 median [kg]**	**Equivalent car-km [km]**
(0.08 cm; 204.65 kN)	1'094	8'847
(0.40 cm; 847.68 kN)	4'931	39'897
(0.48 cm; 927.45 kN) - slight damage	6'908	55'889
(0.56 cm; 1039.51 kN)	9'482	76'716
(0.80 cm, 1207.96 kN) - moderate damage	14'129	114'315
(1.12 cm, 1295.42 kN) - extensive damage	16'551	133'911
(1.44 cm; 1295.42 kN) - max. force	18'802	152'120
(1.52 cm; 1359.96 kN) - failure	19'386	156'847
(1.76 cm; 1274.52 kN)	20'610	166'745

The distance a car can drive causing the same emissions as repair and replacement of the failed elements at the failure point (19'386 kg CO_2 or 156'847 car-km) corresponds to 3.9 times the equator length.

Figure 9 illustrates the distribution of CO_2 emissions at the evaluated displacement values. Despite the failure of some structural elements at a displacement of 1.52 cm (which entails additional CO_2 emissions due to the replacement of the failed walls), the emissions at failure are only slightly higher than at the immediately preceding displacement point, which corresponds to maximum base shear force (1.44 cm). This is due to the small share of failed walls compared to the entire building.

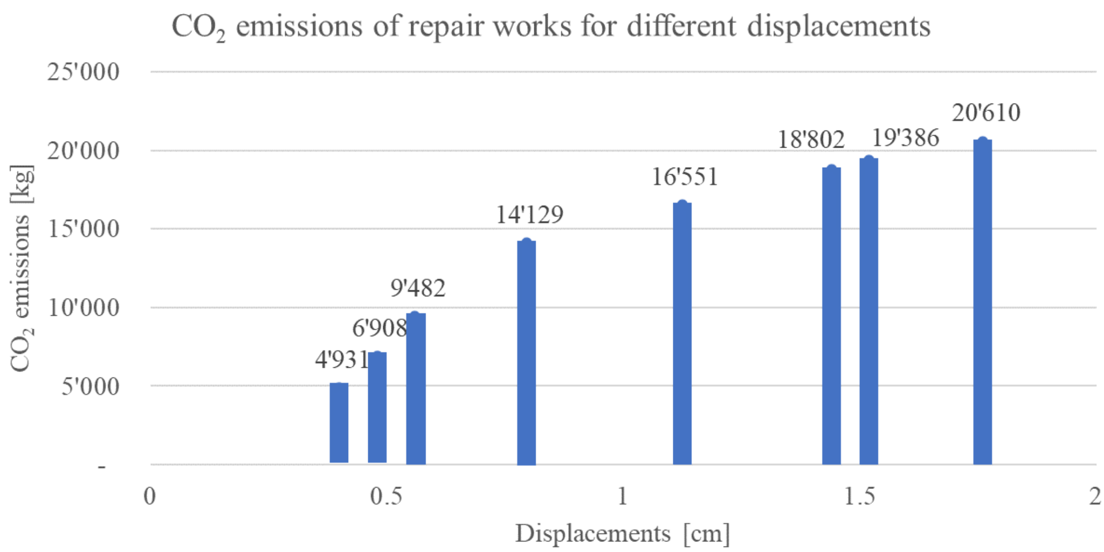


Figure 9: CO_2 emissions for different displacements from pushover curve

To contextualise the calculated CO_2 emissions caused by repair works after earthquakes leading to different damage states, they are confronted in Table 7 with the emissions due to a conventional seismic retrofit [35]. Furthermore, a comparison with the operational heating-related emissions of an existing Swiss building is drawn [36]. The exemplary seismic upgrade is responsible for the emission of 28.34 kg CO_2/m^2 for floors, respectively 14.64 kg CO_2/m^2 for walls [35]. On the other hand, the estimated operational heating emissions amount to approximately 24 kg CO_2/m^2 per heating period [36]. These emissions are predominant, due to the yearly recurrence during the 50 years of estimated remaining service life, in contrast to the singular seismic intervention. Furthermore, Table 7 illustrates the computed CO_2 emissions/m^2 deriving from probable repair works after an earthquake event (sourced from Table 6). Considering the probability of exceedance of the seismic excitations (published by [37]) causing the analysed damage states, it becomes clear from Table 7 that combined energy and seismic retrofitting interventions have a significant potential to reduce greenhouse gas emissions.

Table 7: Comparison of CO_2 emissions of conventional seismic retrofit, heating operation and repair works after an earthquake

	Embodied CO_2 emissions [kg/m^2]	**Occurrence in 50 years [-]-**	**CO_2 Emissions in 50 years [kg/m^2]**
Conventional seismic retrofit of floor [35]	28.34	1	28.34
Conventional seismic retrofit of wall [35]	14.64	1	14.64
Heating residential Swiss building [36]	Per year: ~24	50	1200
Repair work after earthquake:	**Embodied CO_2 emissions [kg/m^2]**	**Probability of exceedance in 50 years [-]**	**Probability weighted emissions [kg/m^2]**
(0.08 cm; 204.65 kN)	1.60	1	1.60
(0.40 cm; 847.68 kN)	7.22	0.5	3.61
(0.48 cm; 927.45 kN) - slight damage	10.11	0.5	5.05
(0.56 cm; 1039.51 kN)	13.88	0.1	1.39
(0.80 cm, 1207.96 kN) - moderate damage	20.68	0.1	2.07
(1.12 cm, 1295.42 kN) - extensive damage	24.22	0.05	1.21
(1.44cm; 1359.96 kN) - max. force	29.69	0.02	0.59
(1.52cm; 1236.25 kN) - failure	32.10	0.02	0.64
(1.76 cm; 1274.52 kN)	28.37	0.02	0.57

The probabilities of exceedance in 50 years displayed in Table 7 are determined through the EFEHR hazard maps [37]. The ground accelerations a_{gr}, sourced from the hazard maps [37], are connected to the displacements d modelled in 3Muri through equations (1), (2) and (3) [30].

$$S_d = d/\Gamma \tag{1}$$

$$S_a = \omega^2 \cdot S_d = (2\pi f)^2 \cdot S_d \tag{2}$$

$$a_{gr} = S_a/g \tag{3}$$

where S_d and S_a indicate the spectral displacement and respectively the spectral acceleration, Γ is the participation factor (here $\Gamma = 1.31$), ω and f are the angular and the vibration frequencies and g is the gravitational acceleration ($g = 9.8042\ m/s^2$ in Sion *[38]*).

Figure 10 illustrates the CO_2 emissions from repair works (from Table 6) and the correlated probabilities of exceedance in 50 years of assumed remaining service life (from Table 7).

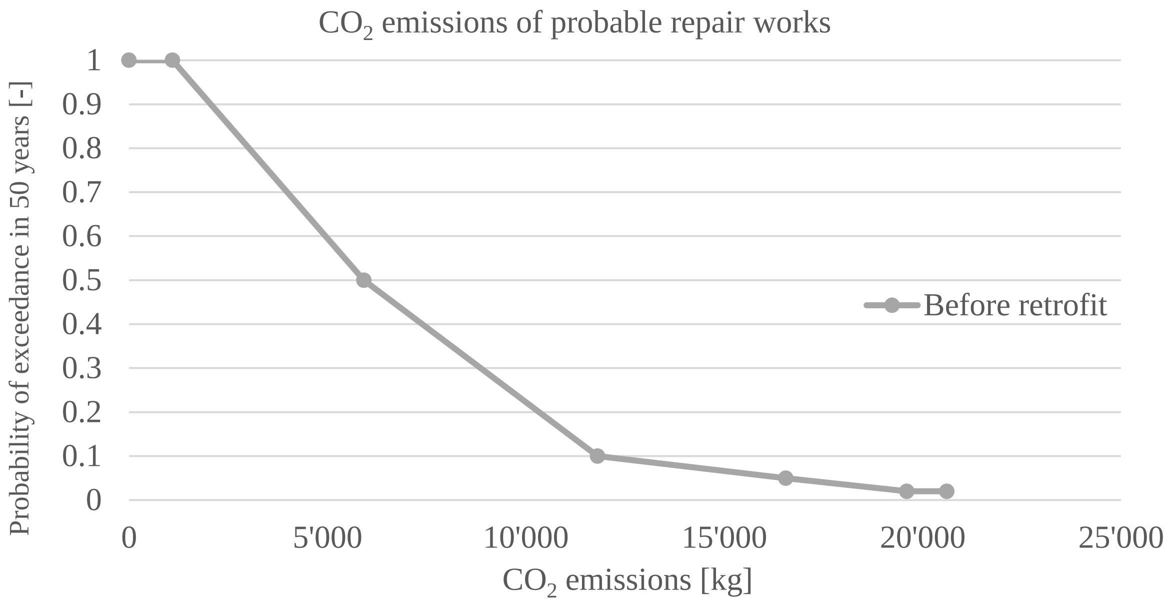


Figure 10: CO_2 emissions of probable repair works for different displacements and related probabilities of exceedance (loss function)

The CO_2-related loss deriving from seismic repair works is computed as the area under the curve. The result of the integral is represented in Table 8. For reference purposes, the losses are also computed for a high seismicity region as Central Italy (Province Perugia), where they are anticipated to be significantly higher (see loss function in Appendix A, Figure 45). Indeed, the CO_2 emissions owed to mending are estimated to be 2.3 times higher in Perugia than in Sion.

Table 8: CO_2-related loss in 50 years

Displacement range [cm]	**CO_2-related loss [kg CO_2] Sion, Switzerland**	**CO_2-related loss [kg CO_2] Perugia, Italy**
0 – 1.76	6'962	16'186

2.1.2.3 Monetarised Cost of CO_2 Emissions from Repair Works

The greenhouse gas emissions of the repair works are converted to a monetary cost. For this purpose, a conversion factor derived for Germany from [39] is interpolated for the current year 2022 between the published values for 2016 and 2030 (in 2022: 190.7 €/ton CO_2). Additionally, the factor is converted from Euro (€) to Swiss Francs (CHF) (1 € = 1.09 CHF in 2016, year used for the interpolation), getting a computed cost of 208 CHF/ton CO_2.

On this base, the following values (Table 9) are obtained by multiplication of the CO_2-related loss displayed in Table 8 and the above-described monetarisation factor. Being the monetarised costs of greenhouse gas emissions directly proportional to the released CO_2, the proportion of monetarised costs quantified for Sion and Perugia is analogous to the one described in Section 2.1.2.2.

Table 9: Monetarised cost of CO_2 emissions from repair works in 50 years

	Sion, Switzerland		**Perugia, Italy**	
Displacement range [cm]	**CO_2- loss in 50 years [kg CO_2]**	**Cost of CO_2 emissions in 50 years [CHF]**	**CO_2- loss in 50 years [kg CO_2]**	**Cost of CO_2 emissions in 50 years [CHF]**
0 – 1.76	6'962	1'447	16'186	3'365

2.1.2.4 Cost of Repair Works

The cost of repair works following a seismic event is quantified according to the approach suggested in [40]. Damage state 2 and damage state 3 of publication [40] are assumed to be equivalent to the considered wall conditions “damaged” and “failed” in this Thesis, based on underlying inter-storey drift ranges and text descriptions given in [40].

The costs of repair/replacement works per unit area of unreinforced masonry walls proposed by the authors of [40] are specified in Table 10.

Table 10: Cost of repair works/replacement of damaged/failed masonry walls ([40])

	Cost [CHF/m²]	
Wall type	**damaged**	**failed**
URM Structural wall	130	430

The probabilities of exceedance of seismic events (sourced from the EFEHR hazard maps [37]) causing given costs of repair/replacement works are plotted in Figure 11, while the detailed calculation of the walls' area to be repaired or replaced is given in Appendix A (Table 40).

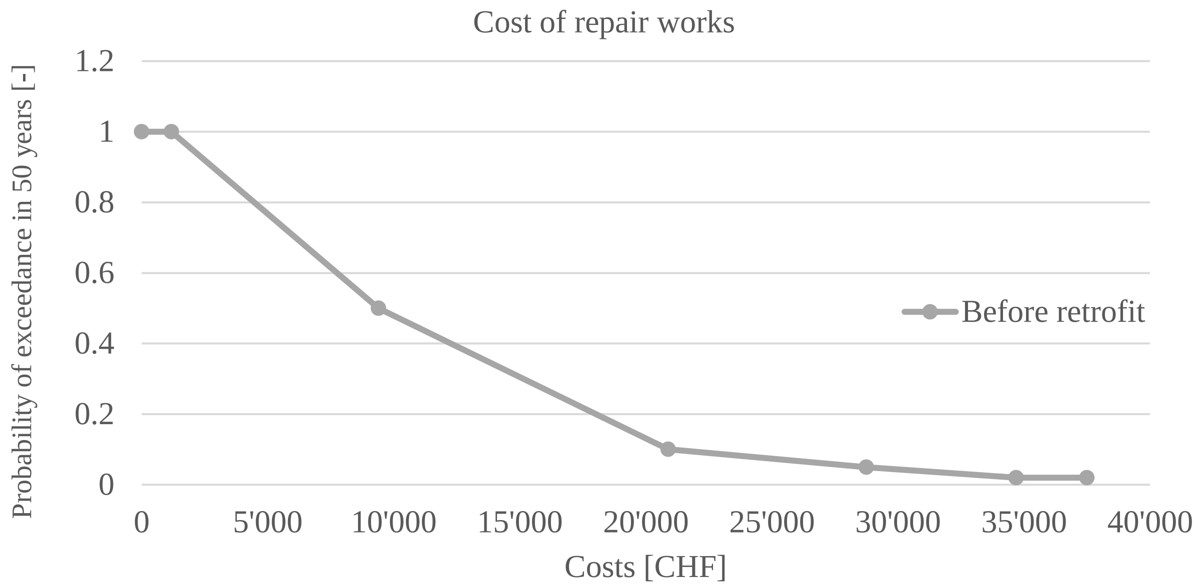


Figure 11: Cost of probable repair works for different displacements and related probabilities of exceedance (loss function)

The monetary loss in 50 years is defined as the integral of the curve illustrated in Figure 11 and is summarised in Table 11. For comparison, the loss which incurs in a high seismicity region is furthermore specified in Table 11. It amounts to more than 2.5 times the loss expected in Sion.

Table 11: Monetary loss in 50 years

Displacement range [cm]	**Monetary loss [CHF] Sion, Switzerland**	**Monetary loss [CHF] Perugia, Italy**
0 – 1.76	11'640	31'087

2.2 Thermal Analysis

2.2.1 Thermal Properties of the Building Envelope

The heat transfer coefficient of a body, also known as U-value, quantifies the heat flow through that body per unit surface area (m^2) and unit temperature degree difference (K) [41]. In this Thesis, the convective and radiative components of the U-value (i.e. heat transfer from the environment to the solid body and viceversa) are neglected, accounting just for the conductive property of the building element.

The structure of the building elements and the correlated U-values are shown in Appendix B, Figure 46, Figure 47 and in Table 42 to Table 48. Figure 46 shows the structure of the perimetral walls as they were constructed in the 1970s and after the thermal insulation intervention which was executed in 1986. Additionally, the mentioned tables display the required U-values after the renovation of a building according to Swiss Cantonal Energy Provisions („Mustervorschriften der Kantone im Energiebereich (MuKEn)“, Appendix 2, Art. 1.7 Abs. 2 [2]). A summary of the actual and the required heat transmittance of the analysed elements is given in Table 12.

Table 12: U-values in is-state and limit U-values after thermal retrofit

	U-value (is-state) [W/(m^2K)]		**U-value (required after retrofit) [W/(m^2K)]**
Exterior walls	0.41	>	0.25
Roof	0.47	>	0.25
Windows	3.20	>	1.0
Interior walls	7.94		-
Floor slabs	1.05		-
Ground floor slab	3.49	>	0.28
Doors	2.61	>	1.2

The estimated U-values of all building elements are higher than the ones required by MuKEn [2] after renovation. Hence, the structure has an increased heating demand compared to a building that meets the thermal requirements.

2.2.2 Modelling in Revit

The case study building is modelled in the software Autodesk Revit 2022. The Revit building model was kindly prepared and shared by Dr. Yves Reuland [42].The analysed structure is categorised as a multi-family building type. As a simplification, the utilisation of all rooms is classified as dormitory use with a 24-hours/7 days home occupancy of the building. Consistent with the occupancy used for the computation of the seismic retrofit commensurability, 16 people are assumed to reside in the modelled structure. According to the default settings of Revit, an airflow of 2.36 l/(s·person), 0.30 l/(s·m^2) and 0.5 air changes per hour (ACH=0.5) [43] are set. The thermal analysis is carried out with the maximum between the three mentioned values of airflow. The set heating temperature inside the building is 21°C, while the value for cooling is 28°C. A central heating system with radiators is selected.

Collected from weather stations around Sion, the climatic conditions are imported into the model. For the quantification of the heating energy demand of the building, yearly simulations are run.

2.2.3 Results: Heating Demand

The calculated yearly heating demand is normalised by the conditioned building surface (683.3 m^2). The required heating energy before and after the facades' renovation executed in 1986 is represented in Figure 12. It is noticeable, that a significant decrease of 48 % of the heating demand is achieved by the interventions executed in 1986.

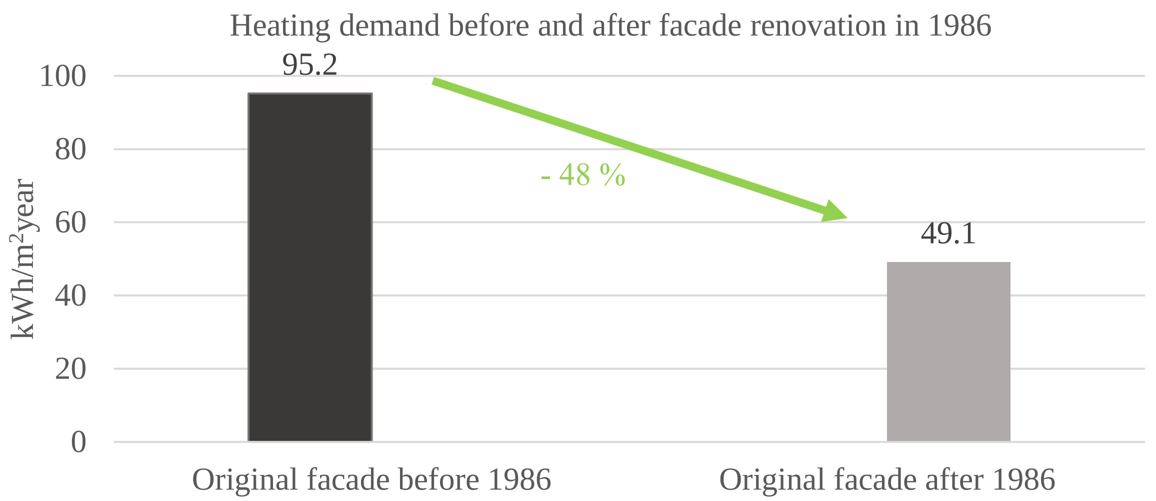


Figure 12: Yearly heating demand before and after the façade renovation in 1986

In the following Table 13, the heating demands described in various literature references are represented for the purpose of plausibilisation of the heating load simulation results. It can be stated that the calculated heating demand per surface unit is concordant with the consulted sources (Table 13).

Table 13: Heating demand from literature sources

[kWh/m² year]	Minergie	Old building	After retrofit
Zurich [4]	30.1	86.8	
Locarno [5]	16.9		
Switzerland [6]	20	120	60
Sion [7]		171-196	46.4 (+50 % = 69)

2.2.3.1 CO_2 Emissions from Heating

To estimate the CO_2 emissions caused by the heating of the building through a gas heating system, a conversion factor from KBOB[8] [46] is applied. The CO_2 emissions are estimated to be 0.228 kg CO_2/kWh final energy. Figure 13 shows the carbon emissions of the analysed residential structure due to heating before and after the façade renovation of 1986. Evidently, the greenhouse gas emissions are proportional to the heating energy demand described in Section 2.2.3, hence the reduction of released CO_2 thanks to the thermal upgrade of 1986 is also 48 %.

Remarkably, the yearly CO_2 emissions due to heating of the building in the is-state (after the façade renovation of 1986) are still higher than the CO_2-related loss caused by seismic events in Sion in 50 years (Table 8).

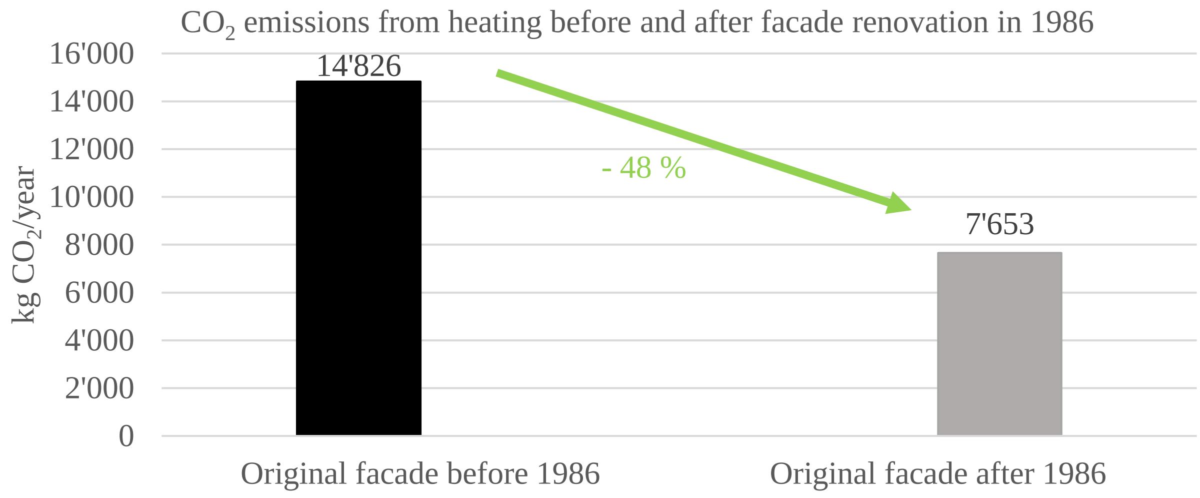


Figure 13: Yearly CO_2 emissions due to heating, before and after the façade renovation of 1986

[4] and [5] [44]

[6] [45]
[7] [43]
[8] KBOB: Koordinationskonferenz der Bau- und Liegenschaftsorgane der öffentlichen Bauherren, translated to English: Swiss Federal Coordination Conference of the Building and Real Estate Organ of the Public Building Owner

2.2.3.2 Monetarised Cost of CO_2 Emissions from Heating

For the computation of theoretical costs linked to CO_2 emissions caused by the gas heating system (Table 14), the conversion factor introduced in Section 2.1.2.3, namely 208 CHF/ton CO_2 is used.

Table 14: Monetarised cost of CO_2 emissions from heating demand (after façade renovation of 1986)

Yearly heating demand [kWh]	Yearly CO_2 emissions [kg CO_2]	Yearly cost of CO_2 emissions [CHF]	Cost of CO_2 emissions in 50 years [CHF]
33'564	7'653	1'591	79'548

Interesting to note is that the computed cost of CO_2 emissions from heating in 50 years is 55 times higher than the one from the expected seismic CO_2-loss due to repair works for Sion (Table 9 in Section 2.1.2.3). If compared to the seismic monetary loss from CO_2 emissions caused by repair works in the high seismicity region of Central Italy, the costs due to heating emissions are still 24 times higher (Table 9). To note, yet, is that a complete reconstruction after building collapse is not accounted for in the calculation of repair/replacement CO_2 emissions and costs, which indeed only considers mending or replacement of the identified damaged or failed walls. Therefore, the impact of high-intensity seismic events in relation to the heating emissions and costs is de facto more significant than illustrated.

2.2.3.3 Cost from Heating

The reference cost for the purchase of natural gas for households (< 30'000 kWh/year) is taken as 0.091 CHF/kWh (date: 01.09.2021) [47]. The costs for the operational heating are shown in Table 15.

Table 15: Costs from heating demand

Yearly heating demand [kWh]	Yearly cost from heating demand [CHF]	Cost from heating demand in 50 years [CHF]
33'564	3'054	152'716

It is to consider that the assumption of a unit price of 0.091 CHF/kWh represents a conservative scenario since the combustible costs are very volatile due to economics, policies, geo-political situations and several other factors. Furthermore, no inflation, depreciation or other increase in prices is accounted for and no net present value of the combustible costs over 50 years is calculated.

3 Retrofit Interventions

To enhance the seismic and thermal analyses' results outlined in Sections 2.1.2 and 2.2.3, in which the building is assessed as not conforming to SIA 269/8: 2017 [1] and to MuKEn: 2018 [2], a set of whenever possible synergetic retrofit measures is suggested.

3.1 Typical Retrofit Interventions

3.1.1 Qualitative Evaluation of Upgrade Potential

The combination of seismic and thermal retrofits shows considerable potential in terms of enhancement of the building's performance in case of an earthquake and during regular operation in heating periods. The implementation of targeted interventions promises savings in terms of CO_2 freed into the atmosphere and operational costs, as well as gains in structural safety. Moreover, a simultaneous retrofit in both scopes allows cost-effective construction works, as for example sharing of site installations or equipment is possible.

In the literature, the application of different retrofitting measures to improve the seismic and thermal behaviour of a building is described. In the following Section 3.1.2, a selection of possible interventions is presented and their implementation is qualitatively evaluated.

3.1.2 Selection of Most Promising Retrofit Interventions

3.1.2.1 Seismic Retrofit Interventions

Seismic retrofit measures are either designed to reduce the seismic demand or increase the seismic capacity of a structure or a combination of both. Examples of demand-reducing interventions are base isolation or dampers [18]. A significant disadvantage of both mentioned retrofittings is their invasiveness in the building's structure and the associated expensiveness. Hence, these retrofit options are not further considered in this Thesis.

To increase the seismic capacity or, more specifically, the lateral strength (and partially the ductility) of the structure, frames, braces [9] or double-skin retrofits have been implemented in several case study buildings around Europe [19]. Not only are they designed to enhance the seismic performance of the structure, but they can also be used to create an additional value to the building, for example by integrating balconies in the frame or the double-skin. Despite the great potential of synergetic seismic and energy retrofit with external frames or upgraded double-skins of buildings [19], these options are abandoned in this Thesis: it is opted for less extensive and costly retrofits. Other strengthening measures like the addition of a massive shear wall [18] are dismissed since their realization would imply substantial carbon emissions.

An innovative, environmentally sustainable [48] seismic retrofit intervention foresees the cladding of unreinforced masonry walls with cross laminated timber (CLT) acting as a bracing system [49]. This retrofitting technique has a remarkable potential to be employed as a combined seismic and energy intervention [49], [50]. Possible synergies of CLT structural strengthening measures with thermal interventions can be obtained by the combination of wooden boards (which themselves have good hygrothermal properties [51]) with insulation layers [48] and cladding [50]. Enhancements of in-plane load bearing capacity [51], [52] and energy dissipation were experimentally observed with this retrofit measure [52]. This intervention alternative is nonetheless discarded in this Thesis: the CLT panels modelled as braced timber studs in 3Muri prove not to enhance the in-plane seismic behaviour substantially, contrary to the expectations raised by the literature review.

Moreover, timber strong-backs can be installed to enhance the out-of-plane [53] and, according to some publications, even the in-plane seismic capacity [54]. However, the evaluation of the action of timber strong backs in 3Muri leads to the result, that the in-plane seismic behaviour is not significantly improved, thus dissenting experimental insight described by [54].

Additionally, there is the possibility to jacket a masonry wall with reinforced concrete (RC) [55]. The confinement of masonry walls with an RC jacket has a partially similar effect as for fibre reinforced polymers (FRP) or textile reinforced mortars (TRM) strengthening [55]. An adequate connection of the RC layer to the existing masonry elements must be ensured. RC jacketing is not further pursued in this Thesis since it is more material-consuming (extensive use of cement) than other techniques as for example the installation of near-surface mounted steel reinforcement and embodies therefore more CO_2 emissions.

An alternative to achieve a reinforcement of structural elements consists in the placement of (prestressed) carbon fibre reinforced polymer (CFRP) laminates [56], [57]. Such interventions lead to an augmented load-carrying capacity and are characterised by an easy installation and only minor invasiveness on the building [58]. The option of vertical (prestressed) CFRP laminates is nevertheless not further deepened in this project, since the option of CFRP in the form of laminates lacks in the used 3Muri software. Thus, no assessment of seismic performance after this type of retrofit intervention is feasible. In fact, in 3Muri it's only possible to select CFRP as a textile reinforcement.

Further, near-surface mounted (NSM) reinforcement made of carbon, glass fibre or steel rebars can be installed in an unreinforced masonry wall. The rebars are positioned in a cut groove and are encased by epoxy resin [59], [60]. The in-plane and the out-of-plane seismic behaviour of a masonry wall reinforced by the described technique is improved by horizontal and, respectively, vertical rebars [59]. The NSM reinforcement is ascertained as an effective seismic retrofit intervention and is selected for deeper investigation in this project.

A different strategy to achieve capacity increase is to act mainly on the ductility of the structural elements. The addition of mass and stiffness to the structure which provokes an attraction of further seismic forces to the walls is thus circumvented. Retrofit alternatives that primarily influence the elements’ ductility are hereafter described.

Firstly, there is the option to apply (carbon) fibre reinforced polymer ((C)FRP) textile strips impregnated with epoxy resins [61] to the affected structural elements [62]. Their action increases the ductility and strength of masonry walls [62]. Owing to the inconspicuousness of this intervention during and after its application [62], it is a widespread retrofitting method [61]. The high strength and the slim thickness of the material also contribute to the popularity of this intervention in practice [61]. The application of CFRP textile strips on the surface of unreinforced masonry walls after polishing them is assessed as a valid seismic retrofit measure, despite the relatively labour-intensive procedure.

Secondly, textile reinforced mortars (TRM) or textile reinforced cementitious matrices (TRCM) can be used to increase the ductility [63] and the strength of masonry infill walls [64], as well as to enhance energy dissipation during an earthquake [63]. An advantage of this technique compared to CFRP interventions is the use of less costly and environmentally harmful (cementitious) mortars instead of epoxy adhesives [61]. The seismic retrofitting through TRM is not further followed since the selection of Swiss codes (SIA) in 3Muri does not allow the assessment of this retrofit measure. In fact, this option is only available when the verification is done according to the Italian codes (NTC). TRMs would also have offered opportunities for a synergetic thermal and seismic intervention, for example through the use of thermal mortars which are characterised by a low thermal conductivity or by the addition of insulation on top of the reinforced mortar [19].

Besides, research is pursued and innovative seismic retrofit solutions are continuously proposed. For instance, the application of natural fibre-based reinforcements such as jute and basalt fibers [65], [66] or sisal fibers [67] is suggested. It is left to practitioners and the industry to test the newly engineered products and to validate their applicability.

3.1.2.2 Thermal Retrofit Interventions

Some of the current practices to decrease the heating demand of a structure act on the heat losses through the building envelope. The heat transmittance can be reduced through the installation of insulation on the envelope and of thermally well-performing windows and doors. Other possible interventions aim at the addition of thermal mass in the building to increase its heat storage capacity [41] and attenuate sudden temperature changes.

In this Thesis, it was chosen to lower the heating demand by reducing the heat losses through an improvement of the thermal insulation of the roof and the external walls, as well as by replacing all windows.

Conventional insulation materials comprise extruded polystyrene (XPS), expanded polystyrene (EPS), glass wool, rock wool, fiberglass or foamglass [68]. More engineered products such as vacuum insulated panels (VIP) or aerogel insulation [68] have lately been developed. Besides, eco-based sustainable alternatives like cork, reed, straw, flax and cellulose panels or wool mats [68] were brought on the market.

To diminish the heat transmittance of the roof, in this Thesis it is decided to install an additional layer of an inorganic insulation material, namely fiberglass, above the already existing fiberglass insulation in the roof structure. For the external walls, flax, cellulose, straw and fiberglass panels are considered. After a closer assessment of the mentioned materials, flax and cellulose panels are discarded. Flax is not further considered due to its thermal conductivity, which is the highest amongst the options in the narrow selection, while cellulose panels contain less bound biogenous carbon compared to straw at parity of U-value.

Also on the front of windows, technological progress was made in the last decades, leading to highly airtight and little heat-emitting products. Examples thereof are double and triple-glazed windows with different filling gases/air-vacuum [69] between the panes and low-E coating. Triple-glazed windows were selected to be applied in the case study building.

3.1.2.3 Selected Retrofit Interventions

To summarize, the seismic upgrade given by either CFRP strips or NSM steel reinforcement combined with thermal interventions is chosen for deeper analysis. The thermal retrofit consists of the placement of triple-glazed windows, thermal insulation of the roof with fiberglass mats and insulation of the walls. The walls' insulation is foreseen with straw panels clad with clay (applied on the interior surface of the perimetral walls), externally applied straw panels or fiberglass mats respectively.

3.1.3 Embodied CO_2 Emissions of Retrofit Interventions

The embodied CO_2 emissions and the bound biogenous carbon related to the selected combined retrofit alternatives of the case study building are shown in Table 16. A detailed composition of the CO_2 emitted to produce the materials used in every retrofitting option is attached in Appendix C (Table 49 to Table 55).

Table 16: Embodied CO_2 emissions in the synergetic retrofit options

Retrofit		**CO_2 emissions [$kgCO_2/m^2$]**	**Bound Biogeneous [$kgCO_2/m^2$]**
Seismic	Alternative 1: CFRP strips	31	-
	Alternative 3: NSM steel reinforcement	13	-
Thermal	Alternative 1: Wall insulation: Straw panels (inside) with clay plaster	4	-6.3
	Alternative 2: Wall insulation: Straw panels (outside)	1.7	-6.3
	Alternative 3: Wall insulation: Fiberglass mats	5.3	-
	Roof insulation: Fiberglass mats	4	-
	Window replacement	115	-7.5

Figure 14 and Figure 15 depict the CO_2 emissions entailed by every considered retrofit option graphically. The greenhouse gas emissions per unit area shown in Table 16 are multiplied by the respective surface of application. It is assumed that the seismic interventions are executed on 30.8 m^2 of unreinforced masonry walls, while the thermal insulation is installed on all perimetral walls (547.8 m^2), the complete roof gets an additional insulation layer (186.8 m^2) and every window is substituted (76.7 m^2). To remark is the fact, that only CO_2 emissions arising from the materials' production are represented in Figure 14 and Figure 15, while the amount of bound biogenous carbon in the organic materials is neglected in these diagrams.

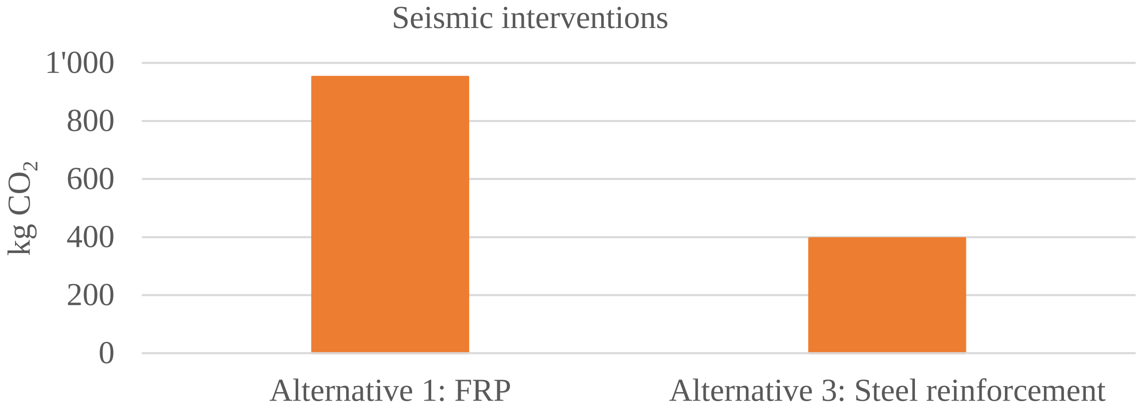


Figure 14: Embodied CO_2 emissions in the seismic retrofit options [46], [70]

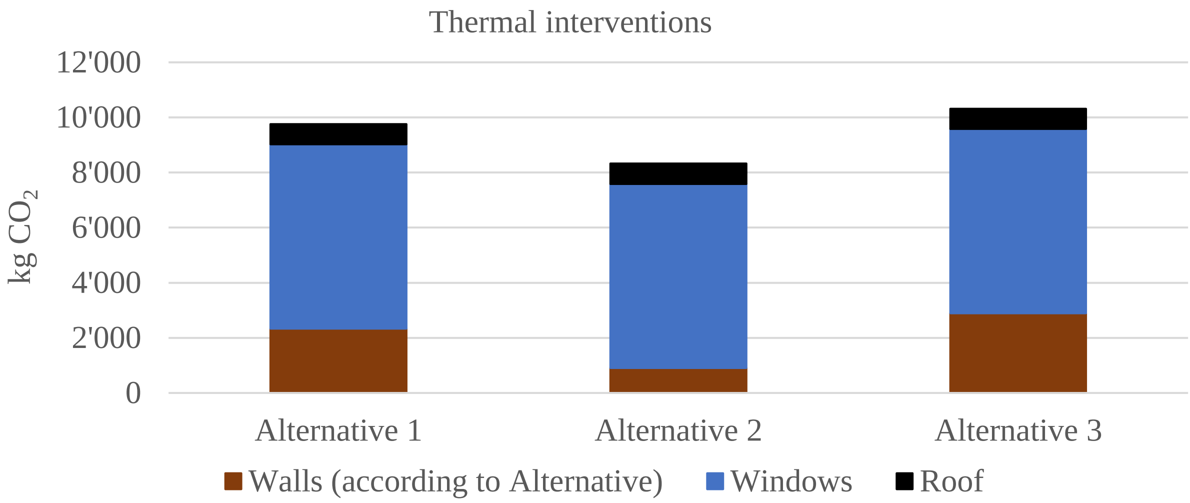


Figure 15: Embodied CO_2 emissions in the thermal retrofit options [46]

Observing the values represented in Figure 14, it is noticeable that NSM steel reinforcement contributes considerably less to CO_2 emissions into the atmosphere than CFRP strips installed on the same wall surface area. On the other hand, Figure 15 highlights the significant impact of window production on greenhouse gas emissions. It is furthermore noticeable, that the walls' insulation of Alternative 2 (straw panels mounted on the outside surface of the perimetral walls) is more environmentally friendly in terms of CO_2 emissions compared to the other two depicted options. It must be kept in mind, that the bound carbon in the straw is not even accounted for in these graphical representations.

4 Building Analysis: After Retrofit

4.1 Seismic Analysis

4.1.1 Modelling in 3Muri

4.1.1.1 Geometrical Properties

The in-plane seismic analysis done with 3Muri indicates that the first failing walls are located on the ground floor and correspond to an exterior wall (wall 12) and an internal wall (wall 14, see Figure 8). They both fail in bending at low inter-storey drifts. Consequently, interventions on these unreinforced masonry walls are proposed (Figure 16). The seismically retrofitted wall surface amounts to 30.8 m^2, in accordance with the calculations executed to depict Figure 14.

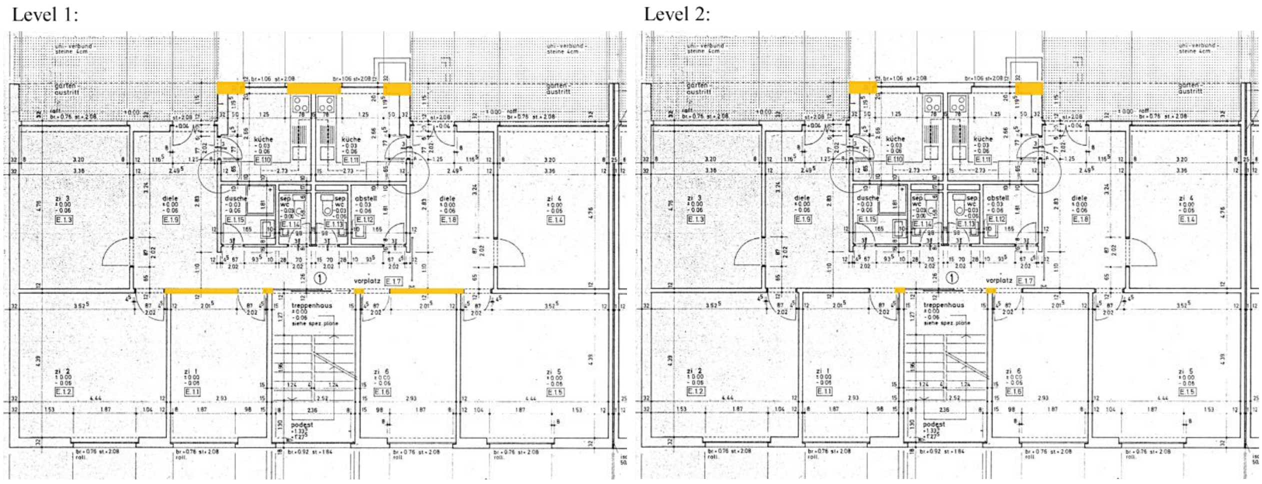


Figure 16: Seismically retrofitted walls (parts of walls 12 and 14, 30.8 m^2)

4.1.1.2 Material Properties

The material properties of the installed seismic retrofits are summarised in Table 17 and Table 18. The selected NSM steel reinforcement is planned with B500B steel rebars of 10 mm diameter, spaced 400 mm for the horizontally installed bars and 600 mm for the vertical reinforcement rebars. On the other hand, the selected CFRP strips, MapeWrap C Uni-Ax 600 – L400, are 400 mm wide and are applied horizontally and vertically in steps of 800 mm. Their material properties are sourced from the 3Muri library of the company Mapei [71].

Table 17 Material properties of seismic retrofit modelled in 3Muri: NSM steel reinforcement

NSM steel reinforcement	**Material**	**A_d, A_{sw} [mm²]**	**S_d, S [mm]**	**Shear drift [-]**	**Bending drift [-]**
Vertical	steel B500B	79	600	-	-
Transversal	steel B500B	79	400	0.0080	0.0160

Table 18: Material properties of seismic retrofit modelled in 3Muri: CFRP strips

CFRP strips	f_{bm} [N/mm²]	f_{btm} [9] [N/mm²]	Block size [mm]	$\gamma_{f,d}$ [-]	A [-]	γ_f [-]	Shear drift [-]	Bending drift [-]
General	7.0	0.7	290	1.20	1.50	1.10	0.0080	0.0160

	b_f [mm]	Step [mm]	t_f [mm]	Layers [-]	η_a [-]	E_f [N/mm²]	ε_{fk} [%]	ε_{fd} [%]	f_{fdd} [N/mm²]
Vertical diffused	400	800	0.337	1	0.75	252000	2.00	0.177	297
Transversal diffused	400	800	0.337	1	0.75	252000	2.00	0.177	297

4.1.2 Results: Seismic Compliance

The structure's seismic performance before and after the proposed retrofits is summarised in Table 19. Detailed overviews of the displacement demand and capacity, as well as the compliance factor for every analysis computed by 3Muri are given in Appendix D (Table 56 and Table 57).

Both suggested interventions lead to the same minimum compliance factor α_{min}. Moreover, in both retrofitted cases the most critical analysis shifts from analysis 3 in X-direction to analysis 17 in Y-direction.

Table 19: Summary of the seismic performance before and after the proposed retrofits applied on walls (30.8 m^2)

	Most critical analysis	Min. compliance factor α_{min}	Improvement of compliance factor α_{min}
Before retrofit	Analysis 3 (-X direction)	0.44	-
Seismic retrofit: **Alternative 1** CFRP strips	Analysis 17 (+Y direction)	0.64	+ 45 %
Seismic retrofit: **Alternative 3** NSM steel reinforcement	Analysis 17 (+Y direction)	0.64	+ 45 %

[9] $f_{btm} = 0.1\ f_{bm}$ [72]

4.1.2.1 Embodied CO_2 Emissions from Repair Works

The damages to the structure for different earthquake intensities and the related CO_2 emissions are quantified. For this purpose, simulations run in 3Muri for the original structure (see also Section 2.1.2.2) and the building with 30.8 m^2 of retrofitted walls with NSM steel reinforcement and CFRP strips respectively are compared. The results are manually evaluated by recording the perimeter and the area of damaged and failed walls. A summary of the walls affected by damage or failure is given in Table 20, while the detailed data is given in Appendix E (Table 58 and Table 60). The values shown in Table 20 are the sum of perimeters and areas of damaged and failed walls over the different displacements of the control node for which damage is assessed (see Figure 7).

Table 20: Sum of perimeters of damaged walls and areas of failed walls over the evaluated displacements before and after retrofit

			Wall thickness 0.20-0.30 m		**Wall thickness 0.10-0.15 m**	
	Analysis	**α_{min} [-]**	**Damaged (perimeter [m])**	**Failed (area [m²])**	**Damaged (perimeter [m]))**	**Failed (area [m²])**
Before retrofit	3	0.44	1773	5.8	1348	9.9
After retrofit (NSM 30.8 m^2)	For comparison: 3	0.69	1828	8.5	1318	10.4
After retrofit (NSM 30.8 m^2)	14	0.66	1769	10.5	1261	10.9
After retrofit (CFRP 30.8 m^2)	13	0.68	1834	7.5	1334	10.9

The building in its original state displays the lowest compliance factor in Analysis 3 (cf. Table 2). Analysis 3 is characterised by a uniform distribution of forces in the negative X direction. To compare the incurred structural damages on the building before and after the seismic interventions, for the retrofitted building the analyses in X-direction with the lowest compliance factor are selected (see Table 20, analyses 14 and 13). Additionally, to assess the influence of the applied strengthening measures on the building's seismic performance, the damages and failures after the NSM steel reinforcement are quantified for the same analysis 3 as for the structure before retrofits (Table 20, second row).

The installation of NSM steel reinforcement and CFRP strips brings valuable improvements in seismic performance, as observable from the rise in minimum compliance factors α_{min}. Nevertheless, the sum of damaged wall perimeters and failed wall surfaces over the considered displacements generally does not decrease but rather increases (Table 20). The cause for this phenomenon is the action of the installed retrofits, which distribute the seismic forces on more structural elements than in the original building. For this reason, after the execution of seismic strengthening measures, more walls are battered by earthquake events.

By consideration of the determined earthquake-induced damage in combination with seismic data from the EFEHR hazard map [37], Figure 17 is elaborated.

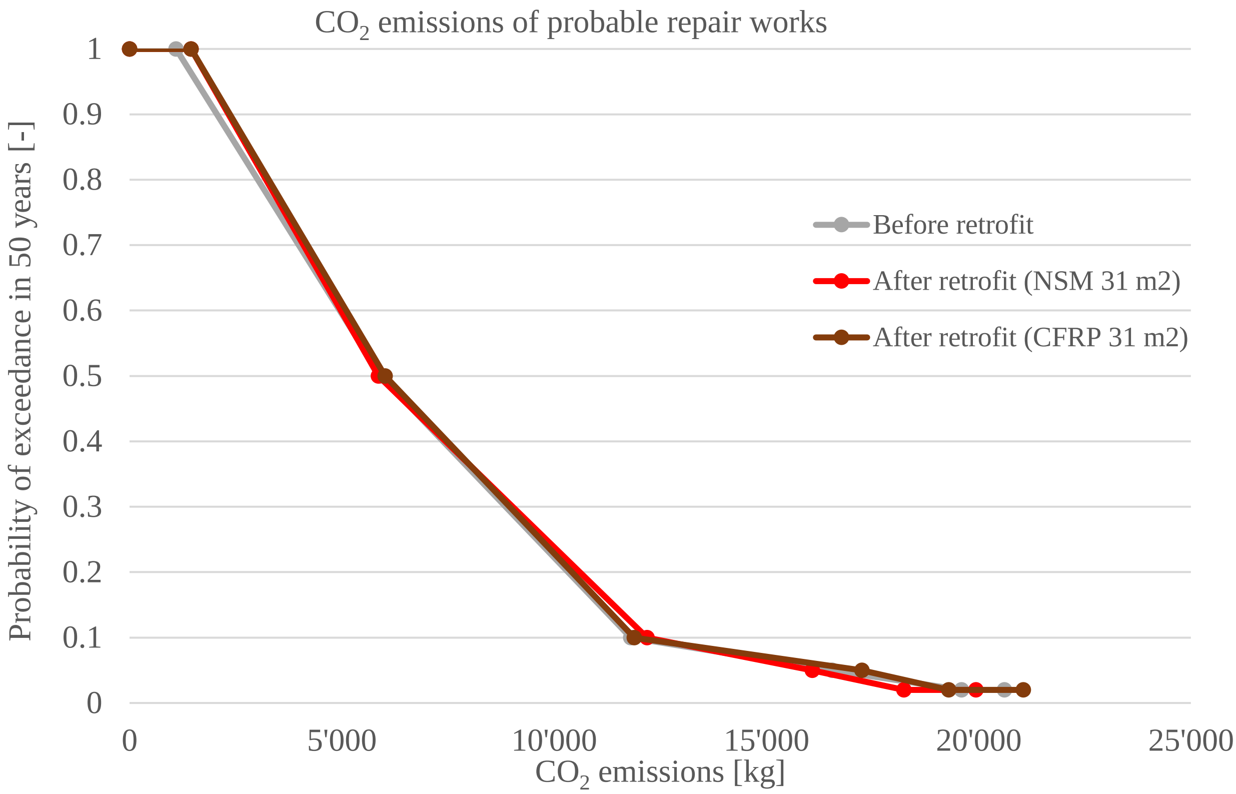


Figure 17: CO_2 emissions of probable repair works for different displacements and related probabilities of exceedance (loss functions) before retrofit and after NSM steel reinforcement or CFRP strips retrofit (area of application: 30.8 m^2)

The general trend which can be noticed in Figure 17 is that for low-intensity earthquakes the retrofitted structure emits more CO_2 due to repair works than before the seismic interventions. The reason therefor is the above-mentioned force redistribution on multiple walls, which can be observed for instance in Appendix E, Table 62. Actually, Table 62 only marginally shows the effect of force spreading since the displayed walls are the retrofitted ones, while the seismic force redistribution mostly affects the other, non-retrofitted walls.

For high earthquake intensities, however, thanks to the seismic interventions the displacement capacity is increased. With that, the collapse of the building occurs at augmented inter-storey drifts and at higher ground accelerations. Despite the improvement of structural safety achieved through the retrofittings, the calculated CO_2 emissions at collapse or immediately previous to collapse may be higher than for the unretrofitted structure, owed to the potentially increased number walls failing simultaneously.

The CO_2-related loss from repair works displayed in Table 21 is again calculated as the integral of the curves depicted in Figure 17. For Sion, the loss results bigger after the seismic retrofits than before. This insight is concordant with the discussion about force redistribution on multiple walls outlined above. To remark is the fact that the seismic retrofit is designed to enhance the compliance factor (i.e. safety in regard to collapse) and not to minimise the CO_2 emissions related to repair works.

For high seismicity zones like Italy, however, losses can be reduced thanks to the seismic reinforcements (cf. NSM steel reinforcement in Table 21). This is explained by the increased weight of high-intensity earthquake events (whose damages previous to collapse may be reduced by seismic strengthening) through increased probabilities of exceedance. In the case of CFRP strips retrofit, the losses are still increased through the intervention. To note, nonetheless, is that the quantification of CO_2 emissions from repair/replacement works only accounts for the damaged and failed walls. It is indeed not considered that significantly higher CO_2 emissions are caused by the partial or total collapse of the building and by consequent reconstruction works of the building.

Table 21: CO_2-related loss in 50 years

	Displacement range [cm]	**CO_2-related loss [kg CO_2] Sion, Switzerland**	**CO_2-related loss [kg CO_2] Perugia, Italy**
Before retrofit	0 – 1.76	6'962	16'186
After retrofit (NSM 30.8 m^2)	0 – 1.76	7'059	16'044
After retrofit (CFRP 30.8 m^2)	0 – 1.76	7'148	16'451

What can be noticed in Table 21 is that in a high seismicity region like Central Italy, the absolute value of CO_2 emissions from repair/replacement works is increased compared to a low seismicity zone like Switzerland. Nevertheless, the trend of additional damages and failures consequent to a seismic retrofit intervention and the concomitant force propagation is not significantly rising by relocating the building from Sion to Perugia. However, it is to be reminded that in high seismicity zones, strong seismic excitations which could lead to a (partial) collapse of the structure and entailed CO_2-intense reconstruction works, which are not considered in this project, are much more probable. Hence, the beneficial action of seismic interventions in earthquake-prone regions is tendentially underrated in the considerations made in this Thesis.

4.1.2.2 Monetarised Cost of CO_2 Emissions from Repair Works

The estimation of CO_2 emissions due to repair works after an earthquake event described in Section 4.1.2.1 is hereafter converted to a monetary cost. The used transformation factor is specified in Section 2.1.2.3.

Table 22 contains the values of the carbon emissions caused by damaged and failed walls' repair. The trend of costs arising from greenhouse gas production is directly proportional to the losses from CO_2 emissions caused by repair works displayed in Table 21. Hence, the discussion made for the CO_2 emissions is also valid for the related monetarised costs.

Table 22: Monetarised cost of CO_2 emissions from repair works in 50 years before and after seismic retrofits

		Sion, Switzerland		**Perugia, Italy**	
	Displacement range [cm]	**CO_2-loss in 50 years [kg CO_2]**	**Cost of CO_2 emissions in 50 years [CHF]**	**CO_2-loss in 50 years [kg CO_2]**	**Cost of CO_2 emissions in 50 years [CHF]**
Before retrofit	0 – 1.76	6'962	1'447	16'186	3'365
After retrofit (NSM 30.8 m^2)	0 – 1.76	7'059	1'468	16'044	3'336
After retrofit (CFRP 30.8 m^2)	0 – 1.76	7'148	1'486	16'451	3'420

4.1.2.3 Cost of Repair Works

The computation of costs arising from the repair or the replacement of unreinforced masonry walls is executed according to the procedure explained in Section 2.1.2.4, which is based on the area of affected walls (see detailed computation in Appendix E, Table 59 and Table 61).

Table 23 summarizes the detected damages and failures after seismic events of variable intensities. More precisely, the listed values are the sum of the areas of damaged and failed walls over various displacements (see values of the considered displacements in Figure 7).

Table 23: Sum of areas of damaged and failed walls before and after retrofit

			Wall thickness 0.20-0.30 m		**Wall thickness 0.10-0.15 m**	
	Analysis	**α_{min} [-]**	**Damaged (area [m^2])**	**Failed (area [m^2])**	**Damaged (area [m^2])**	**Failed (area [m^2])**
Before retrofit	3	0.44	676	5.8	769	9.9
After retrofit (NSM 30.8 m^2)	14	0.66	689	10.5	770	10.9
After retrofit (CFRP 30.8 m^2)	13	0.68	704	7.5	797	10.9

The resulting repair costs are obtained by the multiplication of the unit surface prices listed in Table 10 with the areas of needed repair/replacement shown in Table 23. Complementing the quantified repair costs with probabilities of exceedance of seismic events in 50 years from the EFEHR hazard map [37], Figure 18 is plotted.

The monetary loss for the case study building placed in Sion and, for comparison, also considering a presumed location of it in Perugia, Italy, is calculated by integration from Figure 18 and is displayed in Table 24.

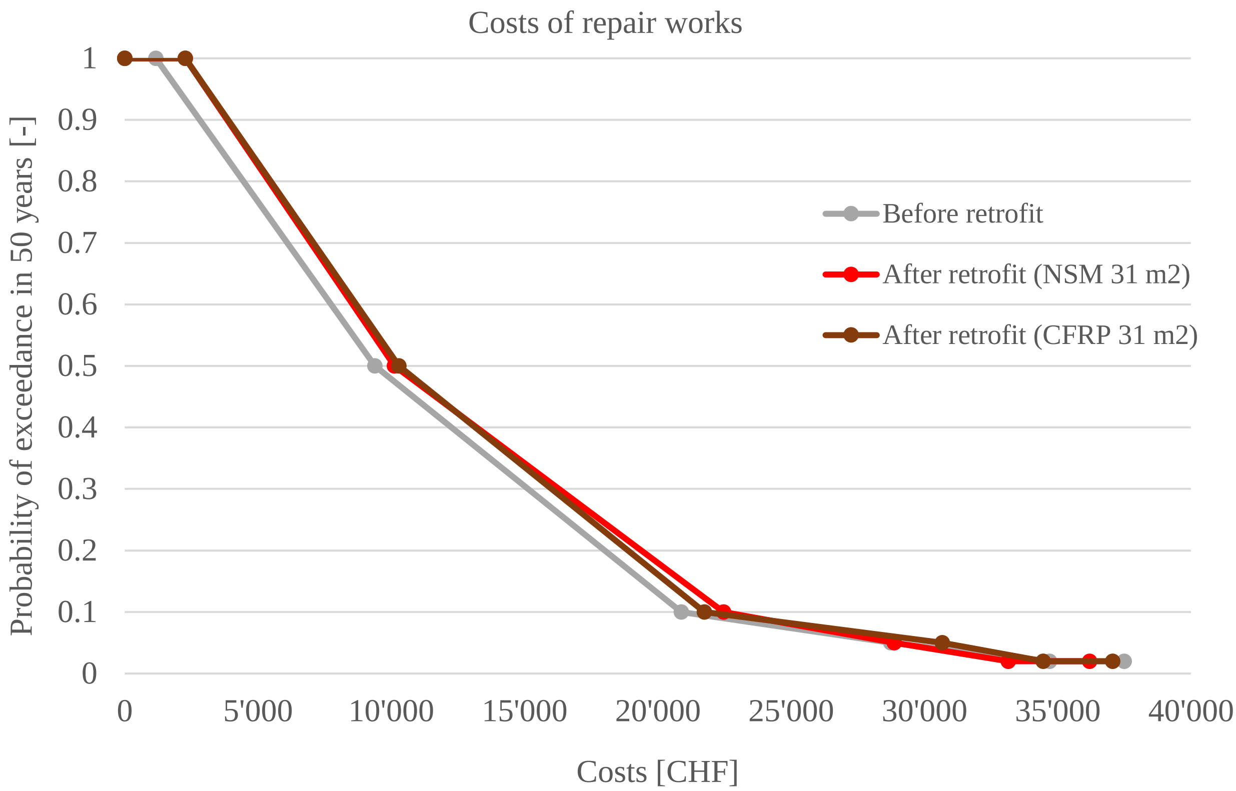


Figure 18: Cost of probable repair works for different displacements and related probabilities of exceedance (loss functions) before and after retrofits

Table 24: Monetary loss in 50 years before and after retrofits

	Displacement range [cm]	**Monetary loss [CHF] Sion, Switzerland**	**Monetary loss [CHF] Perugia, Italy**
Before retrofit	0 – 1.76	11'640	31'087
After retrofit (NSM 30.8 m^2)	0 – 1.76	12'558	30'877
After retrofit (CFRP 30.8 m^2)	0 – 1.76	12'577	31'579

Analogously to the CO_2-related loss from repair works discussed in Section 4.1.2.1, the loss linked to costs of repair works after a seismic event rather increases consequently to seismic retrofit interventions. Again, this is correlated to the force redistribution on more walls due to the action of the reinforcing measures. Additionally, it must not be forgotten, that the partial or total collapse of the structure is only accounted for in the cost estimation of repair works as a mending/replacement of the damaged/failed elements. In fact, involving collapse as a cause for the reconstruction of the entire building or parts of it would lead to much higher expenses for high-intensity earthquakes. Thus, seismic retrofits would certainly show a significant loss reduction, since they imply higher ground accelerations for the structure to collapse.

4.2 Thermal Analysis

4.2.1 Thermal Properties of the Building Envelope After Retrofit

The thermal behaviour of the building's envelope is enhanced through the planned interventions, which are designed to make the retrofitted components meet the requirements of MuKEn [2]. The U-values of the retrofitted elements are collated in Table 25.

The detailed composition of the perimetral walls, the roof and the windows after the thermal upgrade is shown in Appendix F (Figure 48 to Figure 50 and Table 63 to Table 67).

Table 25: U-values in is-state, after thermal retrofit and limit U-values defined by MuKEn [2]

	U-value (is-state) [W/(m²K)]	**Thermal retrofit**	**U-value (after retrofit) [W/(m²K)]**		**U-value (required after retrofit) [W/(m²K)]**
Exterior walls	0.41	Alternative 1: straw panels with clay plaster (inside)	0.23	<	0.25
Exterior walls	0.41	Alternative 2: straw panels (outside)	0.23	<	0.25
Exterior walls	0.41	Alternative 3: fiberglass mats (outside)	0.23	<	0.25
Roof	0.47	Fiberglass mats	0.24	<	0.25
Windows	3.20	Triple-glazed	0.57	<	1.00
Interior walls	7.94	-	-		-
Floor slabs	1.05	-	-		-
Ground floor slab	3.49	-	-	>	0.28
Doors	2.61	-	-	>	1.20

4.2.2 Results: Heating Demand

Thanks to the enhanced thermal properties of the building envelope, the yearly heating demand is significantly decreased. The trend of heating energy per unit conditioned surface before and after the planned interventions is shown in Figure 19. As expected, the heating demand is most diminished when interventions on walls, windows and the roof are made. The three alternatives of wall insulation are nearly identical in terms of thermal performance since all the suggested insulation options are characterised by similar U-values. The used heating energy in the case of retrofits executed on the sole perimetral walls is slightly lower for Alternative 1 compared to the other two options. Supposably, this fact is due to the increase in heat storage capacity of the walls thanks to the clay-gypsum plaster applied on the internal surface of the straw panels. Compared to the heating demand of the building in its original state (before 1986), the retrofit of walls, windows and the roof decreases the yearly heating energy demand from 95 to 27 kWh/m^2·year.

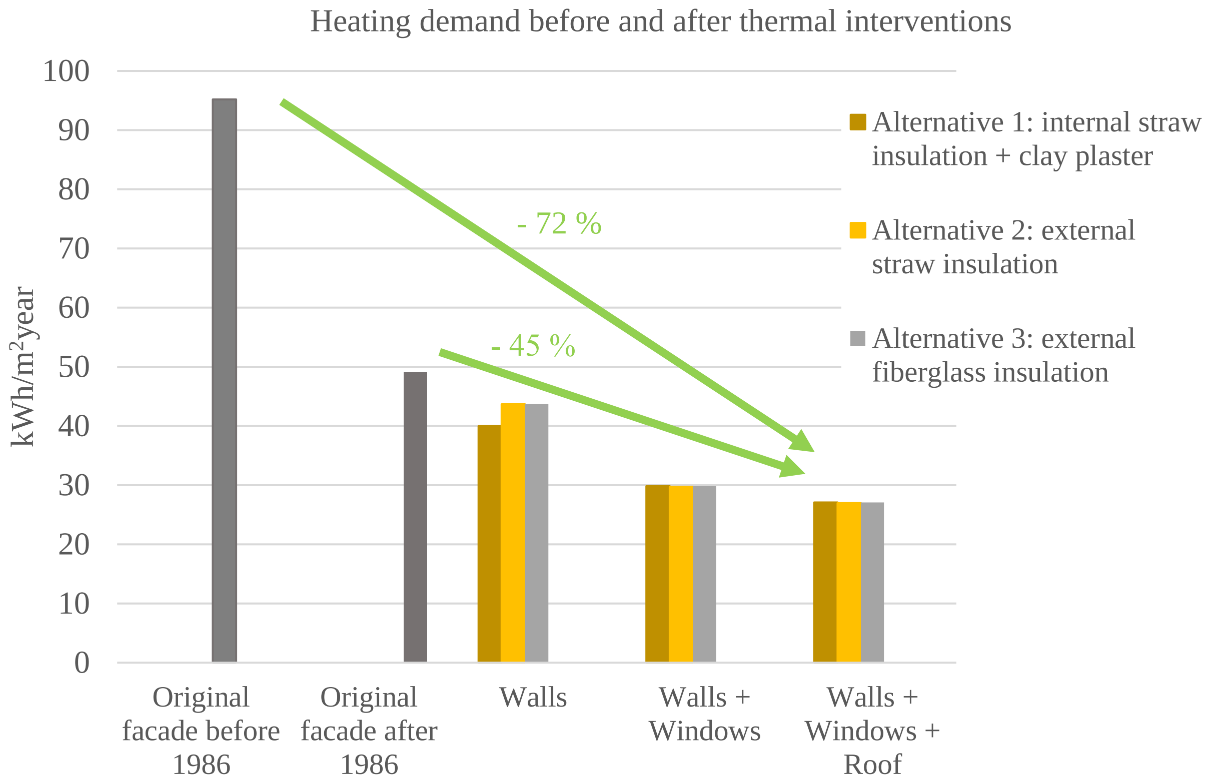


Figure 19: Yearly heating demand before and after renovation of the façade in 1986 and after thermal retrofit on walls Alternatives 1, 2, 3), windows and roof

4.2.2.1 CO_2 Emissions from Heating

The CO_2 emissions caused by the heating of the case study building are depicted in Figure 20. The conversion factor used to calculate the greenhouse gas emissions based on the heating energy use is, identically to the computations in Section 2.2.3.1, 0.228 kg CO_2/kWh final energy. The savings of CO_2 emissions derived from the reduced heating demand of the building with thermally retrofitted walls, windows and roof compared to the is-state (after the façades retrofit of 1986) amount to 45 %. This corresponds to roughly 172'000 kg CO_2 savings in 50 years, which is the emission caused by approximately 1'400'000 equivalent car-km (calculated as in Section 2.1.2.2), which equals 35 times the equator length.

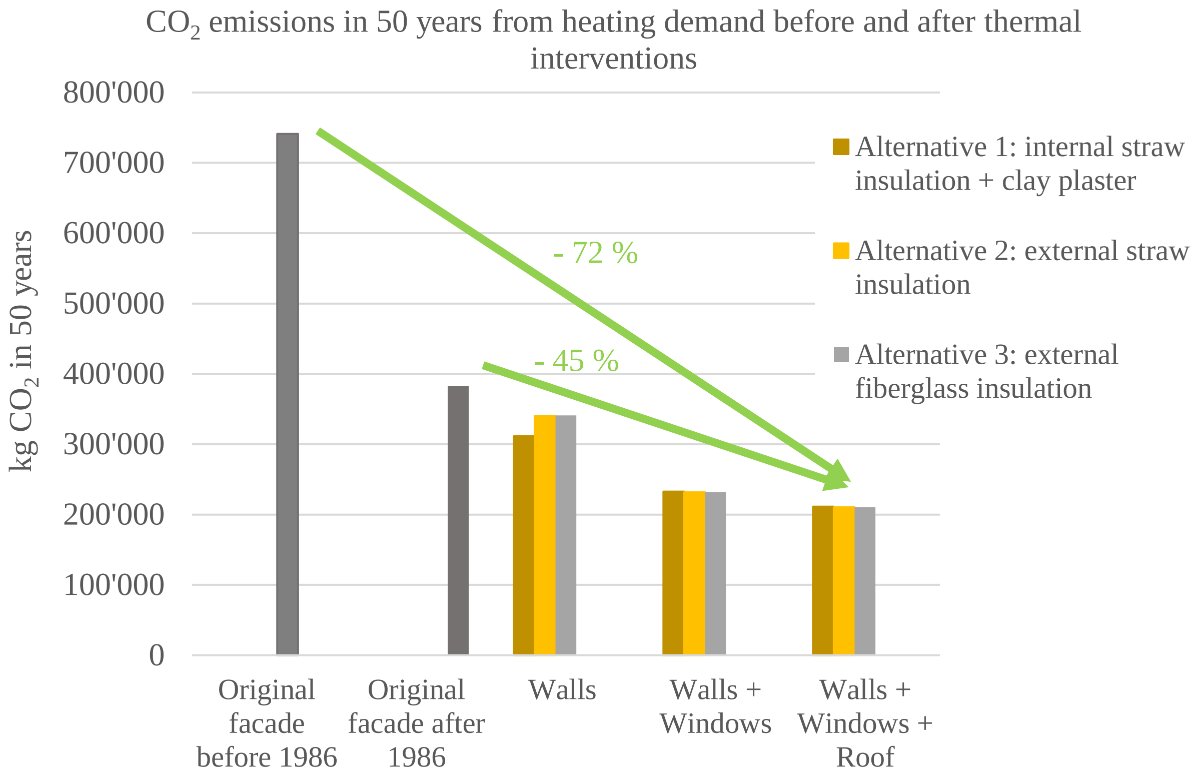


Figure 20: CO_2 emissions in 50 years from heating demand before and after renovation of the façade in 1986 and after thermal retrofit on walls (Alternatives 1, 2, 3), windows and roof

To compare the achieved emission savings from heating with the CO_2 invested for the production of the materials employed for thermal retrofit, graphical representations of the mentioned CO_2 balance over 50 years of remaining service life are given below (Figure 21, Figure 22 and Figure 23).

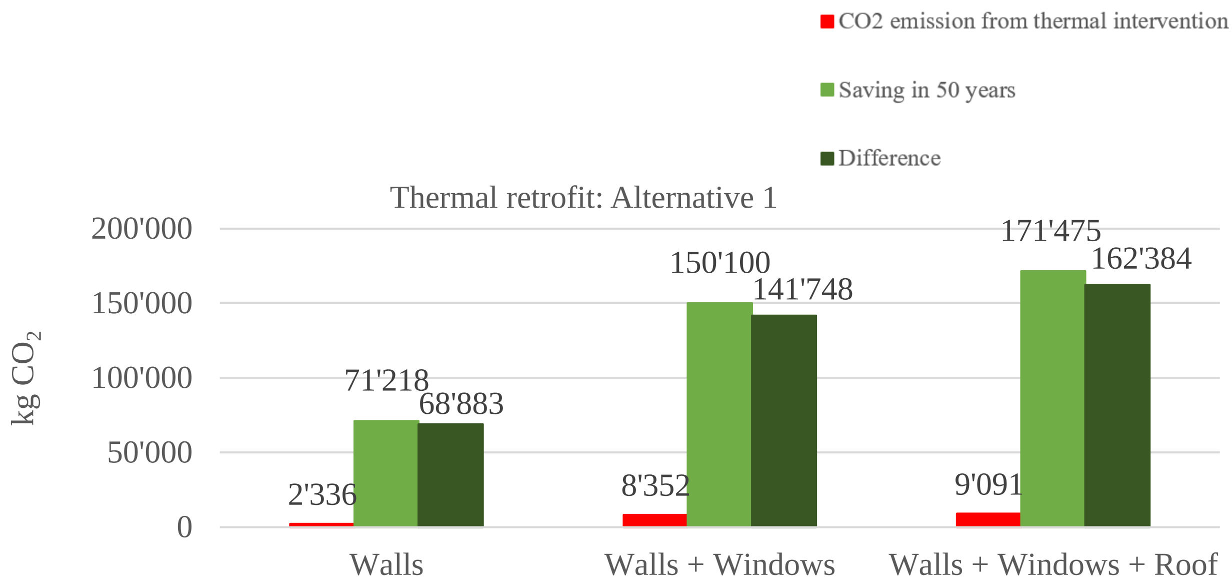


Figure 21: CO_2 emissions from thermal intervention (Alternative 1), savings from reduced heating demand and net savings of CO_2 emissions

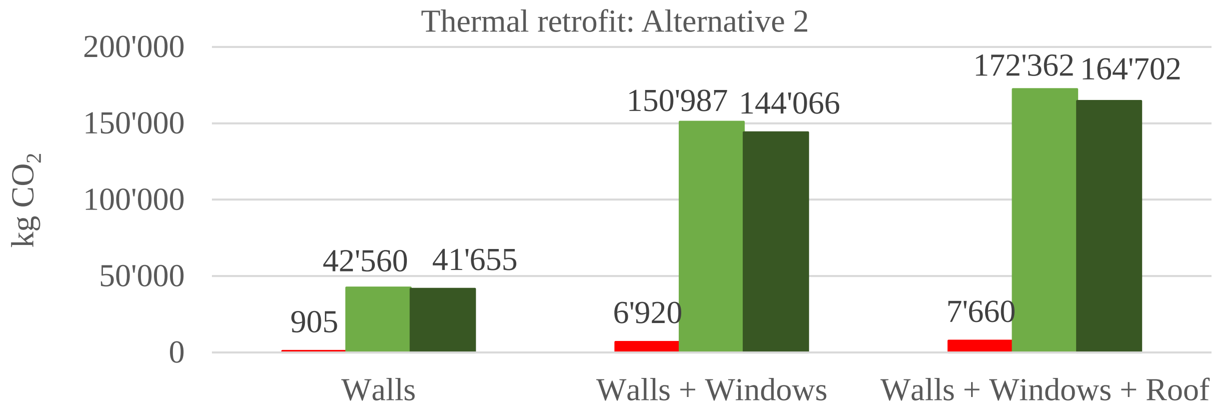


Figure 22: CO_2 emissions from thermal intervention (Alternative 2), savings from reduced heating demand and net savings of CO_2 emissions

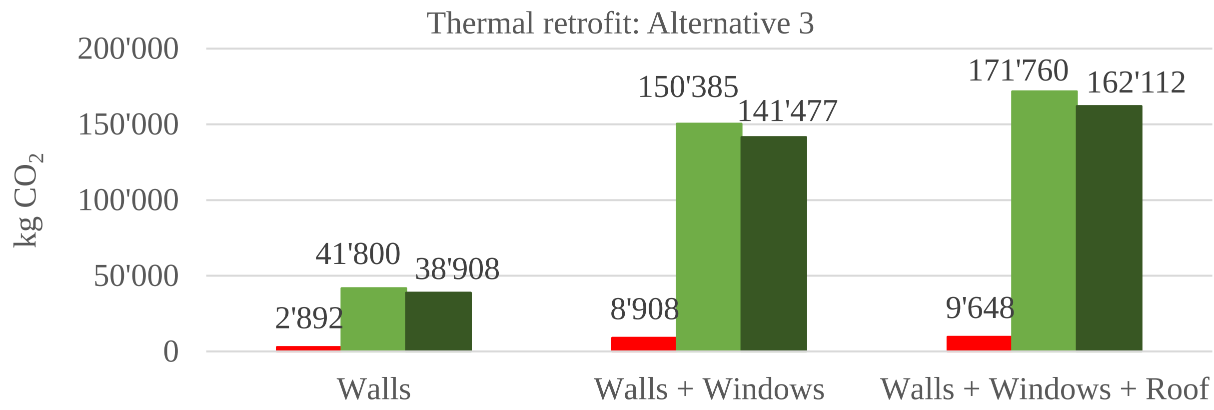


Figure 23: CO_2 emissions from thermal intervention (Alternative 3), savings from reduced heating demand and net savings of CO_2 emissions

As can be seen in the diagrams above (Figure 21, Figure 22 and Figure 23), the production of new windows entails the largest CO_2 emissions among the planned interventions but also leads to the most relevant contribution to CO_2 savings from reduced heating demand. Alternative 2, composed of walls and roof insulation as well as window replacement allows the highest net savings of greenhouse gas emissions. Based on this insight, it is chosen not to further take into account Alternative 1 (wall insulation: straw panels (inside) with clay plaster) and Alternative 3 (wall insulation: fiberglass mats). The interventions included in Alternative 2 are estimated to be accomplished at comparable costs (material and work) to the other two options. Moreover, considerations of occupancy during construction works lead to the choice of insulation applied on the external surface of the perimetral walls, as it does not influence the building's occupants. Due to the explained reasons, Alternatives 1 and 3 are excluded from any further considerations in this project.

4.2.2.2 Monetarised Cost of CO_2 Emissions from Heating

For the estimation of monetarised costs from CO_2 emissions caused by the heating of the thermally retrofitted case study building (renovated walls after Alternative 2, insulated roof and replaced windows) the previously introduced conversion factor of 208 CHF/ton CO_2 is accounted for.

Table 26: Monetarised cost of CO_2 emissions from heating demand after façade renovation of 1986 and after thermal retrofit (Alternative 2)

	Yearly heating demand [kWh]	**Yearly CO_2 emissions [kg CO_2]**	**Yearly cost of CO_2 emissions [CHF]**	**Cost of CO_2 emissions in 50 years [CHF]**
Is-state (after façade renovation of 1986)	33'564	7'653	1'591	79'548
After thermal retrofit (Alternative 2)	18'444	4'205	874	43'711

Significant monetary savings are enabled through the energetic intervention Alternative 2 directed to façade, windows and roof retrofit. As visible in Table 26, the monetarised expenses due to carbon emissions during 50 years of expected remaining service life are drastically reduced from 79'548 CHF from the heating operation of the building in the is-state to 43'711 CHF.

4.2.2.3 Cost from Heating

The cost of combustible for the operation of the gas heating is 0.091 CHF/kWh (date: 01.09.2021) [47]. A comparison of the expenses before and after the suggested thermal intervention (Alternative 2 on walls, windows, roof) is drawn in Table 27 and is graphically illustrated in Figure 24.

Table 27: Costs from heating demand

	Yearly heating demand [kWh]	Yearly cost from heating demand [CHF]	Cost from heating demand in 50 years [CHF]
After façade renovation of 1986	33'564	3'054	152'716
After thermal retrofit (Alternative 2)	18'444	1'678	83'920

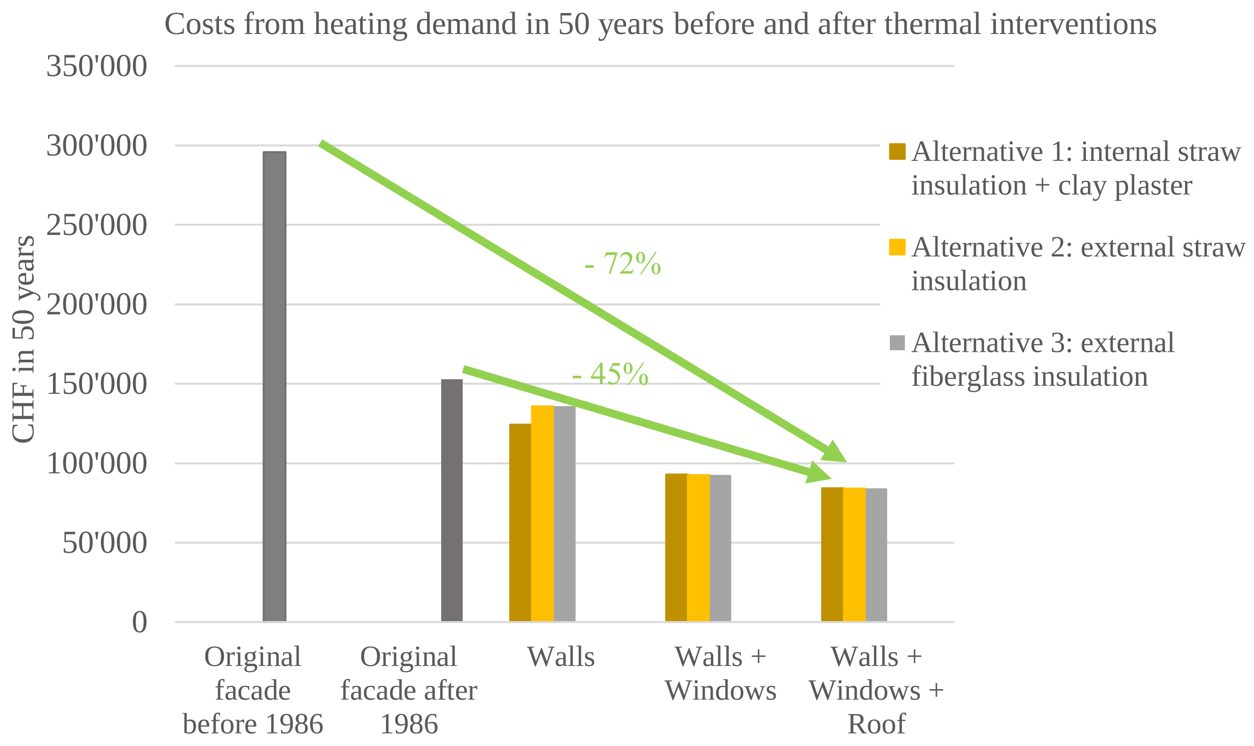


Figure 24: Costs from heating demand in 50 years from heating demand before and after renovation of the façade in 1986 and after thermal retrofit on walls (Alternatives 1, 2, 3), windows and roof

Surely, the employed estimation of constant gas price over the next 50 years is a very conservative and simplified consideration (no net present value calculation). Hence, the benefit of a thermal intervention aimed at reducing the heating demand of a building is underestimated.

5 Construction-Management Analysis of Retrofits

5.1 Time Estimation of Retrofits

Time schedules of the construction works to realise the planned thermal and seismic retrofit interventions are developed as Gantt-Charts in the software Microsoft Project, version 2016.

The retrofits are organised according to a work breakdown structure (see Section 5.2) from the construction phase down to the work packages [73]. Each activity is characterised by the task's name, the estimated duration, the planned start and end date, the predecessor and successor activities and the assigned responsible workforce.

The base assumption for the estimation of activities' duration is that a team of five workers is employed from the construction start to the end of the interventions. A probable duration combined with a typical number of workers is assumed for every activity. The quantity of workforce assigned to every task is given in the Gantt-Chart as a percentage of the worker team (e.g., 60 % of the worker team corresponds to three professionals).

Initially, a sequential schedule, in which the tasks are executed in consecutive order according to their superordinate sub-phases (preparation works, window replacement, facades insulation, roof insulation, seismic retrofit on wall, conclusion of works) is compiled. Thereafter, the activities belonging to thermal and seismic interventions are parallelised. Consequently, a higher workforce allocation is achieved and downtimes are reduced. The simultaneous assignation of workforces on tasks of various genres is an effective instrument to decrease the overall duration of construction works and the interruption of the building's occupancy.

Exemplarily for the decrease of construction works' duration achieved thanks to effective parallelization of activities, Table 28 shows the estimated time necessary for the combined thermal (Alternative 2: straw insulation on walls, fiberglass mats on roof and window replacement) and one of the closely analysed seismic retrofits (CFRP strips).

Table 28: Duration and interruption of occupancy of combined thermal and seismic CFRP retrofit (sequential and parallelised schedule)

	Construction works		**Interruption of occupancy**	
	Calendar dates	**Duration [days]**	**Calendar dates**	**Duration [days]**
Sequential schedule	01.08-24.10.22	85	22.08-20.10.22	60
Parallelised schedule	01.08-13.10.22	74	19.08-21.09.22	34

The Gantt-Chart developed for the thermal intervention selected in Section 4.2.2.1 is displayed in Appendix G, Table 68. Moreover, schedules for the analysed synergetic energy and seismic retrofit options are also given in Appendix G (Table 69 and Table 70), whereat the structural enhancement is achieved, as described in Section 3.1.2.3, through the installation of CFRP strips and NSM steel reinforcement respectively applied on 30.8 m^2 of unreinforced masonry walls. The references from which the procedures of specific activities are sourced are listed in Appendix G.

Across all arranged schedules, the most time-consuming activity is the replacement of the complete set of windows (42 windows). It was assumed that two workers averagely replace windows at a rate of 1 window / 3.25 working hours. In total, 17 working days are employed to complete this activity. During a discussion with Alice Comune [74], a professional energy consultant, it was suggested that by employing the right number of workers, window replacement can be executed very fast, covering an apartment in one day, without causing any temporary relocation of residents. Thus, the estimation done for the time of occupancy interruption due to the intervention on windows may be overly conservative. In fact, by just considering the interruption of occupancy due to the seismic retrofit on the interior, non-perimetral walls, this period of tenants' relocation is shortened by about two weeks. Nevertheless, to eliminate occupancy interruption due to window replacement, the overall construction works inevitably become more expensive or extended. Indeed, either supplementary workers must be hired to accelerate windows substitution (which increases labour costs), or workforces assigned to other, simultaneous tasks must be transferred to window replacement, delaying the affected activities. The longest sub-phase in all construction programmes is the facades' insulation.

Table 29 displays the start and end dates of the planned thermal and seismic interventions, the total working hours (hours in which any workforce is employed), the monthly allocation of workforces, as well as information about the activities which are responsible for the interruption of occupancy.

Table 29: Duration, working hours, monthly allocation and occupancy interruption of retrofit interventions

Intervention type	Start-End	Working hours	Allocation	Interruption of occupancy
Thermal ($547\ m^2$)	**01.08-30.09**	252 h	August: 78 % September: 61%	Windows replacem.: 02.09-26-09 Seismic retrofit: - Occupancy interr..: **02.09-26.09**
Thermal ($547\ m^2$) + seismic (CFRP, $30.8\ m^2$)	**01.08-13.10**	308 h	August: 71 % September: 69% October: 33 %	Windows replacem.: 30.08-21.09 Seismic retrofit: 11.08-06.09 Seismic retr. (interior):19.08-06.09 Occupancy interr.: **19.08-21.09**
Thermal ($547\ m^2$) + seismic (NSM reinf., $30.8\ m^2$)	**01.08-11.10**	293 h	August: 73 % September: 63% October: 26 %	Windows replacem.: 23.08-14.09 Seismic retrofit: 11.08-05.09 Seismic retr. (interior):19.08-05.09 Occupancy interr.: **19.08-19.09**

A graphical representation that summarizes the total duration of the interventions and the related interruption of occupancy is given in Figure 25. The occupancy interruption is due to window replacement and seismic retrofit on the interior, non-perimetral walls. To minimize the impact on the residents, seismic retrofitting works are possibly executed from outside the building. Indeed, the reinforcements are applied at the outer surface of the affected perimetral walls, while the interventions on building elements in the inner part of the ground view are compulsorily done from inside the structure. Additionally, during the development of the schedules, maximization of simultaneity of window replacement and seismic intervention which must be executed inside the building was aimed at, so to reduce the interruption of occupancy to the strictly necessary.

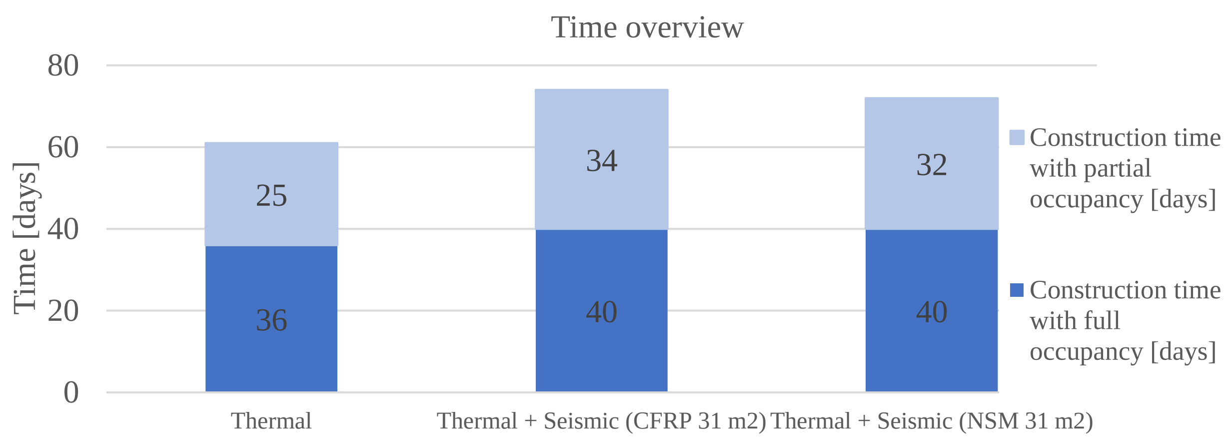


Figure 25: Duration of construction works, subdivided into periods of possible full occupancy and interruption of full occupancy (only partial occupancy possible)

5.1.1 Additional Time from Adding Seismic Retrofit to Thermal Retrofit

As displayed in Figure 25, the total construction time arising from the suggested combined seismic and thermal retrofits is 74, respectively 72 calendar days compared to 61 calendar days planned for the thermal intervention. The period of interrupted occupancy increases from 25 calendar days for the sole energy intervention to 34 and 32 days respectively due to the added seismic upgrade. As mentioned, according to [74] the occupancy interruption due to window replacement can be further reduced.

5.2 Cost Estimation of Retrofits

A bottom-up cost estimation [75] is done to quantify the expenditures related to the developed retrofitting options. Based on the work breakdown structure used for the scheduling in Section 5.1, the cost calculation is executed for every activity. The unit prices for material purchase and equipment rental are sourced from producers and resellers. Disposal costs of dismounted elements are taken from a Swiss waste disposal and recycling company. The references from which the costs are sourced are listed in Appendix H. The workforce fee is estimated to be 90 CHF/hour, accounting for the workers' salary (sourced from [76]) and additional expenses. Work costs are computed through the durations represented in the Gantt-Charts.

The detailed budgets concerning the suggested thermal intervention also combined with the seismic retrofits (CFRP strips or NSM steel reinforcement applied on 30.8 m^2) are given in Appendix H,

Table 71 to Table 73.

An overview of the estimated costs is shown in Figure 26 for the thermal retrofit only and for the analysed synergetic retrofit options.

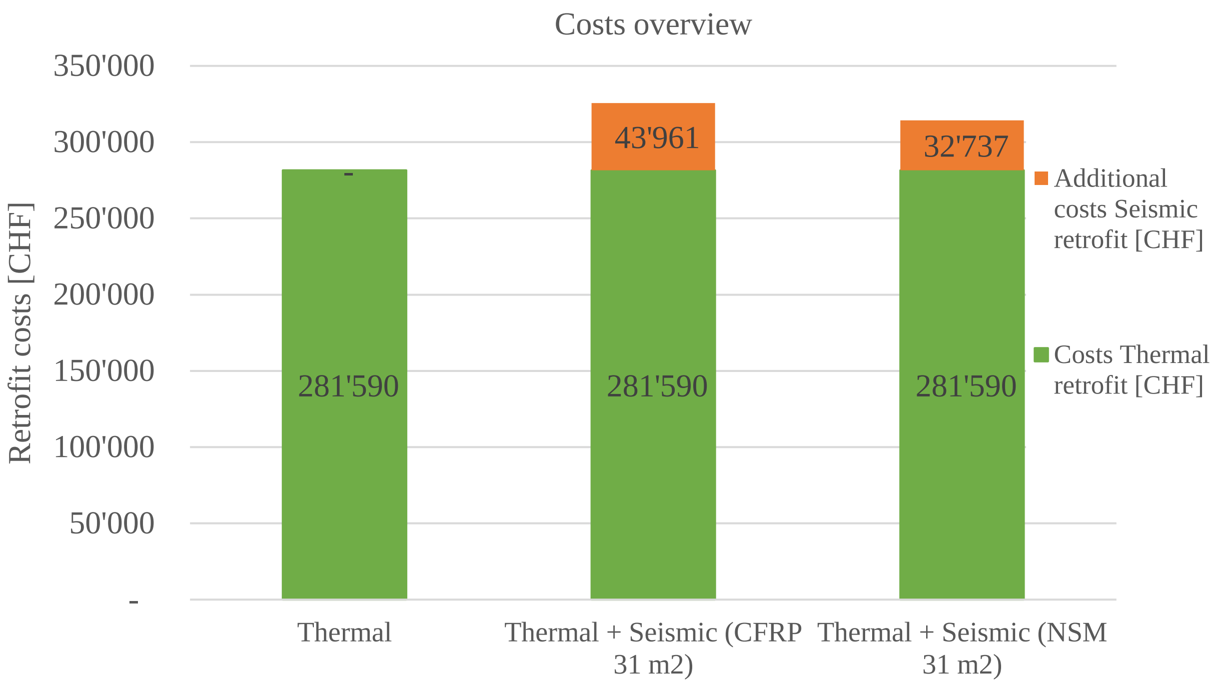


Figure 26: Costs overview of thermal and combined retrofit interventions

5.2.1 Additional Cost from Adding Seismic Retrofit to Thermal Retrofit

Figure 26 visualizes in the left column the cost of the energetic intervention, which amounts to 281'590 CHF. The addition of a seismic retrofit in the form of CFRP strips applied on 30.8 m^2 causes supplementary costs of 43'961 CHF (+ 16 %), while the installation of NSM steel reinforcement on the same wall surface area implicates an investment of 32'737 CHF (+ 12 %).

Compared to the calculated commensurable costs of 16'000 CHF (Section 2.1.2.1) to reach the seismic performance of a new Swiss building (α=1), the expenses incurring from seismic retrofit are expected to be twice to three times higher. To note is the fact that these costs do not even allow to achieve the mentioned full seismic compliance (α=1), but they "only" lead to a minimum compliance factor α_{min}=0.64.

Hence, the actual code provisions of SIA 269/8: 2017 [1] should be modified by raising the commensurable costs to effectively allow an increase in personal safety within costs that are regarded as proportionate.

6 Decision-Making Framework

To illustrate the process followed in this Thesis to select the most appropriate retrofit alternative, a flowchart is drawn (see Figure 27). The chart is divided into a seismic-related part (yellow), a thermal component (green), a brown section which addresses the combined retrofits and a blue loop in which the chosen synergetic intervention is optimised. More specifically, the selected intervention is enhanced by ponderation of the seismic retrofit's application surface in relation to the seismic compliance. Furthermore, its influence with respect to the seismic performance is assessed when installed on one or two sides of a wall. Regarding the thermal aspect, the wall insulation thickness is optimised in relation to the CO_2 balance (investment of CO_2 from materials production and savings coming from reduced heating demand).

6.1 Theoretical Background

This section succinctly introduces the theoretical background on which the decision-making framework developed in this Thesis is established.

In the literature, several multi-criteria decision-making procedures are described. For instance, decision-making matrices whose entries correspond to the relative weight of the criteria assigned to the columns and rows are addressed [77]. There are other various decision-making practices, for example, the Weighted Sum Model (WSM) and the Weighted Product Model (WPM) [78]. They are based on the maximised sum and multiplication respectively of values related to the compared options [78]. Further, in the Analytic Hierarchy Process (AHP) a question is split up into hierarchies and a matrix is consulted to make the decision [78]. The Elimination and Choice Translating Reality (ELECTRE) method consists of the evaluation of options two by two [78]. Last in this brief overview, the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method relies on geometrical considerations of utility functions [78].

In the decision-making procedure suggested in this Thesis, different retrofit interventions are confronted against each other and are rated according to defined criteria. Set-based design postulates, amongst others, the selection of options from the meticulously studied design space by comparison of the alternatives [6], as it is done in the developed decision-making framework. More specifically, the quantitative comparison of options is done through the multiplication of numerical values assigned to the variables related to the herein evaluated criteria. The retrofit alternative with the minimal product is rated as the best, analogously to the Weighted Product Model (WPM) described in [78].

Additionally, target value design (TVD), a management method aimed at ensuring cost, quality and time reliability [79] is implemented in the hereafter described decision-making technique. In fact, the proposed chart contains goal (target) values derived from the owners' interests.

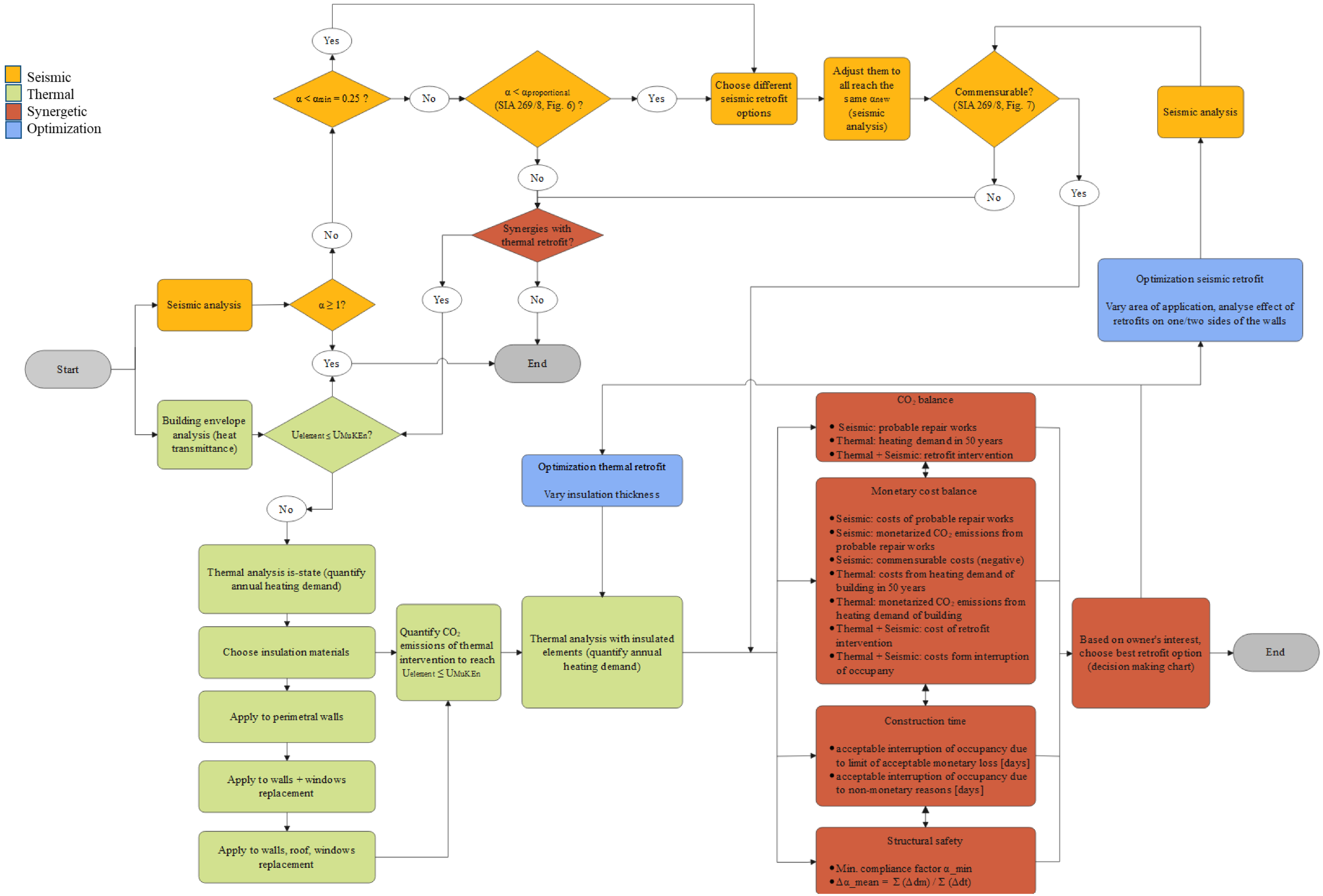


Figure 27: Flowchart for decision-making process

6.2 Criteria for Decision-Making

The elaborated decision-making process incorporates four criteria, according to which each conceived retrofit alternative is rated. The criteria are displayed in the synergetic part (brown) in the flowchart (Figure 27) and are explained in detail in the following sections. The purpose of the evaluation executed for every retrofit option is the selection of the most adequate one, which will be optimised in a further step.

6.2.1 Criterion 1: CO_2 Emissions

The first criterion illustrated in the flowchart (Figure 27) is the CO_2 balance. It includes the carbon emissions coming from the following components:

- Seismic: CO_2 emissions from probable repair works
- Thermal: CO_2 emissions from heating demand in 50 years
- Thermal + Seismic: CO_2 emissions from retrofit intervention

The repair works after a seismic event and the entailed greenhouse gas emissions before and after the planned interventions are quantified in Section 4.1.2.1.

The main part of emissions is caused by the heating during the 50 years of estimated remaining service life of the building. It is referred to Section 4.2.2.1 for the pertaining detailed discussion.

Finally, the interventions planned for the combined thermal and seismic upgrade are a further cause of emissions. They are illustrated in Section 3.1.3. A compilation of CO_2 emissions considering only the thermal retrofit is shown in Figure 28. It balances against each other the investment of carbon contained in the materials used for the thermal interventions and the avoided CO_2 emissions thanks to the reduced heating demand. As it can be seen, the CO_2 balance is already clearly positive after 10 years of operation and is doubtlessly very beneficial for the reduction of greenhouse gas emissions after 50 years of expected remaining service life of the building.

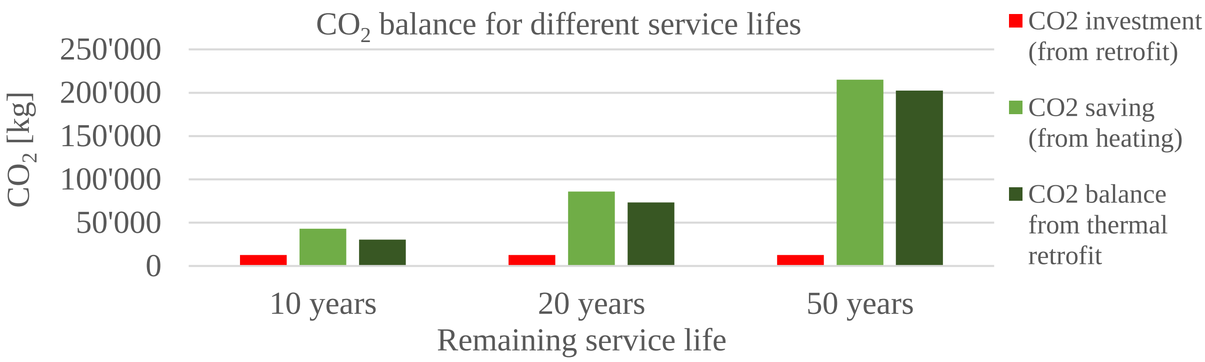


Figure 28: CO_2 balance after thermal retrofit for different remaining service lives

The overall CO_2 emissions, comprising all addressed seismic and energetic aspects before and after the planned synergetic interventions, are shown in Table 30 for every proposed retrofit alternative. Thanks to the thermal retrofit, the overall CO_2 emissions are significantly decreased for all suggested alternatives. In Table 30 it is furthermore noticeable that the addition of the seismic retrofit only contributes to a minor increase in embodied CO_2 entailed by the interventions. On the other hand, the reinforcing measure seems not to bring any reduction of loss in terms of greenhouse gas emissions from probable repair works when calculated as described in Section 4.1.2.1. As discussed in the mentioned section, nevertheless, if building collapse would be considered as the cause for a partial or complete reconstruction of the structure, much higher CO_2 emissions would be expected. Thus, the decrease of collapse probability achieved thanks to the reinforcing interventions would show a significant beneficial impact on the CO_2 balance.

Table 30: CO_2 emissions before and after combined retrofit (thermal: Alternative 2, straw insulation on walls, window replacement, fiberglass insulation on roof / seismic: CFRP strips or NSM steel reinforcement on 30.8 m^2 of walls)

	[kg CO_2 in 50 years]	**Thermal retrofit**	**Thermal + Seismic retrofit (CFRP)**	**Thermal + Seismic retrofit (NSM)**
Is-state	Seismic: probable repair works	6'962	6'962	6'962
	Thermal: heating demand in 50 years	382'628	382'628	382'628
	Total	**389'590**	**389'590**	**389'590**
After retrofit	Seismic: probable repair works	6'962	7'148	7'059
	Thermal: heating demand in 50 years	210'267	210'267	210'267
	Seismic: retrofit intervention	-	952	396
	Thermal: retrofit intervention	7'661	7'661	7'661
	Total	**224'889**	**226'027**	**225'383**

Amongst the options of combined thermal and seismic retrofits, the execution of an energetic upgrade joint with the installation of NSM steel rebars is by a small margin the most convenient in terms of greenhouse gas emissions (see Table 30). For completeness, since the intervention involving NSM steel reinforcement implies an extensive use of rotary cutter machines to cut grooves in masonry bricks and joints, the emissions entailed by electricity consumption are quantified and finally assessed as negligible (0.93 kg CO_2)[10].

To remark is the fact that present and future emissions are equally weighted in the established CO_2 balance.

[10] Total grooves' length = 168 m, (wall area = 30.8 m^2), assumed net cutting rate = 2.5 cm/s, hence 1.9 hours of net cutting time are needed. Average power rotary cutter machine = 4 kW [80]. By utilizing the factor of 0.125 kg CO_2/kWh of Swiss electricity consumer mix [46], the emissions from electricity production used for cutting are calculated to be 0.93 kg CO_2.

6.2.2 Criterion 2: Cost

The total costs arising in the is-state of the case study building and after the developed interventions are subdivided into the undermentioned seismic and thermal elements:

- Seismic: costs of probable repair works
- Seismic: monetarised CO_2 emissions from probable repair works
- Seismic: commensurable costs (negative)
- Thermal: costs from heating demand of building in 50 years
- Thermal: monetarised CO_2 emissions from heating demand of building
- Thermal + Seismic: costs of retrofit intervention
- Thermal + Seismic: costs from interruption of occupancy

The costs related to probable repair works and the monetarised emissions deriving from the mend are extensively treated in Sections 4.1.2.2 and 4.1.2.3.

The expenses valued as commensurate to the increase in personal safety are computed in Section 2.1.2.1. They are added as a negative value to the cost balance since they are considered allowed costs.

Associated with the building's heating, the price for the purchase of combustible and the converted cost caused by the related greenhouse gas emissions are computed in Sections 4.2.2.2 and 4.2.2.3.

Finally, the planned retrofitting costs are estimated in Section 5.2.

Moreover, the retrofit works entail an occupancy interruption of the structure, as shown in Figure 25. Consequently, a deficit of missed rental fees incurs at the expense of the owner. The mean rental of a three-room apartment in Switzerland is 1'327 CHF/month [81]. The following diagram (Figure 29) illustrates the costs the owner must bear because of the outstanding income due to the planned retrofits. As previously mentioned, the occupancy interruption estimated for the thermal interventions is rather conservative [74], provoking a tendential overestimation of rental fee misses.

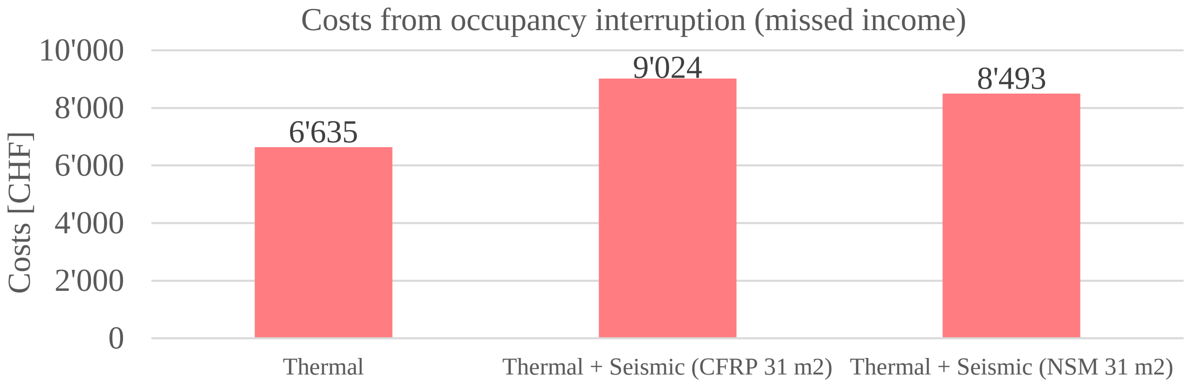


Figure 29: Costs from missed rental fees due to interruption of the building's occupancy

The overall expenditures previous to and after the retrofits' execution are summarised in Table 31. It is observable, that the cost balance is negative for every suggested intervention, for both the thermal upgrade and, even more, for the combined energy and seismic interventions. Hence, the owner must be willing to invest money to improve the building's performance, without expecting a financial return during the remaining service life of 50 years. Thereof exempted is the consideration of a building collapse (whose probability of occurrence is lowered by the seismic interventions), and the consequent expensive reconstruction works, which are not accounted for in this project. Furthermore, seismic strengthening not only makes structural collapse less probable, but also the implicated total destruction of the thermal retrofitting becomes less likely [16], [17], which in turn saves mending costs which are not included in the suggested cost balance. Besides, it must be recalled that the benefit coming from thermal retrofits is undervalued, since no net present value of the gas price is calculated: the investment in a building's renovation incurs in the present, while the gains from the reduced heating demand accumulate over the next 50 years.

Table 31: Costs before and after combined retrofit (thermal: Alternative 2, straw insulation on walls, window replacement, fiberglass insulation on roof / seismic: CFRP strips or NSM steel reinforcement on 30.8 m^2 of walls)

	[CHF in 50 years]	**Thermal retrofit**	**Thermal + Seismic retrofit (CFRP)**	**Thermal + Seismic retrofit (NSM)**
Is-state	Seismic: probable repair works	11'640	11'640	11'640
	Seismic: monetarised CO_2 emissions from probable repair works	1'447	1'447	1'447
	Thermal: costs from heating demand of building in 50 years	152'716	152'716	152'716
	Thermal: monetarised CO_2 emissions from heating demand of building	79'548	79'548	79'548
	Total	**245'351**	**245'351**	**245'351**
After retrofit	Seismic: probable repair works	11'640	12'577	12'558
	Seismic: monetarised CO_2 emissions from probable repair works	1'447	1'486	1'468
	Thermal: costs from heating demand of building in 50 years	83'922	83'922	83'922
	Thermal: monetarised CO_2 emissions from heating demand	43'714	43'714	43'714
	Seismic: retrofit intervention	-	43'961	32'737
	Thermal: retrofit intervention	281'590	281'590	281'590
	Seismic: commensurable costs	-	-16'000	-16'000
	Thermal+Seismic: costs occupancy interr.	6'635	9'024	8'493
	Total	**428'949**	**460'275**	**448'483**

6.2.3 Criterion 3: Time

Crucial for the acceptance of a retrofit intervention is the time of the building's occupancy interruption. Because of the missed income of the apartments affected by the construction works, the owner of the structure incurs supplementary expenses added to the bare cost of the construction works. The acceptable time of interrupted occupancy is hereinafter regarded as the minimum between:

- time linked to the limit of tolerable monetary loss from missed flat rentals
- time linked to other, non-monetary reasons

The following Table 32 summarizes the considered aspects related to the duration of occupancy interruption for the suggested retrofit alternatives.

Table 32: Occupancy interruption because of retrofit (thermal: Alternative 2, straw insulation on walls, window replacement, fiberglass insulation on roof / seismic: CFRP strips or NSM steel reinforcement on 30.8 m^2 of walls)

	[days, CHF]	**Thermal retrofit**	**Thermal +Seismic retrofit (CFRP)**	**Thermal +Seismic retrofit (NSM)**
Is-state	Rent of apartment [CHF/month] [81]	1'327	1'327	1'327
	Number of simultaneously non-usable apartments during construction works	6	6	6
	Limit of acceptable monetary loss from occupancy interruption [11]	10'000	10'000	10'000
	Acceptable occupancy interruption derived from limit of acceptable monetary loss [days]	38	38	38
	Acceptable occupancy interruption due to non-monetary reasons [days] [12]	60	60	60
	Min(occupancy interruption monetary loss; non-monetary reasons)	**38**	**38**	**38**
Retrofit	effective occupancy interruption	**25**	**34**	**32**

[11] Value defined by the owner, here exemplificatory 10'000 CHF
[12] Value defined by the owner, here exemplificatory 60 days

6.2.4 Criterion 4: Structural Safety

The fourth criterion included in the decision-making process is structural safety, hereafter denoted by α^*. It is calculated as the sum of the compliance factor α_{min} reached by the most critical analysis computed by 3Muri and a mean increase in compliance factor after the retrofit $\Delta\alpha_{mean}$. The minimum compliance factor α_{min} usually indicates the pushover curve which mimics the dynamic behaviour of the structure best since it represents the collapse mechanism according to the least energy principle. However, the worst-case is not always easily identifiable, reason why also the mean increase of compliance $\Delta\alpha_{mean}$, which considers all 24 analyses of 3Muri, is accounted for. It is included in the evaluation of structural safety to capture the overall enhancement of the seismic behaviour, for which the structure is subjected to different loading cases. In other words, the structural safety α^* is quantified as the sum of:

- Min. compliance factor α_{min}
- $\Delta\alpha_{mean}$ = $(\sum_{i=1}^{24}(\Delta d_{m,i})$ / $\sum_{i=1}^{24}(\Delta d_{t,i}))/24$, whereas $\Delta d_{m,i}$ and $\Delta d_{t,i}$ are calculated with respect to the values of $d_{m,i}$ and $d_{t,i}$ before the retrofit

Structural safety is the only quantity amongst the four decision-making criteria which has a positive correlation with the quality of the building's behaviour. Indeed, large CO_2 emissions (criterion 1), elevated costs (criterion 2) and a long interruption of occupancy (criterion 3) are valued as undesirable, while a high structural safety (criterion 4) is a good property. To obviate this incongruence, the opposite of structural safety, namely structural safety deficiency, is taken as a measure in the decision-making process. The structural safety deficiency is computed as:

$$\text{Safety deficiency} = 1 - \alpha^* = 1 - [\alpha_{min} + \Delta\alpha_{mean}] = 1 - [\alpha_{min} + \frac{1}{24} \cdot \left(\frac{\sum_{i=1}^{24}(\Delta d_{m,i})}{\sum_{i=1}^{24}(\Delta d_{t,i}))}\right)] \quad (4)$$

Table 33 shows the structural safety before and after the suggested synergetic retrofits. It is noticeable, that the seismic interventions with CFRP strips and with NSM steel reinforcement, both applied on the selected 30.8 m^2 of masonry wall, lead to the same enhancement of seismic behaviour, being α_{min} and α_{mean} very similar for both interventions.

Table 33: Structural safety before and after combined retrofit (thermal: Alternative 2, straw insulation on walls, window replacement, fiberglass insulation on roof / seismic: CFRP strips or NSM steel reinforcement on 30.8 m^2 of walls)

	[-]	Thermal retrofit	Thermal +Seismic retrofit (CFRP)	Thermal +Seismic retrofit (NSM)
Is-state	Min. compliance factor α_{min}	0.44	0.44	0.44
	Structural safety deficiency 1 – α^*	**0.56**	**0.56**	**0.56**
After retrofit	Min. compliance factor α_{min}	0.44	0.64	0.64
	$\Delta\alpha_{mean}=(\Sigma(\Delta d_m)/\Sigma(\Delta d_t))/24$	-	0.07	0.07
	Structural safety deficiency: 1 – α^*	**0.56**	**0.29**	**0.29**

6.3 Comparison of Retrofit Options

The above-described criteria are evaluated in a decision-making table (Appendix K, Table 79 to Table 81) and implemented into a decision-making chart. The chart is used in the step subsequent to the criteria's evaluation of the considered retrofit options (see flowchart in Figure 27). The four axes of the suggested decision-making diagram, which is illustrated in Figure 30, represent the criteria. The chart includes a dotted grey polygon, which marks the buildings' performance in the is-state, respectively the acceptable interruption of occupancy (cf. Table 32). Furthermore, the green area designates the desired zone in which the building's owner intends the retrofitting alternatives to lie in. Finally, the dashed lines (blue, red and beige in Figure 30) depict the effective CO_2 emissions, costs, interruption of occupancy and structural safety deficit related to the illustrated retrofit options. The chart below compares against each other three retrofit interventions: thermal retrofit (blue), synergetic thermal and seismic intervention with CFRP strips applied on 30.8 m^2, and combined retrofitting with NSM steel reinforcement also installed on 30.8 m^2.

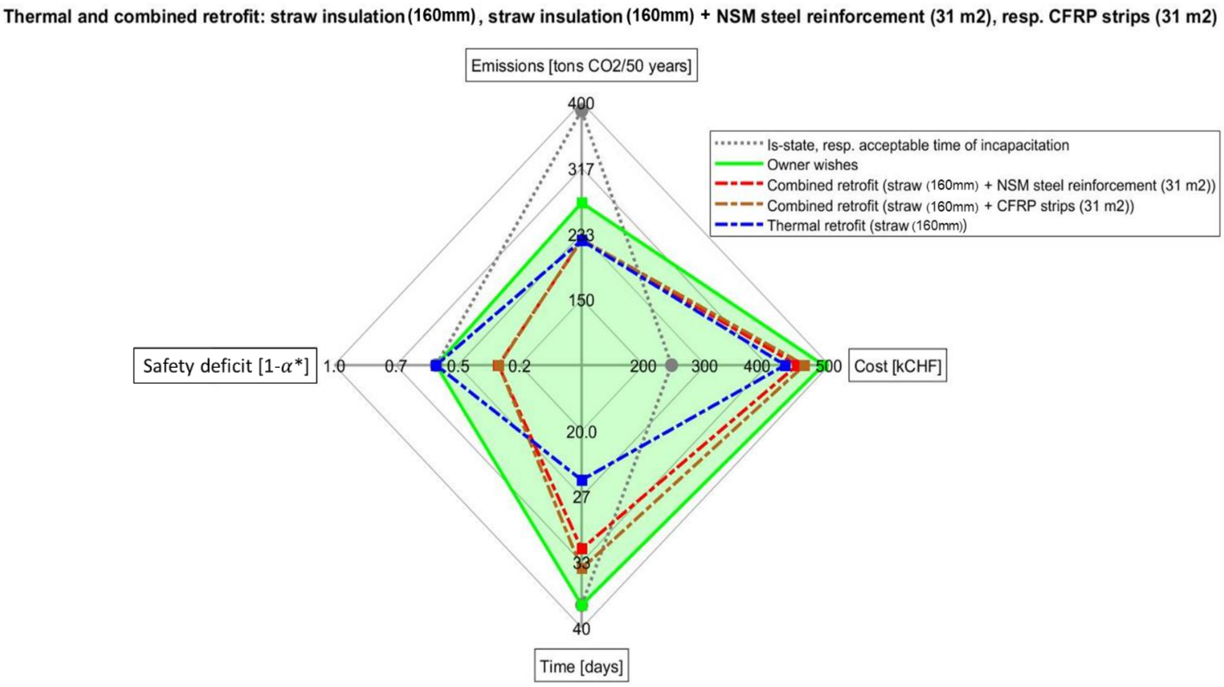


Figure 30: Decision-making chart

The decision-making chart visually represents the information gathered from Table 30 to Table 33. Thus, it can be noted that the combined interventions compared to the sole thermal upgrade implicate decently higher overall costs over 50 years (+ 4.6-7.3 %, in absolute values nonetheless 19'534-31'326 CHF) at almost identical CO_2 emissions (+ < 0.5 %). To keep in mind is the fact that no reconstruction works after building collapse are accounted for in the monetary costs and CO_2 balance and therefore the benefit of seismic retrofit measures is underestimated. The addition of seismic retrofits to energetic interventions shows its usefulness in particular when confronting the seismic performance of the structure, which is enhanced by more than 50 % in terms of structural safety α^*, contributing to a significant increase in life safety. Eventually, the probably deciding factor whether to execute seismic interventions simultaneously with thermal upgrade works is the willingness of the building's owner to accept an occupancy interruption of the structure. In effect, the elongation of tenants' relocation owed to seismic retrofit is estimated to be 7-9 days according to Figure 25. Accounting for the notice of Alice Comune [74] about the overestimation of occupancy interruption due to window replacement, the difference in occupancy interruption time between only thermal and combined retrofit rather amounts to around three weeks.

By a close comparison of the two suggested combined retrofit interventions, the NSM steel reinforcement is preferable over the intervention with CFRP strips, since the product of the quadrilaterals' semiaxes of the beige polygon is smaller benchmarked to the red one (cf. Weighted Product Model (WPM) [78]).

The above-explained choice of the combined thermal and seismic retrofit option consists of:

- walls' insulation with straw insulation panels (thickness: 80 mm of removed fiberglass insulation mat dated 1986 + 80 mm additional insulation = 160 mm straw panel), see Figure 31
- window replacement with triple-glazed windows
- roof insulation with 60 mm of additional fiberglass insulation
- NSM steel reinforcement of vertical (spacing: 600 mm) and horizontal rebars (spacing: 400 mm) with 10 mm diameter on a wall surface of 30.8 m^2, see Figure 31

Only this alternative will be further investigated in this Thesis.

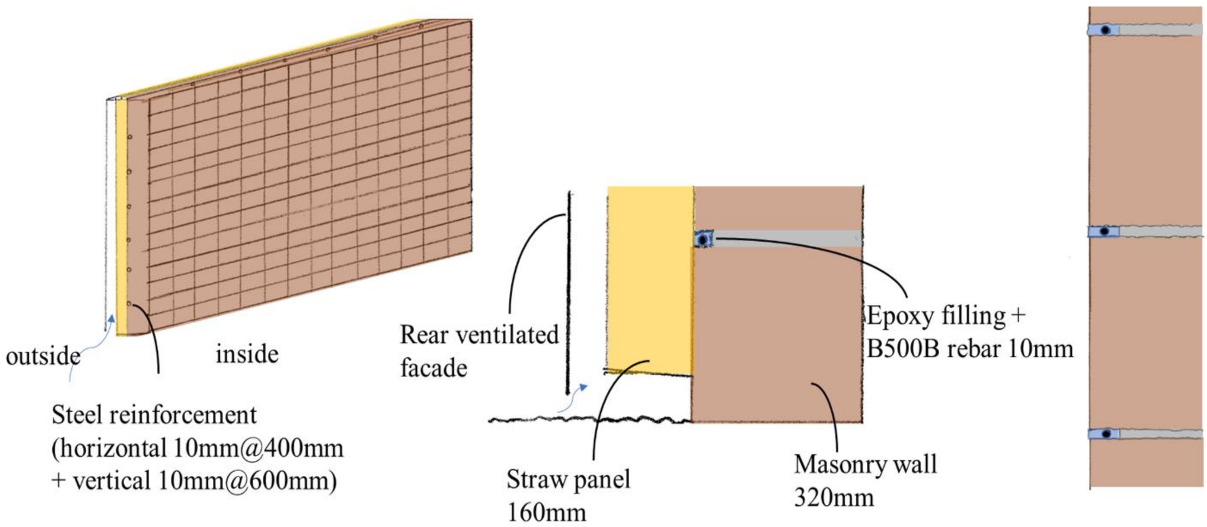


Figure 31: Wall structure of the selected combined retrofit intervention

6.4 Optimisation of Retrofit

As illustrated by the process flowchart (Figure 27, see blue coloured backward loop), the chosen synergetic retrofit alternative is optimised.

Related to the seismic aspect, the effectiveness of the retrofit is assessed for different areas of installation of the strengthening measure. Additionally, the influence of the retrofit application on one or both sides of the selected masonry walls is investigated.

Regarding the thermal intervention, the insulation thickness mounted on the perimetral walls is varied and an optimal CO_2 balance, which considers the investment done for the installed materials and the carbon savings from reduced heating demand, is sought.

6.4.1 Influence of Seismic Retrofit on One or Both Sides of Walls

To analyse the effect of reinforcing a wall on one or two sides, parts of wall 12 (see Figure 8) are modelled as retrofitted with NSM steel reinforcement and, for completeness, also with CFRP strips on one and respectively both wall sides.

From Table 34 it can be observed that the displacement capacity d_m increases from one-sided to two-sided retrofit and so does the compliance factor. The considered analyses are the most critical ones before the seismic intervention (they both have a min. compliance factor α_{min}=0.44) and are both oriented in negative X-direction.

Table 34: Increase in displacement capacity d_m thanks to retrofit on two sides of wall 12

Parts of wall 12	CFRP (analysis 3)	NSM (analysis 13)
Retrofit on 1 wall side	$\alpha = d_m/d_t$=2.16 cm/3.17 cm= 0.68	$\alpha = d_m/d_t$= 2.24 cm/3.10 cm=0.72
Retrofit on 2 wall sides	$\alpha = d_m/d_t$= 2.24 cm/3.13 cm=0.72	$\alpha = d_m/d_t$= 2.32 cm/3.13 cm=0.74

This procedure aimed at revealing the influence of seismic interventions on one or both wall sides is extended from parts of wall 12 (for which the results are shown in Table 34) to all walls which are planned to be retrofitted (30.8 m^2). The outcome of this latter evaluation is displayed in Figure 32 to Figure 35 for both the CFRP strips and the NSM steel reinforcement interventions.

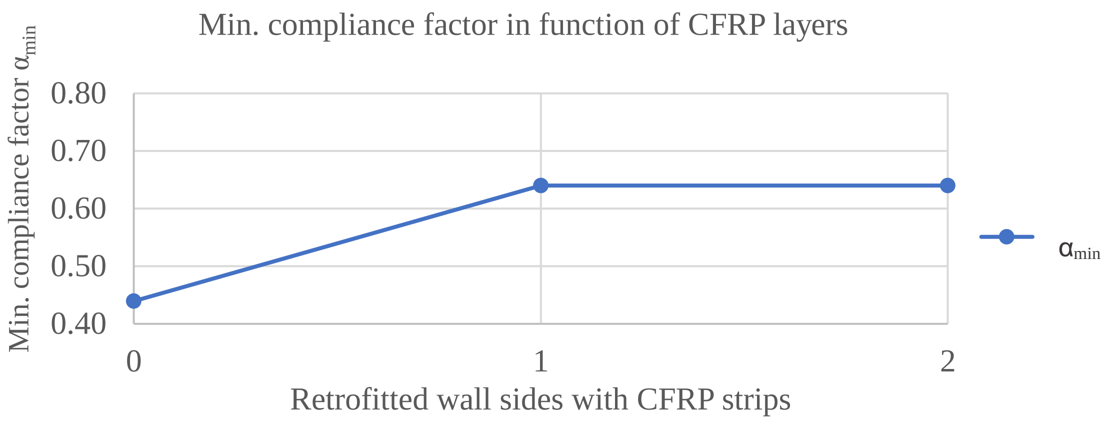


Figure 32: Minimum compliance factor α_{min} over all 24 analyses in 3Muri in function of the number of retrofitted wall sides (CFRP strips)

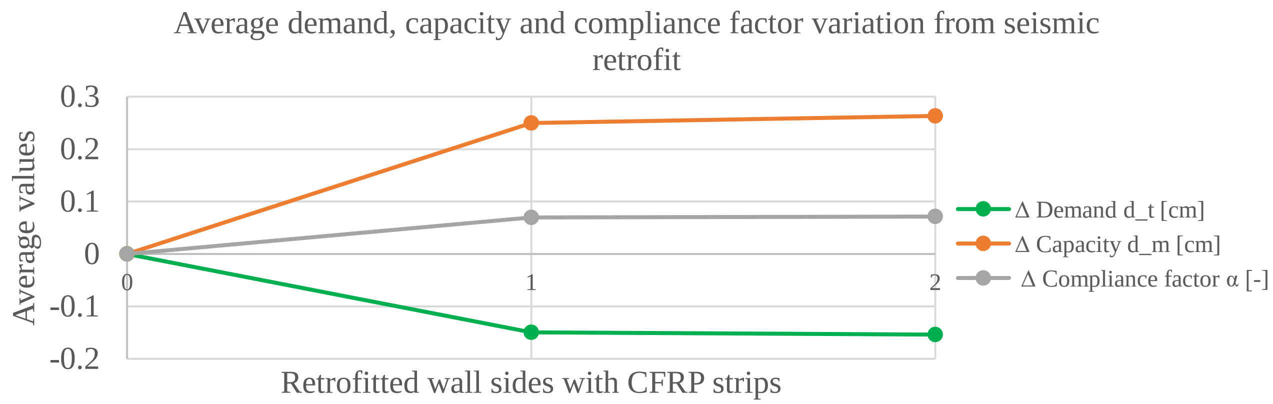


Figure 33: $\sum_{i=1}^{24}(\Delta d_{m,i})/24$, $\sum_{i=1}^{24}(\Delta d_{t,i})/24$ and $\Delta\alpha_{mean}$ defined according to Section 6.2.4 in function of the number of retrofitted wall sides (CFRP strips)

For the CFRP strips retrofit, the minimum compliance factor α_{min} found among all 24 analyses computed in 3Muri increases from the building's original state ($\alpha_{min} = 0.44$) to one retrofitted side of walls ($\alpha_{min} = 0.64$) and then stagnates passing from one to two retrofitted sides. Also $\sum_{i=1}^{24}(\Delta d_{t,i})/24$ (denoted by ΔDemand d_t in Figure 33), as well as $\sum_{i=1}^{24}(\Delta d_{m,i})/24$ (denoted by ΔCapacity d_m) and $\Delta\alpha_{mean}$ (denoted by ΔCompliance factor α) remain constant when the CFRP strips are applied on both sides of the designated walls instead of only on one side.

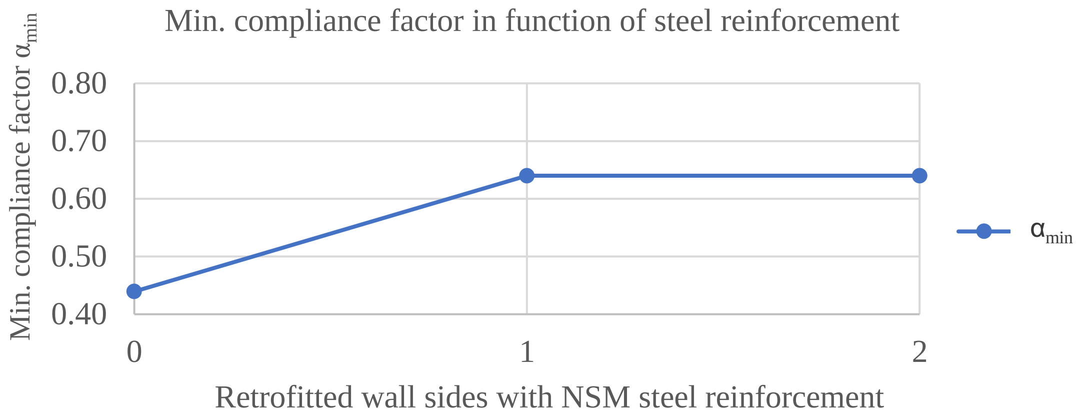


Figure 34: Minimum compliance factor α_{min} over all 24 analyses in 3Muri in function of the number of retrofitted wall sides (NSM steel reinforcement)

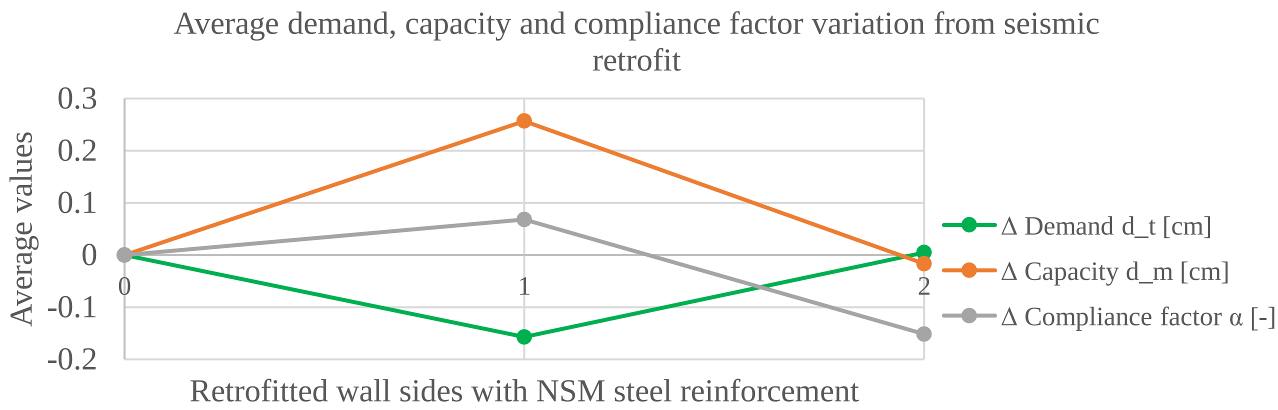


Figure 35: $\sum_{i=1}^{24}(\Delta d_{m,i})/24$, $\sum_{i=1}^{24}(\Delta d_{t,i})/24$ and $\Delta\alpha_{mean}$ defined according to Section 6.2.4 in function of the number of retrofitted wall sides (NSM steel reinforcement)

Regarding the NSM steel reinforcement, for the minimum compliance factor α_{min} the same trend as described for the retrofit executed with CFRP strips is observable in Figure 34. On the other hand, the behaviour of $\Delta\alpha_{mean}$ is different: Figure 35 shows an apparent deterioration in seismic performance due to the installation of steel rebars on both sides of the retrofitted walls.

These unexpected differences between one-sided and two-sided NSM steel rebars retrofits are probably due to numerical reasons and to some not straightforward-visible interaction of building elements. Eventually, the displacement differences are in the range of 0-0.3 cm. Also, the displacements of the chosen control node in the 3Muri model, influenced by the retrofits, could not be representatively showing the behaviour of the entire building. Furthermore, the software 3Muri inserts the reinforcement in the ideal centre line of the walls [82]. This has two effects: firstly, the eccentricity of a one-sided reinforcement measure from the walls' centre line is not considered, which could lead to unconservative results in terms of seismic performance, and secondly, the confinement action of a two-sided strengthening is not considered. In general, it must always be remembered that the model set up in 3Muri is not perfectly coincident with reality and thus the probably beneficial effect of both-sided seismic retrofits is not accurately captured by the model.

Nevertheless, the seismic intervention with NSM steel reinforcement applied on only one side of the walls is selected and further deepened in this Thesis. This choice is owed to the lack of a proper record of two-sided retrofits in the software 3Muri.

6.4.2 Optimisation of Application Area of Seismic Retrofit

The walls on which the seismic retrofit is planned are selected according to the identification of the ones most prone to fail at low values of inter-storey drift. To assess the effect of application surface area on the seismic performance of the building, a sensitivity analysis with different retrofitted wall areas is done.

The surface of installed seismic reinforcement is progressively extended from the first failing walls in the original building to the next failing walls after the applied strengthening measures. The evolution of the minimum compliance factor α_{min} in function of the area of seismically retrofitted walls is displayed in Figure 36, while the trend of $\sum_{i=1}^{24}(\Delta d_{m,i})/24$, $\sum_{i=1}^{24}(\Delta d_{t,i})/24$ and $\Delta\alpha_{mean}$ defined according to Section 6.2.4 is shown in Figure 37.

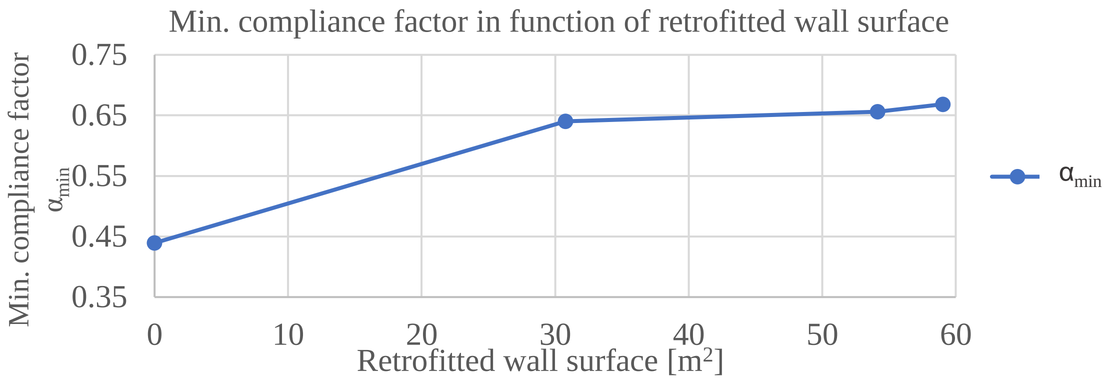


Figure 36: Minimum compliance factor α_{min} over all 24 analyses in 3Muri in function of retrofitted wall surface (NSM steel reinforcement)

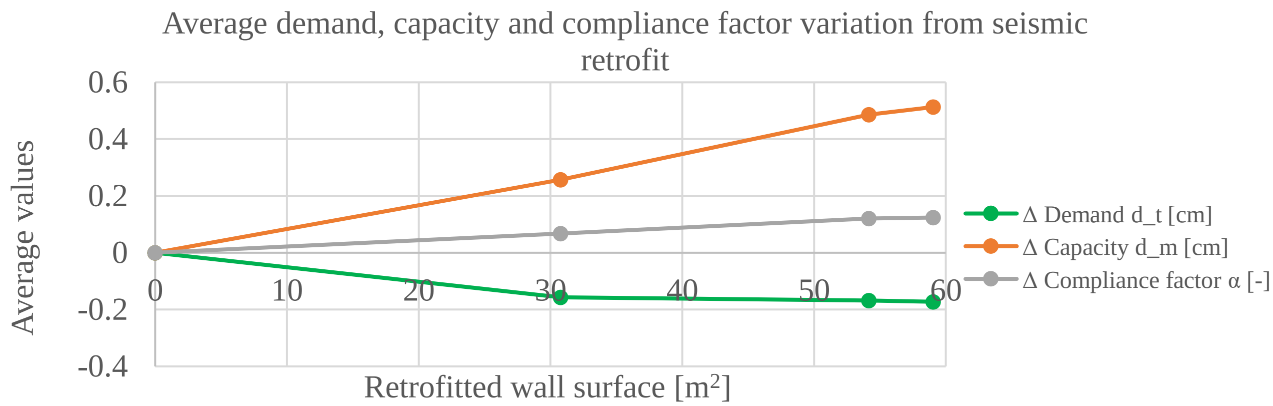


Figure 37: $\sum_{i=1}^{24}(\Delta d_{m,i})/24$, $\sum_{i=1}^{24}(\Delta d_{t,i})/24$ and $\Delta\alpha_{mean}$ defined according to Section 6.2.4 in function of the retrofitted wall surface (NSM steel reinforcement)

As can be noticed in Figure 36, the trend of α_{min} initially increases substantially with the retrofitted area and then reaches a plateau at higher values of wall surface. The same observation pertains also to the averaged increase in compliance factor $\Delta\alpha_{mean}$ over all 24 analyses. Therefore, a wall surface of 54.2 m^2 is selected for the seismic retrofitting, since it can be seen as the point of break of slope of $\Delta\alpha_{mean}$ in Figure 37 and a higher number of reinforced walls is evaluated as not worthwhile. Figure 38 illustrates the walls (54.2 m^2) on which the optimised strengthening measures with NSM steel reinforcement are foreseen, while Figure 39 shows the elevation of the building model with the retrofitted walls visible from the exterior.

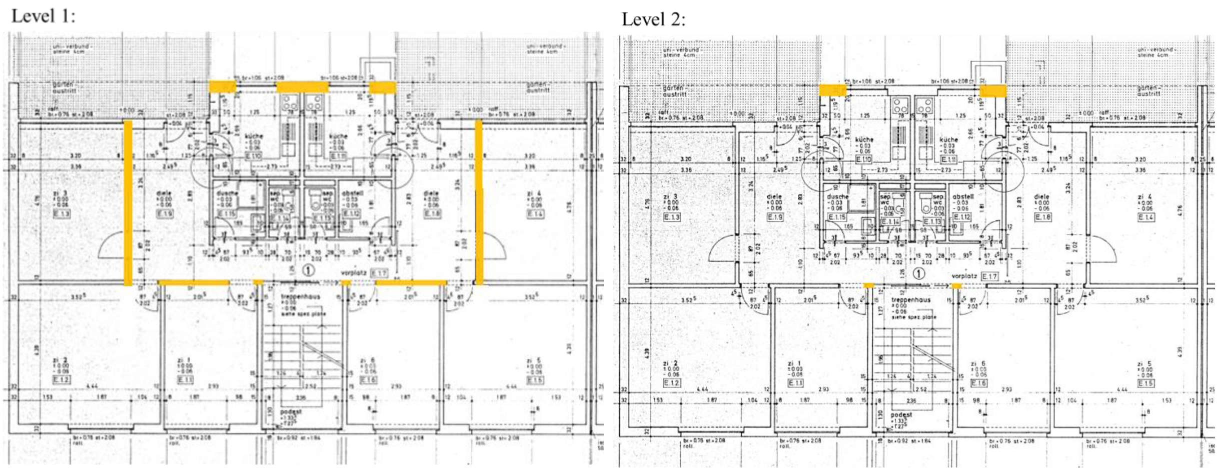


Figure 38: Walls of planned optimised seismic retrofit (54.2 m^2, NSM steel reinforcement)

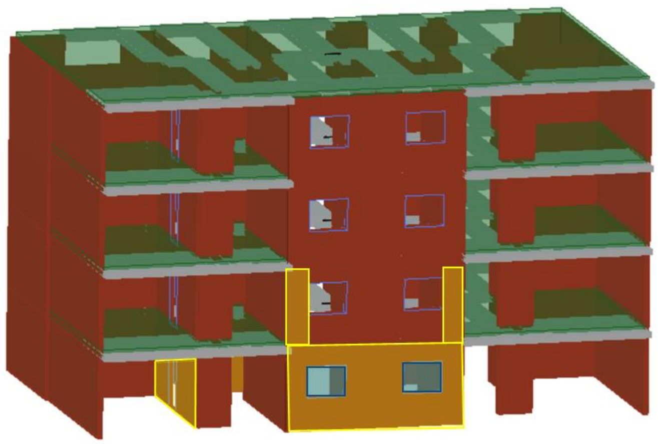


Figure 39: Elevation showing the seismically retrofitted walls (yellow) visible from the exterior (54.2 m^2, NSM steel reinforcement)

The detailed results of the seismic analysis executed in 3Muri for the optimised seismic intervention on 54.2 m^2 are reported in Table 76 in Appendix J.

Analogously to the procedure followed in the previous quantifications of CO_2 emissions, the emissions due to repair works are plotted against their probabilities of exceedance in Figure 40. The comparison between the needed mending before any intervention and after the optimised seismic retrofit with NSM steel reinforcement on 54.2 m^2 of walls is based on the same displacement values of the control node. In other words, the CO_2 emissions caused by repair works caused by the same inter-storey drifts (and hence at the same ground accelerations) are displayed in Figure 40 and compared against each other.

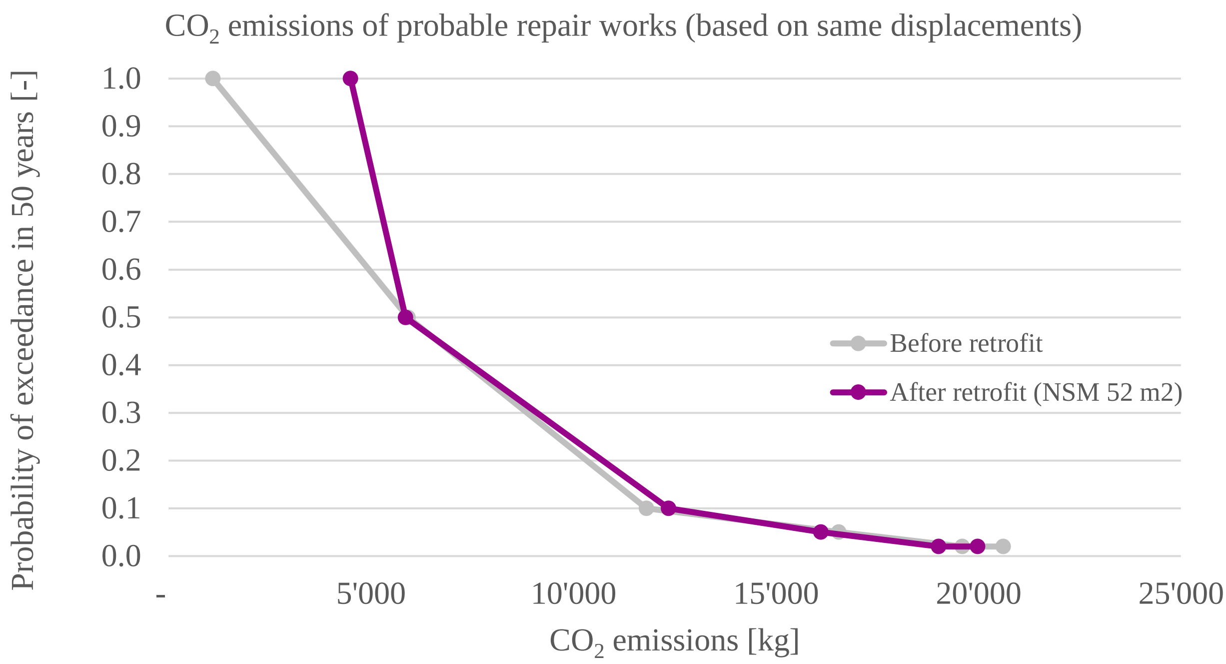


Figure 40: CO_2 emissions of probable repair works for different displacements and related probabilities of exceedance (loss functions) before retrofit and after optimised NSM steel reinforcement (area of application: 54.2 m^2)

The trend which can be observed is equivalent to the one identified in Figure 17: at low earthquake intensities the retrofit causes higher emissions entailed by repair works (caused by the seismic force redistribution on more walls), while at high ground accelerations (high CO_2 emissions), the repair works are reduced thanks to the seismic reinforcement measure. Nevertheless, the real potential of seismic retrofit becomes only visible when the CO_2 emissions from repair works in the unretrofitted and the retrofitted structure are displayed for equivalent damage states instead of for the same displacements.

The mentioned alternative way to plot the extent of repair works after earthquake events accompanied by the relative CO_2 emissions is reported in Figure 41. The damage states of the structure are calculated based on the equations illustrated in Table 4. The consideration of damage states is akin to the design levels defined in several design codes. Amongst them, there are Eurocode EC (limited damage (LD), significant damage (SD), near collapse (NC)) and the American Code Provisions ASCE Standard (immediate occupancy, life safety, collapse prevention,…) [9]. From Figure 41 it is noticeable that the seismic intervention shifts the damage states to higher inter-storey drifts: a certain damage state occurs at higher earthquake intensities and thus tendentially at lower related probabilities of exceedance. Also collapse of the structure is retarded, as it occurs at a higher ground acceleration. However, when the collapse of the retrofitted structure finally occurs, it is owed to the simultaneous failure of multiple walls. For this reason, the CO_2 emissions computed for the repair/replacement works at the failure point of the retrofitted building are higher than before any intervention. To note, still, is the fact that no emissions linked to major reconstruction works after building collapse are considered in this framework. Moreover, the seismic retrofit is optimised with respect to structural safety and not with a particular focus on reducing damages.

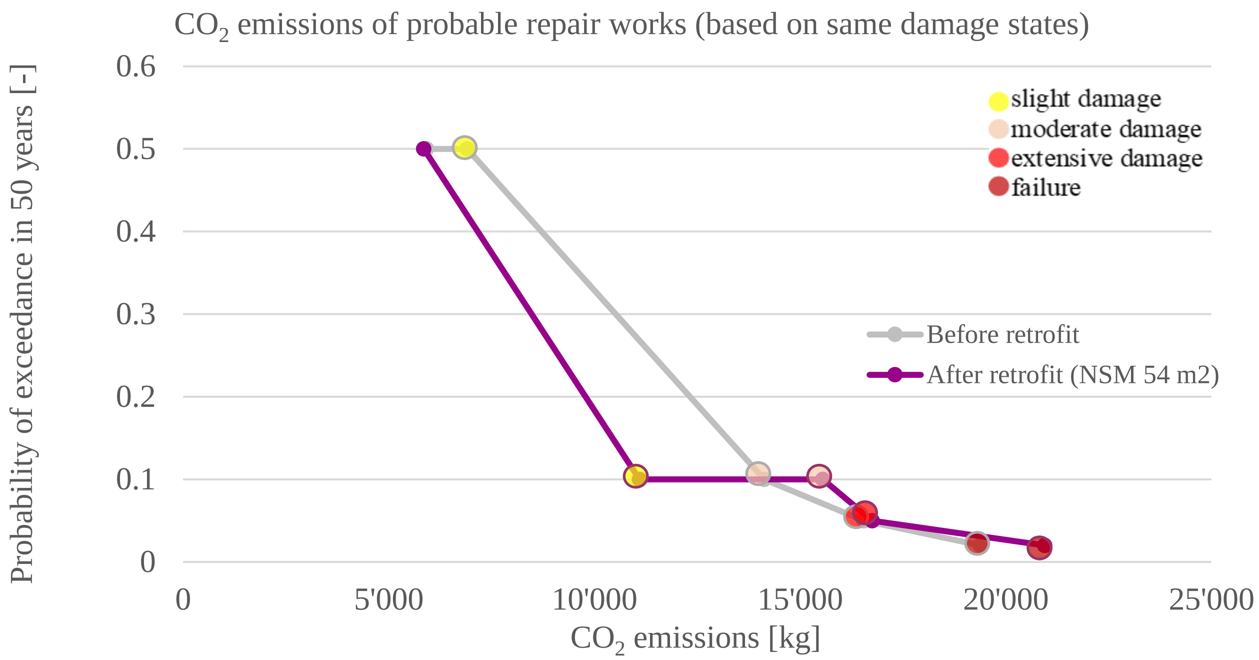


Figure 41: CO_2 emissions of probable repair works for damage states before retrofit and after optimised NSM steel reinforcement (area of application: 54.2 m^2)

The damage states and the displacements at which they appear are confronted for the original and the retrofitted structure (Table 35). The delay of damages becomes clearly visible: after the retrofit intervention, a certain damage state occurs at higher displacements and thus at higher ground accelerations.

Table 35: Displacements related to damage states before and after optimised seismic retrofit (54.2 m^2)

Displacements [cm]	**Before retrofit**	**After optimised retrofit (54.2 m^2)**
Slight damage	0.48	0.64
Moderate damage	0.80	0.88
Extensive damage	1.12	1.20
Failure	1.52	2.08

6.4.3 Optimisation of Thermal Insulation Thickness

The selected combined retrofit intervention includes the seismic reinforcement with NSM steel rebars (optimised to 54.2 m^2) and the thermal upgrade consisting of window replacement, roof insulation and perimetral walls insulation. Since the intervention on windows and the roof is considered fixed (installation of triple-glazed windows and an additional 60 mm thick fiberglass layer on the roof), the optimisation is focused on the walls' insulation. For this purpose, the thickness of the chosen straw panels is varied. Figure 42 plots the net CO_2 savings which derive from the thermal upgrade of the building in function of the wall insulation thickness. The net savings are computed as the difference between the savings from reduced heating demand and the CO_2 invested in the thermal retrofit intervention.

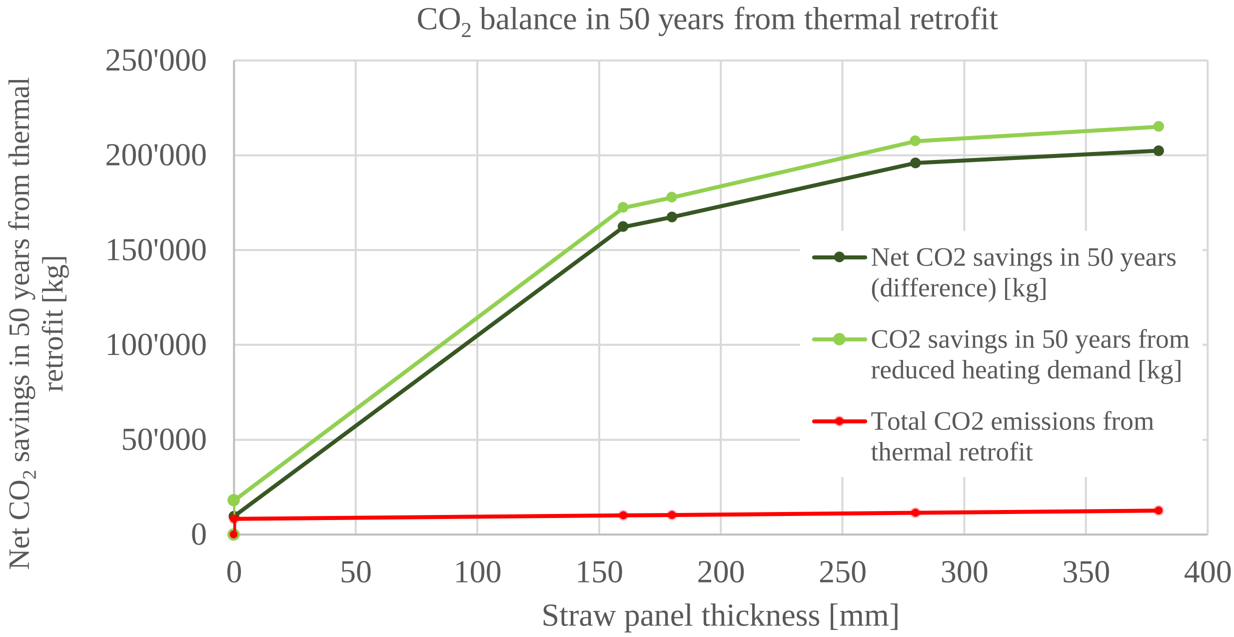


Figure 42: Net CO_2 savings from thermal interventions (savings from reduced thermal demand-investment for thermal retrofit) in function of wall insulation thickness

In Figure 42 it is observable that the CO_2 savings from reduced heating demand increase as expected with the thickness of the wall insulation and then flatten at higher thicknesses. The trend of carbon freed during the production of the materials used for the energy intervention is linear with the insulation thickness and displays an initial vertical offset, which is due to the embodied CO_2 in the replaced windows and the installed fiberglass roof insulation. The origin of the graph corresponds to the building before any thermal intervention. To notice is the fact that the plotted CO_2 emissions from the thermal retrofit include the embodied carbon caused by the fabrication process without accounting for the bound biogenous carbon in the organic materials such as straw and the wood used for the windows' frames.

The net CO_2 savings seem to reach an asymptote at high wall insulation thickness. Thus, a straw panel of 380 mm is chosen, since no substantial enhancement of the thermal behaviour of the building is observed at greater thicknesses. Moreover, it is physically neither realistic nor desirable to apply even broader insulation layers.

6.5 Comparison of Optimised Retrofit with Retrofit Before Optimisation and with Is-State

As elucidated in Sections 6.4.2 and 6.4.3, the selected retrofit is seismically optimised with respect to structural safety during an earthquake event and thermally improved in terms of CO_2 emissions, leading to the optimised combined intervention summarised in Table 36.

Table 36: Summary of retrofit optimisation

		Selected retrofit	**Optimised retrofit**
Thermal	Wall insulation	160 mm straw panel	**380 mm** straw panel
	Window replacement	Triple-glazed	Triple-glazed
	Roof insulation	60 mm fiberglass mat	60 mm fiberglass mat
Seismic	Wall retrofit	30.8 m^2 NSM steel reinf.	**54.2 m^2** NSM steel reinf.

A representation of the selected and the optimised retrofit alternative is given in the decision-making chart in Figure 43.

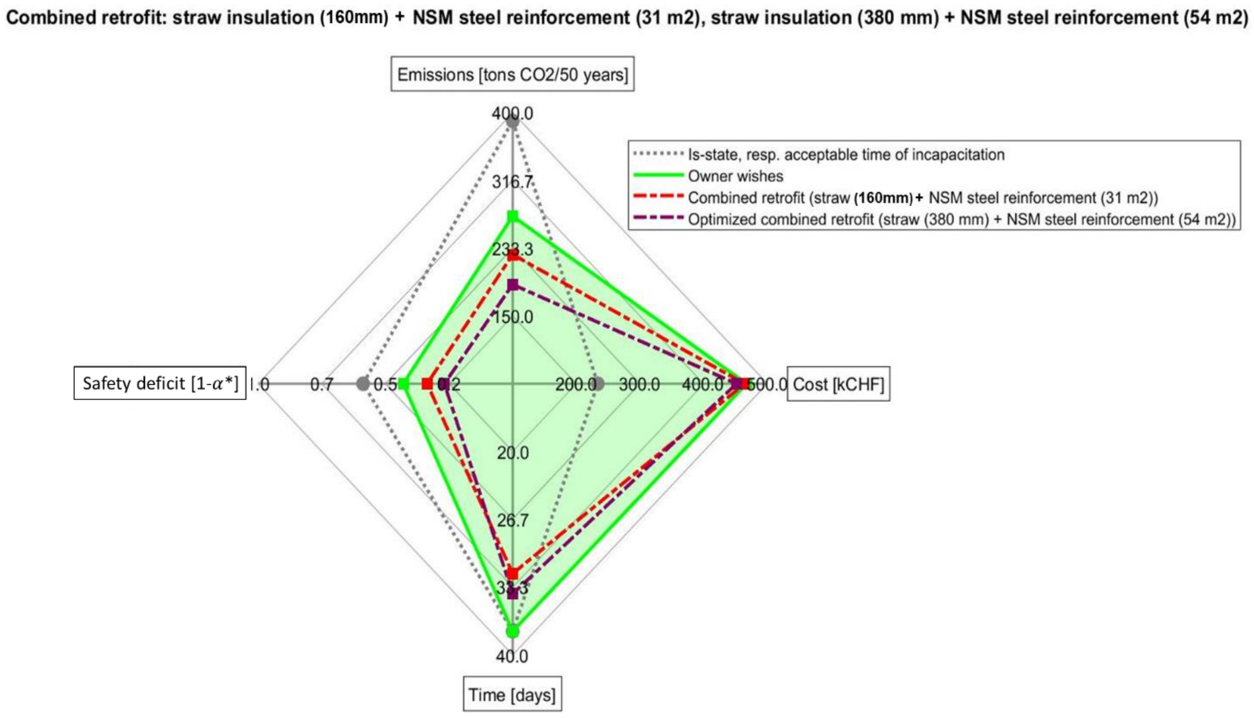


Figure 43: Decision-making chart comparing selected retrofit option before and after optimisation

The decision-making chart in Figure 43 directly compares the chosen combined retrofit with its optimised version (see calculations in Appendix K, Table 81 and Table 86). It can be recognised that the optimised intervention decreases structural safety deficit, overall CO_2 emissions (see detailed computation of CO_2 from probable repair works in Appendix J, Table 74) and costs (see computation of costs from probable repair works in Appendix J, Table 75 and retrofit costs in Table 78) when measured against the selected intervention before optimisation. It must however be accounted for a slight increase in occupancy interruption due to the rise of the seismically retrofitted wall surface of non-perimetral walls (see schedule in Appendix J, Table 77). Nonetheless, the semiaxes' product of the optimised combined intervention (purple) is smaller compared to the one of the selected synergetic retrofit before optimisation (red), and hence the optimised version is valued as the better option.

Based on the gained insight, dedicated structural and energy engineers can enhance the design of combined interventions just by optimisation and thereby contribute to reducing the carbon footprint of a building and improving its structural safety, without causing negative consequences on the monetary cost balance.

A more complete examination of non-optimised, partially optimised (either thermally or seismically) and fully optimised alternatives is given in Figure 44 (calculations see Appendix K, Table 79 to Table 86). The decision-making chart graphically represents the chosen purely thermal intervention (wall insulation: Alternative 2 (straw panels 160 mm), roof insulation: fiberglass mats 60 mm, window replacement: triple-glazed) and its optimised version (wall insulation: optimised Alternative 2 (straw panels 380 mm), roof insulation: fiberglass mats 60 mm, window replacement: triple-glazed), as well as the combined retrofit options.

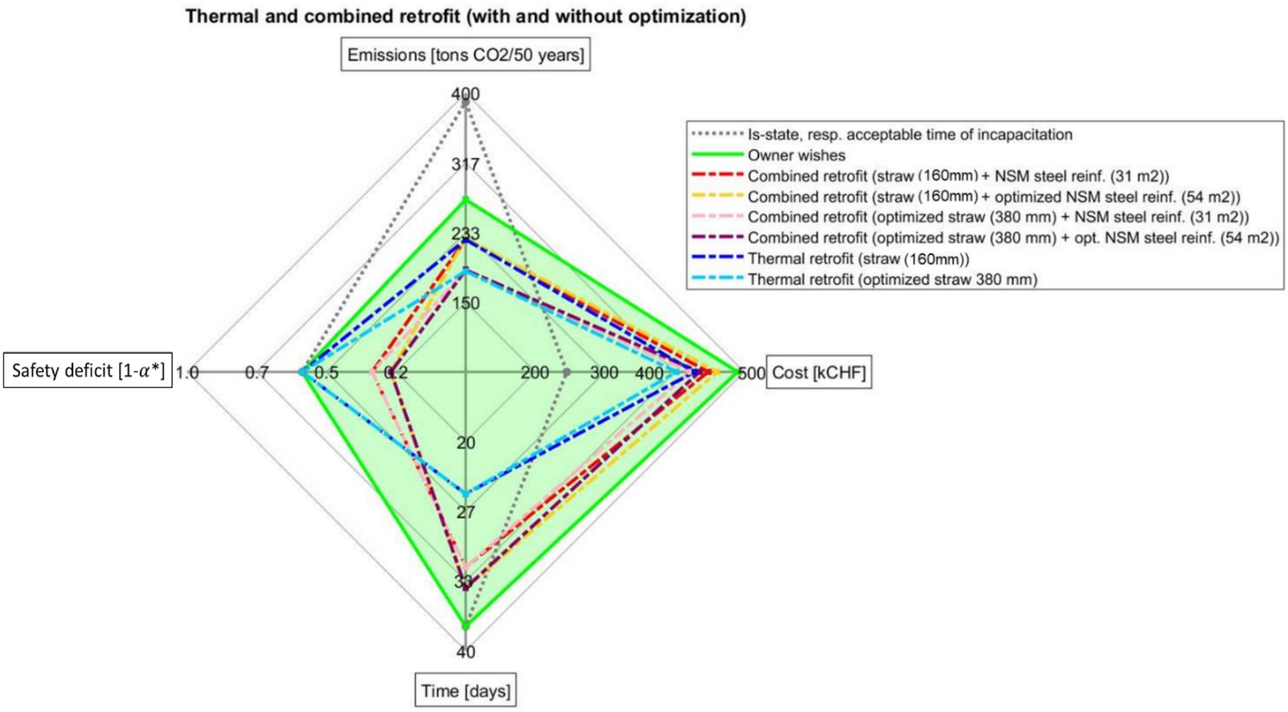


Figure 44: Decision-making chart comparing thermal and selected combined retrofit options before and after (partial) optimisation

Thanks to the execution of synergetic thermal and seismic interventions, the structural performance during earthquake events is improved. Though, higher overall costs (+ 20'000 CHF from thermal to combined intervention, both non-optimised options) will incur at practically equivalent levels of CO_2 emissions (difference of around 500 kg CO_2 = 0.2 % of total emissions), see Table 37. Also, the duration of occupancy interruption is augmented.

Nevertheless, on account of the optimisation process, the CO_2 emissions of the synergetic retrofit can be decreased below the value of the sole non-optimised thermal intervention and the overall costs of the combined intervention are also reduced by 12'591 CHF. In summary, the optimised synergetic thermal and seismic retrofit is assessed as the most favourable option, owing to the improvement of structural safety at less greenhouse gas emissions and slightly increased monetary costs and time of occupancy interruption compared to the sole non-optimised thermal upgrade.

A quantitative comparison of the chosen (combined) intervention before and after (partial) optimisation is given in Table 37. The ranking of the options is based on the product of the semiaxes of the quadrilaterals representing the retrofit alternatives in Figure 44. Thanks to the proposed quantitative evaluation of alternatives, the efficacy of optimisation is demonstrated.

Table 37: Quantitative comparison of the chosen (combined) intervention before and after (partial) optimisation, values referred to 50 years of remaining service life

	CO_2 emissions [kg]	**Cost [CHF]**	**Time**	**Safety deficit [-]**	**Product semiaxes [-]**	**Ranking**
Thermal	224'889	428'949	25	0.56	1.35E+12	6
Thermal opt.	187'025	403'037	25	0.56	1.06E+12	5
Combined	225'383	448'483	32	0.29	9.38E+11	4
Combined (thermal+seismic opt.)	226'497	461'803	34	0.22	7.82E+11	3
Combined (thermal opt.+seismic)	187'519	422'571	32	0.29	7.35E+11	2
Combined (thermal opt+seismic opt.)	188'632	435'891	34	0.22	6.15E+11	1

Table 38 displays the conditions before retrofit, after the sole chosen thermal intervention alternative and after the optimised combined retrofitting. It can be stated that the planned thermal and synergetic upgrades are very beneficial in terms of total CO_2 emissions.

For the cost-related aspect, a remaining service life of 50 years is proven not to be sufficient to compensate the investments of the retrofits. It should nevertheless be noticed that the supplement of the seismic retrofit, merged with the optimisation process of the planned synergetic intervention, only contributes to an additional 10 % of costs (which nonetheless corresponds to 23'000 CHF) compared to the purely thermal intervention.

An occupancy interruption of approximately one month (conservative estimation) must be accepted to allow the execution of the interventions. To remark is the fact that the replacement of windows is planned to be executed by two workers in this project. By adding workforces to this activity, its duration can be diminished, at the expense of other activities which will be delayed, extending the overall work duration. Alternatively, auxiliary professionals must be mobilised.

In terms of structural safety, as expected, the seismic intervention brings a considerable gain, lowering the personal risk factor from $4.2 \cdot 10^{-6}$ to $2 \cdot 10^{-6}$ when calculated according to SIA 269/8: 2017 [1], figure 7.

Table 38: Overview of conditions (four criteria) before retrofit, after thermal retrofit (non-optimised) and after optimised combined retrofit

	Overall CO_2 emissions [tons CO_2]	**Overall costs [kCHF]**	**Occupancy interruption [days]**	**Structural safety deficit (1-α*) [-]**
Before retrofit	390	234	-	0.56
After thermal retrofit (straw 160 mm)	225	429	25	0.56
After optimised combined retrofit (straw 380 mm + NSM steel 54.2 m^2)	189	452	34	0.22

7 Discussion

The combined retrofits are not only beneficial in terms of structural safety but present also an effective measure for the reduction of greenhouse gas emissions (see Table 38). Naturally, the building's owner, accounting also for the interests of tenants, must be willing to accept an interruption of the occupancy and consequently a lack of income to perform the retrofitting works. However, this kind of intervention in Switzerland is not cost-effective per se. In the following section, proposed approaches directed to alleviate the financial burden for the owner are discussed.

7.1 Suggestions for Cost-Effective Combined Interventions and International Policies' Comparison

To achieve a net-zero cost balance after the assumed remaining service life of 50 years, the monetarised costs of CO_2 should be remarkably higher than the currently assumed 208 CHF/ton CO_2 (based on [39]). Indeed, to reach cost-effectiveness of the suggested combined interventions, the price should be set to 1'100 CHF/ton CO_2, which corresponds to an increase of 429 % compared to the nowadays used value.

A more verisimilar practice to decrease the financial burden of building owners is to act on policies with financial subsidies or taxes/fines. Currently, in Canton Zurich, fiscal incentives are established to support thermal renovation interventions [83]. Namely, building owners are reimbursed 40 CHF/m^2 of thermally retrofitted roofs and 70 CHF/m^2 of insulated external walls [83]. Applied to the analysed case study building, these incentives would amount to 46'250 CHF. However, in Switzerland, such monetary aids are oftentimes regulated by Cantonal institutions [84] and are not uniform at a national level.

A nationwide policy is operative for example in Italy, where, as regulated by the "Stability Law 2017", monetary refund amounts to up to 85 % of the incurred costs for seismic retrofit [77]. According to the regimentation of Sisma Bonus [85], the previously described percentual deduction applies up to a maximum of 96'000 € of intervention cost per residential unit in a multi-family residential complex if the seismic intervention is directed at common sectors of the building [85].

The Italian Sisma Bonus, additionally, regulates incentives applying to the combined thermal and seismic retrofit: a maximal cost of the synergetic retrofit of 136'000 € per residential unit in a multi-family complex is considered for the percentual recovery of the expenses [85].

Other financial incitements are granted through the introduction of Superbonus in 2020 [86]. A rate of 110 % refund is set for the execution of thermal upgrades (Super Ecobonus) and seismic interventions (Super Sismabonus) [86]. The thermal retrofit must either include an upgrade of the building envelope's thermal properties or a replacement of heating systems [86]. Concurrently, the most widespread thermal retrofits in Italy, according to Alice Comune [74], professional energy consultant, are indeed by default directed to the envelope and the heating system: for single-homes air-water heat pumps are mainly installed, while in residential complexes energy-efficient centralised heating systems are disposed of [74]. Furthermore, the radiators are often replaced by underfloor heating [74].

Finally, it can be suggested to implement such fiscal advantages for owners who seismically or synergistically retrofit their buildings also in Switzerland. However, the refund methodology should be adjusted: the reimbursement should be decreased compared to the Italian bonus since several problems related to the released laws are observed in Italy. Firstly, due to the shortage of building materials and the presence of the above-described monetary incentives, product sellers unjustifiably increase material prices [74]. Secondly, since the defined rate of 110 % recovery specified by the Superbonus [86] not only covers the expenses but even brings a financial surplus, inappropriate, purely economic motivations for retrofit interventions are raised in certain circumstances [74]. Moreover, it may be argued that the refund should not even be cost-covering (100 % recover), since the retrofits already are intrinsically value-adding and increase the real estate market price. Therefore, a full rebate would also lead to a monetary profit for the owner.

Another approach to obtain more cost-effective interventions is to adjust the value of commensurable costs. Indeed, for the analysed case study building, SIA 269/8: 2017 [1] defines commensurable costs of 512 CHF/year or 16'000 CHF in 50 years, including a 2 % yearly discount rate. To attain a net-zero cost balance, though, proportionate costs of 206'550 CHF would be requested. Considering the above-mentioned yearly discount rate, this would imply outgoings of 6'610 CHF/year. Such a sum of commensurable costs would entail very large expenses to bring the personal safety of the building's users to the level of a new Swiss structure.

Currently, commensurability specified by SIA 269/8: 2017 [1] for a common residential building only considers life safety of the occupants. This is in contrast to the principle stated by the same code provision in Section 10.1.1, page 31 [1], according to which seismic interventions should be designed to "enhance the protection of people, material assets, cultural values and the environment" [1]. Thus, it is proposed to raise commensurable costs at least by adding the estimated costs of probable repair works after earthquakes, coherently with the stated principle. By doing so, it would be possible to cover the expenses of seismic retrofit for the most part (cf. loss of repair works in Table 24: 11'640 to 12'577 CHF and cf. cost estimation of seismic retrofit in Figure 26: 32'737 to 43'961 CHF).

Alternatively, the concept of commensurability, complemented and adjusted by financial subsidies, could be extended from the purely seismic context to thermal and/or synergetic applications. It is thinkable to base such a commensurability definition on more than the sole life safety which is considered in the conventional commensurable costs as specified by SIA 269/8: 2017 [1]. It is indeed suggested to also account for the thermal/combined intervention's sustainability in terms of saved CO_2 emissions and include them in the proportionate costs through an appropriate monetarisation factor. Further, the efficiency of materials in terms of greenhouse gas emissions should be a criterion for the financial support to foster the use of low-carbon construction materials. More specifically, the balance of saved CO_2 emissions thanks to the retrofit in relation to the invested CO_2 due to the materials' production should be regarded.

8 Conclusion

8.1 Conclusion on the Potential of Synergetic Upgrade

Not only does the addition of seismic retrofits to energetic interventions enhance structural safety during earthquake events, but it also reduces the probability of building collapse. Thus, it has the potential to increase societal resilience and avoid major reconstruction works of destroyed buildings, and hence high CO_2 emissions and costs. Moreover, since the suggested thermal interventions are already inherently CO_2-effective, such combined interventions also significantly contribute to lowering society's carbon footprint. This effect can be further enhanced by the use of sustainable materials with low – or negative – carbon impact. Through the suggested practices, the cost of construction works incurring on the building owner may be alleviated to prevent them from being financially burdensome.

What is certain, is that a combination of seismic and thermal upgrades is promising from the construction management perspective, since site installations are shared and during downtimes of one intervention type due to curing processes or similar, the tasks that are required for the other retrofit category can be executed.

Besides, combined interventions can further be enhanced by optimising the retrofit design. In this Thesis, it was proven that, without increasing monetary costs, the design of synergetic retrofits that even more reduce carbon emissions and improve structural safety is possible. To facilitate and spread such reasoned designs in practice, standards must be developed. As a result of this Thesis, a tool may be offered to engineers which supports them in planning and realising low-carbon and cost-efficient, high-quality, synergetic retrofits.

8.2 Outlook for Future Projects

This Thesis is based on a specific Swiss case study building, on which the application of synergetic interventions is analysed in detail. Nevertheless, the results of this Thesis can be transferred and adopted without major adaptation to generic seismic and thermal retrofitting projects. The developed flowchart which displays the process followed in this Thesis can be used for any seismic and energy upgrade. Additionally, the concurrently suggested decision-making chart can be employed for any type of retrofit, just by modification of the decision-making criteria.

The followed procedure has the potential to be implemented with visual programming tools, which are able to automize the process which has been manually executed in this Thesis. For instance, a visual programming tool compatible with Autodesk Revit, namely Dynamo, could be employed for such purposes. Examples of applications can be found in literature: in [3] the assessment of masonry buildings through a BIM model is described. The publication illustrates the automatization of a flowchart through Dynamo, to compute the vulnerability of the modelled structure [3]. An alternative to the use of Dynamo consists for example in the recourse to the programming tool Rhino Grasshopper [87]. A great potential of parametric [5] and generative design [4] is recognised for its application in optimisation processes, as the one followed to enhance the chosen retrofit option (see the blue backward loop in the flowchart, Figure 27).

In the suggested decision-making methodology, the considered criteria are all seen as equally relevant. The interests of the building's owner are incorporated in the chart, denoting the acceptable region in which the retrofit options should lie. However, the criteria are all evenly weighted, which represents a simplification. To obviate this limitation, decision matrices could be integrated into the developed decision-making framework to allow different weighting of criteria [77]. The weights of the criteria could for instance be determined through surveys.

This Thesis provides a solid base for further development of the proposed practices in the design of synergetic thermal and seismic retrofitting projects of buildings. Hopefully, the suggested powerful approach will be implemented and elaborated in future works, for which proposals were provided in this last section.

9 Literature

Building models

[23] S. Arslantürkoglu, „3Muri (S.T.A. DATA) building model“, Chair of Structural Dynamics and Earthquake Engineering, ETH Zurich, 2022.

[42] Dr. Y. Reuland, „Autodesk Revit building model“, Chair of Structural Dynamics and Earthquake Engineering, ETH Zurich, 2022.

References

[1] „SIA 269/8: 2017: Erhaltung von Tragwerken – Erdbeben“. Schweizerischer Ingenieur- und Architektenverein, Dec. 2017.

[2] Konferenz Kantonaler Energiedirektoren, Bern, „Mustervorschriften der Kantone im Energiebereich (MuKEn)“, Ausgabe 2014, Deutsche Version, (Nachführung 2018-Aufgrund geänderter Normen). 2018.

[3] E. Ambrassa, A. Comune, S. Podestà, L. Diana, P. Lestuzzi, „Seismic vulnerability assessment of masonry buildings through BIM“, *IABSE Symposium 2019 Guimarães*, Portugal, 2019, pp. 1496–1503. doi: 10.2749/guimaraes.2019.1496.

[4] E. Abumounshar, E. Ambrassa, S. Fruin, P. Serra, L. Smith, „Moving Toward the Future of Design with Generative Design in Revit“, 2022. [Online]. Available under: https://www.autodesk.com/autodesk-university/class/Moving-Toward-Future-Design-Generative-Design-Revit-2021

[5] K. W. Chen, P. Janssen, A. Schlueter, „Multi-objective optimisation of building form, envelope and cooling system for improved building energy performance“, *Automation in Construction*, Vol. 94, pp. 449–457, 2018, doi: 10.1016/j.autcon.2018.07.002.

[6] K. Parrish, J.-M. Wong, I. D. Tommelein, B. Stojadinovic, „Set-Based Design: Case Study on Innovative Hospital Design“, *Proceedings of the 16th Annual Conference of the International Group for Lean*, 2008, pp. 413-423.

[7] Bundesamt für Statistik BFS – GWS, „Gebäude nach Gebäudekategorie sowie Bauperiode und Geschosszahl, T 09.02.02.02“, 2021. [Online]. Available under: https://www.bfs.admin.ch/asset/de/je-d-09.02.02.02

[8] Dr. Y. Reuland, S. Arslantürkoglu, „Assignment Master Thesis Spring Semester 2022“, Chair of Structural Dynamics and Earthquake Engineering, ETH Zurich ,Feb. 2022.

[9] Dr. A. Tsiavos, „Lecture slides Seismic Evaluation and Retrofitting of Existing Structures“. Chair of Structural Dynamics and Earthquake Engineering, ETH Zurich, 2022.

[10] S. Arslantürkoglu, N. Volken, N. Mojsilović, B. Stojadinović, „Seismic Assessment of an Existing Swiss Unreinforced Masonry Building with Flexible Floor Diaphragms“, *17th World Conference on Earthquake Engineering, 17WCEE*, 2020.

[11] Bundesamt für Energie, „Energy Strategy 2050“, Dec. 2021. [Online]. Available under: https://www.bfe.admin.ch/bfe/en/home/policy/energy-strategy-2050.html

[12] Bundesamt für Energie, „Gebäude“, Mar. 2022. [Online]. Available under: https://www.bfe.admin.ch/bfe/de/home/effizienz/gebaeude.html

[13] Bundesamt für Statistik, BFS– Erhebung der Energieträger von Wohngebäuden (SETW), „Verteilung der Gebäude nach Energieträger für die Heizung und das Warmwasser“, 2017. [Online]. Available under: https://www.google.ch/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwiZ5vDw-

tn4AhWVm_0HHYV1D3QQFnoECAwQAQ&url=https%3A%2F%2Fwww.bfs.admin.ch%2Fbfsstatic%2Fdam%2Fassets%2F3982424%2Fmaster&usg=AOvVaw37bwhwIOhs56LAwp2xN1Nk

[14] Prof. Dr. A. Schlüter, „Lecture slides Energie- und Klimasysteme I“, Institute of Technology in Architecture, ETH Zurich, 2021.

[15] Bundesamt für Energie, „Schweizerische Gesamtenergiestatistik 2018“, 2018. [Online]. Available under: https://www.bfe.admin.ch/bfe/de/home/versorgung/statistik-und-geodaten/energiestatistiken/gesamtenergiestatistik.html

[16] A. Belleri, C. Passoni, A. Marini, P. Riva, „The Impact of Earthquakes on the Life Cycle Carbon Footprint of Existing Buildings.“, *16th World Conference on Earthquake, 16WCEE 2017*, Jan. 2017.

[17] M. Lamperti Tornaghi, A. Loli, P. Negro, „Balanced Evaluation of Structural and Environmental Performances in Building Design“, *Buildings*, Vol. 8, Nr. 4, Mar. 2018, doi: 10.3390/buildings8040052.

[18] E.-S. Georgescu et al., „Seismic and Energy Renovation: A Review of the Code Requirements and Solutions in Italy and Romania“, *Sustainability*, Vol. 10, Nr. 5, May 2018, doi: 10.3390/su10051561.

[19] D. A. Pohoryles, C. Maduta, D. A. Bournas, L. A. Kouris, „Energy performance of existing residential buildings in Europe: A novel approach combining energy with seismic retrofitting“, *Energy and Buildings*, Vol. 223, 110024, Sep. 2020, doi: 10.1016/j.enbuild.2020.110024.

[20] „SIA 261: 2020: Einwirkung auf Tragwerke“. Schweizerischer Ingenieur- und Architektenverein, 1. Aug. 2020.

[21] „Heizgradtage“, Mar. 2022. [Online]. Available under: https://www.hev-schweiz.ch/vermieten/nebenkostenabrechnungen/heizgradtage-hgt/

[22] A. Caprino, F. Lorenzoni, L. Carnieletto, L. Feletto, M. De Carli, F. da Porto, „Integrated Seismic and Energy Retrofit Interventions on a URM Masonry Building: The Case Study of the Former Courthouse in Fabriano“, *Sustainability*, Vol. 13, Nr. 17, Aug. 2021, doi: 10.3390/su13179592.

[24] D. Gass, P. Walker, „Allgemeine Bedienung und Beispiel, 3muri - Tutorial, Version 1.1“, IngWare GmbH, p. 22, Erlenbach, Jan. 2009.

[25] Federal Emergency Management Agency, FEMA 273, „NEHRP Guidelines for the Seismic Rehabilitation of Buildings (FEMA Publication 273)“, p. 240 (7-3), Oct. 1997.

[26] B. V. Wilding, M. Godio, K. Beyer, „The ratio of shear to elastic modulus of in-plane loaded masonry“, *Mater Struct*, Vol. 53, Nr. 2, p. 13, Apr. 2020, doi: 10.1617/s11527-020-01464-1.

[27] L. S. Wijanto, „Seismic Assessment of Unreinforced Masonry Walls“, Department of Civil Engineering, University of Canterbury, Christchurch, New Zealand, [PhD Thesis], p. 182007

[28] „SIA 260: 2013: Grundlagen der Projektierung von Tragwerken“. Schweizerischer Ingenieur- und Architektenverein, 1. Aug, 2013.

[29] N. Volken, „Evaluation of an Existing Masonry Building with Flexible Diaphragms in Switzerland“, Institute of Structural Engineering, ETH Zurich, [Master Thesis in Structural Engineering], p.44, Jun. 2019.

[30] P. Fajfar, „Capacity spectrum method based on inelastic demand spectra“, *Earthquake Engng. Struct. Dyn.*, Vol. 28, Nr. 9, pp. 979–993, 1999, doi: 10.1002/(SICI)1096-9845(199909)28:9<979::AID-EQE850>3.0.CO;2-1.

[31] L. Martins, V. Silva, „Development of a fragility and vulnerability model for global seismic risk analyses“, *Bull Earthquake Eng*, Vol. 19, Nr. 15, pp. 6719–6745, 2020, doi: 10.1007/s10518-020-00885-1.

[32] „Seismic Performance Assessment of Buildings, Volume 1 -- Methodology, Second Edition, FEMA P-58-1“, p. 63, Dec. 2018.
[33] „Seismic Performance Assessment of Buildings, Volume 2 -- Implementation Guide, Second Edition, FEMA P-58-2 “, p. 256 (8-10), Dec. 2018.
[34] Bundesamt für Statistik, „Durchschnittlicher CO2-Ausstoss neuer Personenwagen, T 02.03.05.06.01“, Aug. 2021. [Online]. Available under: https://www.bfs.admin.ch/asset/de/18384654
[35] R. Hüsser, „Investigation of an Energy-Efficient and Low-Carbon_Emission Strategy for Seismic Retrofitting of an Existing Masonry Building“, ETH Zurich, [Master Thesis], pp. 54,57, Jun. 2021.
[36] Konferenz Kantonaler Energiedirektoren, „Energieverbrauch von Gebäuden“, Fact Sheet, Aug. 2014. [Online]. Available under: https://www.google.ch/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwiJudXHxNr4AhWL57sIHSnYDD0QFnoECAMQAQ&url=https%3A%2F%2Fwww.endk.ch%2Fde%2Fablage%2Fendk-1%2F20140828-factsheet.pdf&usg=AOvVaw3Jrb6ptcg7B16gC6yYDyRG
[37] SED Swiss Seismological Service, ETH Zürich, GEM Global Earthquake Model, EPOS European Plate Observing System, „EFEHR Hazard Maps“, 2021. [Online]. Available under: http://hazard.efehr.org/en/hazard-data-access/hazard-maps/
[38] „Swiss Gravity Zones“, Swiss Federal Institute of Metrology METAS, Apr. 2022. [Online]. Available under: https://www.metas.ch/metas/en/home/dok/gravitationszonen.html
[39] Dr. A. Matthey, Dr. B. Bünger, „Methodenkonvention 3.0 zur Ermittlung von Umweltkosten, Kostensätze, Stand 02/2019“, Umweltbundesamt Wörlitzer Platz 1 06844 Dessau-Roßlau, Feb. 2019. [Online]. Available under: https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2019-02-11_methodenkonvention-3-0_kostensaetze_korr.pdf
[40] U. von Rotz, T. Y. Yang, S. Brzev, B. Stojadinovic, „Seismic Performance Evaluation of an Unreinforced Masonry Building in Switzerland“, *Tenth U.S. National Conference on Earthquake Engineering Frontiers of Earthquake Engineering*, Anchorage, Alaska, Jul. 2014.
[41] A. Kubilay, „Lecture slides Building physics: Theory and Applications“, Chair of Building Physics, ETH Zurich, 2021.
[43] M. Schmid, „Synergies Between Seismic and Energy Retrofitting of Existing Buildings“, ETH Zurich, [Master Thesis], pp. 21, 19, 2021.
[44] J. Iturralde (TECNALIA), L. Alonso (TECNALIA), A. Carrera (IREC), J. Salom (IREC), M. Battaglia (SPF-HSR), D. Carbonell (SPF-HSR), „Energy demands for multi-family buildings in different climatic zones, Version 2.0“, TRI-HP Project, Sep. 2019.
[45] R. Gloor, „Energieverbrauch von Gebäuden“, pp. 18-19, 2022. [Online]. Available under: energie.ch/heizenergieverbrauch
[46] Koordinationskonferenz der Bau- und Liegenschaftsorgane der öffentlichen Bauherren KBOB, „Ökobilanzdaten im Baubereich, KBOB / ecobau / IPB 2009/1:2022“, Apr. 2022. [Online]. Available under: https://www.kbob.admin.ch/kbob/de/home.html
[47] „Switzerland fuel prices, electricity prices, natural gas prices“, 2022. [Online]. Available under: https://www.globalpetrolprices.com/Switzerland/
[48] T. Dalla Mora, A. Righi, F. Peron, P. Romagnoni, „Functional, Energy and Seismic Retrofitting in Existing Building: An Innovative System Based on xlam Technology“, *Energy Procedia*, Vol. 82, pp. 486–492, Dec. 2015, doi: 10.1016/j.egypro.2015.11.851.
[49] F. Stazi, M. Serpilli, G. Maracchini, A. Pavone, „An experimental and numerical study on CLT panels used as infill shear walls for RC buildings retrofit“, *Construction and*

Building Materials, Vol. 211, pp. 605–616, Jun. 2019, doi: 10.1016/j.conbuildmat.2019.03.196.
[50] G. Margani, G. Evola, C. Tardo, E. M. Marino, „Energy, Seismic, and Architectural Renovation of RC Framed Buildings with Prefabricated Timber Panels“, *Sustainability, Vol. 12*, 4845, Jun. 2020.
[51] M. R. Valluzzi, E. Saler, A. Vignato, M. Salvataggio, F. Croatto, G. Dorigatti, U. Turrini, „Nested Buildings: An Innovative Strategy for the Integrated Seismic and Energy Retrofit of Existing Masonry Buildings with CLT Panels“, *Sustainability*, Vol. 13, Nr. 3, S. 1188, Jan. 2021, doi: 10.3390/su13031188.
[52] I. Giongo, E. Rizzi, D. Riccadonna, M. Piazza, „On-site testing of masonry shear walls strengthened with timber panels“, *Proceedings of the Institution of Civil Engineers - Structures and Buildings*, Vol. 174, Nr. 5, pp. 389–402, May 2021, doi: 10.1680/jstbu.19.00179.
[53] D. Y. Dizhur, M. Giaretton, I. Giongo, J. Ingham, „Seismic Retrofit of Masonry Walls using Timber Strong-Backs“, *Journal of the Structural Engineering Society of New Zealand Inc*, Vol 3, Nr. 2, pp. 30-44, Sep. 2017.
[54] U. J. Maduh, D. Shedde, J. Ingham, D. Dizhur, „In-plane Testing of URM Wall Panels Retrofitted Using Timber strong-backs“, *Australian Earthquake Engineering Society 2019 Conference*, 2019.
[55] T. Li, M. Deng, M. Jin, Y. Zhang, „Experimental study on axial compressive behavior of full-scale masonry columns strengthened with reinforced high ductile concrete (RHDC)“, *Engineering Structures,* Vol. 252, 113650, School of Civil Engineering, Xi’an University of Architecture and Technology, Xi’an 710055, China, 2021.
[56] S&P Clever Reinforcement GmbH, „S&P FRP Systeme“, Bad Nauheim (D), May 2022. [Online]. Available under: https://www.sp-reinforcement.at/de-AT/systeme/sp-frp-systeme
[57] StressHead AG, „StressHead AG, Unsere Dienstleistungen“, Luzern, May 2022. [Online]. Available under: https://www.stresshead.ch/service-produkt.html
[58] S&P Clever Reinforcement GmbH, „S&P C-Laminate“, Bad Nauheim (D), May 2022. [Online]. Available under: https://www.sp-reinforcement.at/sites/default/files/field_product_col_doc_file/tds_c-laminates_ch-de_ver202007.pdf
[59] J. G. Tumialan, N. Galati, S. M. Namboorimadathil, A. Nanni, „Strengthening Of Masonry With Near Surface Mounted FRP Bars“, *International conference on composites in infrastructure (ICCI2002),* San Francisco, USA; 2002. [Online]. Available under: https://quakewrap.com/frp%20papers/Strengthening-Of-Masonry-With-Near-Surface-Mounted-FRP-Bars.pdf
[60] R. Soti, A. R. Barbosa, A. Stavridis, „Numerical Assessment of URM Infilled RC Frames Retrofitted With Near-Surface Mounted Reinforcing Steel Bars“, *Front. Built Environ.*, Vol. 6, Nov. 2020, doi: 10.3389/fbuil.2020.590302.
[61] L. N. Koutas, Z. Tetta, D. A. Bournas, T. C. Triantafillou, „Strengthening of Concrete Structures with Textile Reinforced Mortars: State-of-the-Art Review“, *J. Compos. Constr.*, Vol. 23, Nr. 1, 03118001, Feb. 2019, doi: 10.1061/(ASCE)CC.1943-5614.0000882.
[62] R. B. Petersen, M. J. Masia, R. Seracino, R. Associate, „In-Plane Shear Behavior of Masonry Panels Strengthened with NSM CFRP Strips. I: Experimental Investigation“, *Journal Of Composites For Construction © ASCE*, pp. 754-763, 2010.
[63] D. A. Pohoryles, D. A. Bournas, „Innovative seismic and energy retrofitting of the existing building stock“, European Commission, JRC Technical Report, 2021.

[64] L. N. Koutas, D. A. Bournas, „Out-of-Plane Strengthening of Masonry-Infilled RC Frames with Textile-Reinforced Mortar Jackets“, *J. Compos. Constr.*, Vol. 23, Nr. 1, 04018079, Feb. 2019, doi: 10.1061/(ASCE)CC.1943-5614.0000911.
[65] P. Joyklad, S. Suparp, Q. Hussain, „Flexural Response of JFRP and BFRP Strengthened RC Beams“, *IJET*, Vol. 11, Nr. 3, pp. 203–207, Jun. 2019, doi: 10.7763/IJET.2019.V11.1147.
[66] K. Chaiyasarn, N. Ali, P. Phuphasuwan, N. Poovarodom, P. Joyklad, H. Mohamad, M. Zhou, Q. Hussain., „Flexural Behavior of Natural Hybrid FRP-Strengthened RC Beams and Strain Measurements Using BOTDA“, *Polymers*, Vol. 13, Nr. 20, 3604, Oct. 2021, doi: 10.3390/polym13203604.
[67] S. Yinh, Q. Hussain, P. Joyklad, P. Chaimahawan, W. Rattanapitikon, S. Limkatanyu, A. Pimanmas., „Strengthening effect of natural fiber reinforced polymer composites (NFRP) on concrete“, *Case Studies in Construction Materials*, Vol. 15, e00653, 2021, doi: 10.1016/j.cscm.2021.e00653.
[68] SmartHouses Portugal, „Insulation materials“, Portugal, 2019. [Online]. Available under: https://www.ecopassivehouses.com/insulation-materials/
[69] M. Jakob, R. Madlener, „Exploring experience curves for the building envelope: an investigation for Switzerland for 1970–2020“, CEPE – Centre for Energy Policy and Economics, Swiss Federal Institutes of Technology, ETH Zentrum WEC C, p. 17, Mar 2003.
[70] N. Stoiber, M. Hammerl, B. Kromoser, „Cradle-to-gate life cycle assessment of CFRP reinforcement for concrete structures: Calculation basis and exemplary application“, *Journal of Cleaner Production*, Vol. 280, 2020, doi: 10.1016/j.jclepro.2020.124300.
[71] „Material library, Mapei, Version 09/2021“. [Online]. Available under: http://www.stadata.com/?area=Software&table=DownloadLibEn&mnu=810, website last visited 04.2022
[72] H. Maljaee, B. Ghiassi, P. B. Lourenço, D. V. Oliveira, „Moisture-induced degradation of interfacial bond in FRP-strengthened masonry“, *Composites Part B*, Vol. 87, pp. 47-58, ISISE, University of Minho, Departement of Civil Engineering, Guimarães, Portugal doi: 10.1016/j.compositesb.2015.10.022.
[73] J. J. Hoffman, „Lecture slides Project Management for Construction Projects“, Institut für Bau-&Infrastrukturmanagement, Swiss Federal Institute of Technology, ETH Zurich, 2020.
[74] „Discussion with Alice Comune, professional energy consultant“, Jun. 2022.
[75] J. J. Hoffman, „Lecture slides Project Management: Pre-Tender to Contract Execution“, Institut für Bau-&Infrastrukturmanagement, Swiss Federal Institute of Technology, ETH Zurich, 2021.
[76] Renovero, „Was kostet ein Handwerker eigentlich pro Stunde?“. [Online]. Available under: https://www.renovero.ch/de/tipps/renovation-allgemein/was-kostet-handwerker-pro-stunde, website last visited 05.2022
[77] N. Caterino, E. Cosenza, „A multi-criteria approach for selecting the seismic retrofit intervention for an existing structure accounting for expected losses and tax incentives in Italy“, *Engineering Structures*, Vol. 174, pp. 840–850, 2018, doi: 10.1016/j.engstruct.2018.07.090.
[78] E. Triantaphyllou, *Multi-criteria Decision Making Methods: A Comparative Study*, Vol. 44. Boston, MA: Springer US, pp.5-21, 2000. doi: 10.1007/978-1-4757-3157-6.
[79] D. Zimina, G. Ballard, C. Pasquire, „Target value design: using collaboration and a lean approach to reduce construction cost“, *Construction Management and Economics*, Vol. 30, Nr. 5, S. 383–398, May 2012, doi: 10.1080/01446193.2012.676658.

[80] Amazon.com, „Rotary cutter machine“. [Online]. Available under: https://www.amazon.com/Hengwei-Electric-Cutting-Concrete-Slotting/dp/B07R57KJCV, website last visited 05.2022
[81] Federal Statistical Office, „Rented dwellings“, Federal Statistical Office, Section Population, Neuchâtel. [Online]. Available under: https://www.bfs.admin.ch/bfs/en/home/statistics/construction-housing/dwellings/rented-dwellings.html, website last visited 05.2022
[82] S.T.A. DATA srl, „3muri, User Manual, Release: 12.2.0“, C.so Raffaello, 12 - 10126 Torino, Italy.
[83] Kanton Zürich, Baudirektion, Amt für Abfall, Wasser, Energie und Luft, „Förderprogramm 2022“, Apr. 2022. [Online]. Available under: https://www.zh.ch/content/dam/zhweb/bilder-dokumente/themen/umwelt-tiere/energie/energieberatung-und-energiefoerderung/F%C3%B6rderprogramm%202022%20Gesamtbrosch%C3%BCre%20web.pdf
[84] Energieheld Schweiz, „Förderung für Sanierungen in der Schweiz in 2022“, 2022. [Online]. Available under: https://www.energieheld.ch/renovation/foerderung
[85] Agenzia delle Entrate, Sezione pubblicazioni on line dell’ ufficio comunicazione e stampa, „Sisma Bonus: Le Detrazioni per gli Interventi Antisismici“, Jul. 2019. [Online]. Available under: https://www.agenziaentrate.gov.it/portale/web/guest/schede/agevolazioni/detrristredil36
[86] Governo Italiano, Presidenza del Consiglio dei Ministri, „Superbonus 110%, cos’è?“, Rome, Italy, 2020. [Online]. Available under: https://www.governo.it/it/articolo/superbonus-110-case-pi-efficienti-e-sicure-costo-zero/15948
[87] W. Sung, Y. Jeong, „Site planning automation of apartment complex through grid-based calculation in grasshopper“, *Automation in Construction*, Vol. 138, 2022, doi: 10.1016/j.autcon.2022.104216.
[88] „Plans Überbauung Lerchenrain, 8046 Zürich, Facade Details“, 1986.
[89] Lowe’s, „How to Install Replacement Windows“, Apr. 2021. [Online]. Available under: https://www.lowes.com/n/how-to/install-a-replacement-window
[90] Asphalt Roofing Manufacturers Association, „Decking Recommendations for Built-Up Roofing and Modified Bitumen Membranes“, 2021. [Online]. Available under: https://www.asphaltroofing.org/decking-recommendations-for-built-up-roofing-and-modified-bitumen-membranes/
[91] Mapei Corporation, „MapeWrap C Uni-Ax 300, Uni-Directional Carbon Fiber Fabric“, Apr. 2013. [Online]. Available under: https://www.mapei.com/ch/de-ch/produkte-und-loesungen/produktliste/produktdetails/mapewrap-c-uni-ax
[92] Schmid AG Entsorgung und Recycling, „Muldenservice, Entsorgungspreise“, Affoltern am Albis. [Online]. Available under: Preise Muldenservice – SCHMID AG (muldenschmid.ch), website last visited 05.2022
[93] Max Schweizer AG, „Richtpreisofferte Aussenbereich“, 2022. [Online]. Available under: https://www.schweizerag.com/aussenarbeiten.html
[94] EVB BauPunkt Einkaufs- und Handelsgemeinschaft GmbH & Co. KG, „Absturzsicherung - Temporäres Schutzgeländer für die Sicherheit auf dem Dach“, 2020. [Online]. Available under: https://www.mietverbund.com/de/mieten/bauzaun/absturzsicherung-sicherheit-auf-dem-dach-222790.html
[95] Energieheld Schweiz, „Kosten für neue Fenster - mit Einbau und Förderung“, 2022. [Online]. Available under: https://www.energieheld.ch/fenster/kosten

[96] Dr. G. Habert, „Lecture slides Materials and Constructions“. Chair of Sustainable Construction, ETH Zurich, 2021.
[97] OBI, „Sakret Zementmörtel“, 2022. [Online]. Available under: https://www.obi.ch/trockenmoertel/sakret-zementmoertel-grau-25-kg/p/4249405
[98] THEIS Fassadenbaustoffe - WDV-S, „Fischer termoz sv II ecotwist WDVS Dübel“. [Online]. Available under: https://www.theis-wdvs.de/wdvs/wdvs-duebel/fischer-termoz-sv-ii-ecotwist/4528/fischer-termoz-sv-ii-ecotwist-wdvs-duebel?c=21, website last visited 05.2022
[99] Isover Saint-Gobain, „PB F 030“, 2022. [Online]. Available under: https://www.isover.ch/de/produkte/pb-f-030-60-x-100-cm
[100] Hornbach, „Abdichtungsrolle Swisspor Bitumen“. [Online]. Available under: https://www.hornbach.ch/shop/Abdichtungsrolle-Swisspor-Bitumen-EP5-WF-S-flam/10310806/artikel.html?wt_mc=ch.paid.sea.google.alwayson_assortment..pla.12312770338.118505499358.&wt_cc1=12312770338&wt_cc2=118505499358&wt_cc3=497919820955&wt_cc4=&&wt_cc6=10310806&wt_cc7=756&gclid=Cj0KCQjwpv2TBhDoARIsALBnVnlbZPX9mrVMbTvMt49Nt5yxCbQbJBRXEOTrTDxsC-1kT6jBYs7rlJMaAlkWEALw_wcB, website last visited 05.2022
[101] Hornbach, „Sand“. [Online]. Available under: https://www.hornbach.ch/shop/Gartenbau-Landschaftsbau/Sand-Steine-Zierkies/Sand/S13133/artikelliste.html, website last visited 05.2022
[102] Gummischwarz AG, „Montagekleber Polyflex 444“, 2022. [Online]. Available under: https://www.gummischwarz.ch/de/Montagekleber-Polyflex-444----Fuer-Stahl_-Ste-7882-23626.html?EANCode=824.444&gclid=Cj0KCQjwyYKUBhDJARIsAMj9lkG0ipXlrJ8faItOLV2U4-18KnXKTS_CyDg5WUrEfAuFoVarJkjaVcMaAhu1EALw_wcB
[103] Hornbach, „Rundstange Ø 10 mm“. [Online]. Available under: https://www.hornbach.ch/shop/Rundstange-10-mm-2-m/5199879/artikel.html?wt_mc=ch.paid.sea.google.alwayson_assortment..pla.12312770338.118505499358.&wt_cc1=12312770338&wt_cc2=118505499358&wt_cc3=497919820955&wt_cc4=&&wt_cc6=5199879&wt_cc7=757&gclid=Cj0KCQjwyYKUBhDJARIsAMj9lkFZ_IOUnJ_1tEOT1PRQGe2T6TXZv45amdu5_rbyDDeVhWf5xJW8f4UaArM1EALw_wcB, website last visited 05.2022
[104] BENZ24, „Innenputz“. [Online]. Available under: https://benz24.ch/innenputze/, website last visited 05.2022
[105] Jumbo, Division der Coop Genossenschaft, „Innendispersionen“, 2022. [Online]. Available under: https://www.jumbo.ch/de/bodenbelaege-wandverkleidungen-farben/farben/dispersionen/innendispersionen
[106] meinhausshop.de, „Mapei Dispersionshaftgrundierung ‚Primer G‘“, 2020. [Online]. Available under: https://www.meinhausshop.de/Mapei-Dispersionshaftgrundierung-Primer-G?campaign=google_shopping.ch&spartner=google_shopping.ch&utm_source=google_shopping.ch&utm_medium=cpc&gclid=CjwKCAjw7IeUBhBbEiwADhiEMXEemkKv215IsMZWHdj69PuYgC0Fupna_gCBUe1-DIvQjFTG3qsvOxoCZ3UQAvD_BwE
[107] Giemme SNC (Mingozzi A. and M.), „Mapewrap 11“, Argenta, Italy. [Online]. Available under: https://www.giemmeargenta.it/de/spezielle-zusatze/18975-idrosilex-liquid-kg-mapei-6.html, website last visited 05.2022
[108] Giemme SNC (Mingozzi A. and M.), „Mapewrap 31“, Argenta, Italy. [Online]. Available under: https://www.giemmeargenta.it/de/spezielle-zusatze/20570-idrosilex-liquid-kg-mapei-6.html, website last visited 05.2022
[109] ContructProshop, „Mapewrap C UNI-AX 300“, 2019-2022. [Online]. Available under: https://www.constructproshop.be/produit/mapewrap-c-uni-ax-300/

Appendix A

Table 39: Before retrofit: calculation of damaged or failed walls (perimeter and area) for the estimation of CO_2 emissions from repair/replacement works

(0.08 cm; 20465 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick		standard walls 8" (=0.2032 m) to 12" (=0.3048) thick [-]		standard walls 4" (=0.1016 m) to 6" (=0.1524 m) thick [-]	
		damaged perimeter [m]	failed area [m2]	damaged perimeter [m]	failed area [m2]	damaged standard walls [-]	failed standard walls [-]	damaged standard walls [-]	failed standard walls [-]
Wall 1		0.00	0.00			0.00	0.00	0.00	0.00
Wall 2				0.00	0.00	0.00	0.00	0.00	0.00
Wall 3				0.00	0.00	0.00	0.00	0.00	0.00
Wall 4				0.00	0.00	0.00	0.00	0.00	0.00
Wall 5				0.00	0.00	0.00	0.00	0.00	0.00
Wall 6				0.00	0.00	0.00	0.00	0.00	0.00
Wall 7				0.00	0.00	0.00	0.00	0.00	0.00
Wall 8				0.00	0.00	0.00	0.00	0.00	0.00
Wall 9				0.00	0.00	0.00	0.00	0.00	0.00
Wall 10				0.00	0.00	0.00	0.00	0.00	0.00
Wall 11				0.00	0.00	0.00	0.00	0.00	0.00
Wall 12		10.08	0.00			0.66	0.00	0.00	0.00
Wall 13		8.52	0.00			0.56	0.00	0.00	0.00
Wall 14				12.40	0.00	0.00	0.00	0.81	0.00
Wall 15		0.00	0.00			0.00	0.00	0.00	0.00

(0.40 cm; 84768 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick		standard walls 8" (=0.2032 m) to 12" (=0.3048) thick [-]		standard walls 4" (=0.1016 m) to 6" (=0.1524 m) thick [-]	
		damaged perimeter [m]	failed area [m2]	damaged perimeter [m]	failed area [m2]	damaged standard walls [-]	failed standard walls [-]	damaged standard walls [-]	failed standard walls [-]
Wall 1		0.00	0.00			0.00	0.00	0.00	0.00
Wall 2				0.00	0.00	0.00	0.00	0.00	0.00
Wall 3				0.00	0.00	0.00	0.00	0.00	0.00
Wall 4				0.00	0.00	0.00	0.00	0.00	0.00
Wall 5				0.00	0.00	0.00	0.00	0.00	0.00
Wall 6				0.00	0.00	0.00	0.00	0.00	0.00
Wall 7				0.00	0.00	0.00	0.00	0.00	0.00
Wall 8				0.00	0.00	0.00	0.00	0.00	0.00
Wall 9				0.00	0.00	0.00	0.00	0.00	0.00
Wall 10				14.62	0.00	0.00	0.00	0.96	0.00
Wall 11				0.00	0.00	0.00	0.00	0.00	0.00
Wall 12		38.46	0.00			2.52	0.00	0.00	0.00
Wall 13		49.14	0.00			3.22	0.00	0.00	0.00
Wall 14				37.12	0.00	0.00	0.00	2.44	0.00
Wall 15		0.00	0.00			0.00	0.00	0.00	0.00

slight damage (0.48 cm; 92745 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick		standard walls 8" (=0.2032 m) to 12" (=0.3048) thick [-]		standard walls 4" (=0.1016 m) to 6" (=0.1524 m) thick [-]	
		damaged perimeter [m]	failed area [m2]	damaged perimeter [m]	failed area [m2]	damaged standard walls [-]	failed standard walls [-]	damaged standard walls [-]	failed standard walls [-]
Wall 1		0.00	0.00			0.00	0.00	0.00	0.00
Wall 2				0.00	0.00	0.00	0.00	0.00	0.00
Wall 3				0.00	0.00	0.00	0.00	0.00	0.00
Wall 4				0.00	0.00	0.00	0.00	0.00	0.00
Wall 5				0.00	0.00	0.00	0.00	0.00	0.00
Wall 6				0.00	0.00	0.00	0.00	0.00	0.00
Wall 7				0.00	0.00	0.00	0.00	0.00	0.00
Wall 8				0.00	0.00	0.00	0.00	0.00	0.00
Wall 9				0.00	0.00	0.00	0.00	0.00	0.00
Wall 10				14.62	0.00	0.00	0.00	0.96	0.00
Wall 11				0.00	0.00	0.00	0.00	0.00	0.00
Wall 12		49.38	0.00			3.24	0.00	0.00	0.00
Wall 13		65.46	0.00			4.30	0.00	0.00	0.00
Wall 14				58.21	0.00	0.00	0.00	3.82	0.00
Wall 15		7.56	0.00			0.50	0.00	0.00	0.00

(0.56 cm; 103951 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick		standard walls 8" (=0.2032 m) to 12" (=0.3048) thick [-]		standard walls 4" (=0.1016 m) to 6" (=0.1524 m) thick [-]	
		damaged perimeter [m]	failed area [m2]	damaged perimeter [m]	failed area [m2]	damaged standard walls [-]	failed standard walls [-]	damaged standard walls [-]	failed standard walls [-]
Wall 1		0.00	0.00			0.00	0.00	0.00	0.00
Wall 2				3.10	0.00	0.00	0.00	0.20	0.00
Wall 3				0.00	0.00	0.00	0.00	0.00	0.00
Wall 4				0.00	0.00	0.00	0.00	0.00	0.00
Wall 5				0.00	0.00	0.00	0.00	0.00	0.00
Wall 6				0.00	0.00	0.00	0.00	0.00	0.00
Wall 7				0.00	0.00	0.00	0.00	0.00	0.00
Wall 8				0.00	0.00	0.00	0.00	0.00	0.00
Wall 9				0.00	0.00	0.00	0.00	0.00	0.00
Wall 10				14.62	0.00	0.00	0.00	0.96	0.00
Wall 11				14.62	0.00	0.00	0.00	0.96	0.00
Wall 12		49.38	0.00			3.24	0.00	0.00	0.00
Wall 13		103.74	0.00			6.81	0.00	0.00	0.00
Wall 14				75.86	0.00	0.00	0.00	4.98	0.00
Wall 15		7.56	0.00			0.50	0.00	0.00	0.00

moderate (0.80 cm; 120796 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick		standard walls 8" (=0.2032 m) to 12" (=0.3048) thick [-]		standard walls 4" (=0.1016 m) to 6" (=0.1524 m) thick [-]	
		damaged perimeter [m]	failed area [m2]	damaged perimeter [m]	failed area [m2]	damaged standard walls [-]	failed standard walls [-]	damaged standard walls [-]	failed standard walls [-]
Wall 1		0.00	0.00			0.00	0.00	0.00	0.00
Wall 2				6.20	0.00	0.00	0.00	0.41	0.00
Wall 3				0.00	0.00	0.00	0.00	0.00	0.00
Wall 4				0.00	0.00	0.00	0.00	0.00	0.00
Wall 5				0.00	0.00	0.00	0.00	0.00	0.00
Wall 6				0.00	0.00	0.00	0.00	0.00	0.00
Wall 7				0.00	0.00	0.00	0.00	0.00	0.00
Wall 8				0.00	0.00	0.00	0.00	0.00	0.00
Wall 9				0.00	0.00	0.00	0.00	0.00	0.00
Wall 10				14.62	0.00	0.00	0.00	0.96	0.00
Wall 11				14.62	0.00	0.00	0.00	0.96	0.00
Wall 12		54.42	0.00			3.57	0.00	0.00	0.00
Wall 13		149.82	0.00			9.83	0.00	0.00	0.00
Wall 14				156.78	0.00	0.00	0.00	10.29	0.00
Wall 15		7.56	0.00			0.50	0.00	0.00	0.00

extensive damage (1.12 cm, 129542 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick		standard walls 8" (=0.2032 m) to 12" (=0.3048) thick [-]		standard walls 4" (=0.1016 m) to 6" (=0.1524 m) thick [-]	
		damaged perimeter [m]	failed area [m2]	damaged perimeter [m]	failed area [m2]	damaged standard walls [-]	failed standard walls [-]	damaged standard walls [-]	failed standard walls [-]
Wall 1		0.00	0.00			0.00	0.00	0.00	0.00
Wall 2				9.30	0.00	0.00	0.00	0.61	0.00
Wall 3				0.00	0.00	0.00	0.00	0.00	0.00
Wall 4				0.00	0.00	0.00	0.00	0.00	0.00
Wall 5				0.00	0.00	0.00	0.00	0.00	0.00
Wall 6				0.00	0.00	0.00	0.00	0.00	0.00
Wall 7				0.00	0.00	0.00	0.00	0.00	0.00
Wall 8				0.00	0.00	0.00	0.00	0.00	0.00
Wall 9				0.00	0.00	0.00	0.00	0.00	0.00
Wall 10				17.72	0.00	0.00	0.00	1.16	0.00
Wall 11				14.62	0.00	0.00	0.00	0.96	0.00
Wall 12		59.46	0.00			3.90	0.00	0.00	0.00
Wall 13		182.34	0.00			11.96	0.00	0.00	0.00
Wall 14				165.16	0.00	0.00	0.00	10.84	0.00
Wall 15		22.68	0.00			1.49	0.00	0.00	0.00

max. force (1.44cm; 135996 daN)	Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick		standard walls 8" (=0.2032 m) to 12" (=0.3048) thick [-]		standard walls 4" (=0.1016 m) to 6" (=0.1524 m) thick [-]	
	damaged perimeter [m]	failed area [m2]	damaged perimeter [m]	failed area [m2]	damaged standard walls [-]	failed standard walls [-]	damaged standard walls [-]	failed standard walls [-]
Wall 1	0.00	0.00			0.00	0.00	0.00	0.00
Wall 2			18.74	0.00	0.00	0.00	1.23	0.00
Wall 3			0.00	0.00	0.00	0.00	0.00	0.00
Wall 4			0.00	0.00	0.00	0.00	0.00	0.00
Wall 5			0.00	0.00	0.00	0.00	0.00	0.00
Wall 6			0.00	0.00	0.00	0.00	0.00	0.00
Wall 7			0.00	0.00	0.00	0.00	0.00	0.00
Wall 8			0.00	0.00	0.00	0.00	0.00	0.00
Wall 9			0.00	0.00	0.00	0.00	0.00	0.00
Wall 10			17.72	0.00	0.00	0.00	1.16	0.00
Wall 11			14.62	0.00	0.00	0.00	0.96	0.00
Wall 12	74.66	0.66			4.90	0.05	0.00	0.00
Wall 13	190.80	0.00			12.52	0.00	0.00	0.00
Wall 14			173.86	0.00	0.00	0.00	11.41	0.00
Wall 15	37.80	0.35			2.48	0.02	0.00	0.00

failure (1.52cm; 123625 daN)	Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick		Equivalent number of standard walls 8"		Equivalent number of standard walls 4"	
	damaged perimeter [m]	failed area [m2]	damaged perimeter [m]	failed area [m2]	damaged standard walls [-]	failed standard walls [-]	damaged standard walls [-]	failed standard walls [-]
Wall 1	0.00	0.00			0.00	0.00	0.00	0.00
Wall 2			18.74	0.00	0.00	0.00	1.23	0.00
Wall 3			0.00	0.00	0.00	0.00	0.00	0.00
Wall 4			0.00	0.00	0.00	0.00	0.00	0.00
Wall 5			0.00	0.00	0.00	0.00	0.00	0.00
Wall 6			0.00	0.00	0.00	0.00	0.00	0.00
Wall 7			0.00	0.00	0.00	0.00	0.00	0.00
Wall 8			0.00	0.00	0.00	0.00	0.00	0.00
Wall 9			0.00	0.00	0.00	0.00	0.00	0.00
Wall 10			17.72	0.00	0.00	0.00	1.16	0.00
Wall 11			14.62	0.00	0.00	0.00	0.96	0.00
Wall 12	69.62	1.88			4.57	0.14	0.00	0.00
Wall 13	190.80	0.00			12.52	0.00	0.00	0.00
Wall 14			175.76	4.67	0.00	0.00	11.53	0.34
Wall 15	37.80	0.35			2.48	0.02	0.00	0.00

beyond failure (1.76 cm; 127452 daN)	Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick		Equivalent number of standard walls 8"		Equivalent number of standard walls 4"	
	damaged perimeter [m]	failed area [m2]	damaged perimeter [m]	failed area [m2]	damaged standard walls [-]	failed standard walls [-]	damaged standard walls [-]	failed standard walls [-]
Wall 1	0.00	0.00			0.00	0.00	0.00	0.00
Wall 2			18.74	0.00	0.00	0.00	1.23	0.00
Wall 3			0.00	0.00	0.00	0.00	0.00	0.00
Wall 4			15.36	0.00	0.00	0.00	1.01	0.00
Wall 5			0.00	0.00	0.00	0.00	0.00	0.00
Wall 6			0.00	0.00	0.00	0.00	0.00	0.00
Wall 7			0.00	0.00	0.00	0.00	0.00	0.00
Wall 8			0.00	0.00	0.00	0.00	0.00	0.00
Wall 9			0.00	0.00	0.00	0.00	0.00	0.00
Wall 10			27.16	0.00	0.00	0.00	1.78	0.00
Wall 11			14.62	0.00	0.00	0.00	0.96	0.00
Wall 12	69.62	1.88			4.57	0.14	0.00	0.00
Wall 13	190.80	0.00			12.52	0.00	0.00	0.00
Wall 14			175.76	5.23	0.00	0.00	11.53	0.38
Wall 15	45.36	0.69			2.98	0.05	0.00	0.00

Table 40: Before retrofit: calculation of damaged or failed walls (area) for the estimation of costs from repair/replacement works

(0.08 cm; 20465 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick	
		damaged area [m2]	failed area [m2]	damaged area [m2]	failed area [m2]
Wall 1		0.00	0.00		
Wall 2				0.00	0.00
Wall 3				0.00	0.00
Wall 4				0.00	0.00
Wall 5				0.00	0.00
Wall 6				0.00	0.00
Wall 7				0.00	0.00
Wall 8				0.00	0.00
Wall 9				0.00	0.00
Wall 10				0.00	0.00
Wall 11				0.00	0.00
Wall 12		2.46	0.00		
Wall 13		4.21	0.00		
Wall 14				2.37	0.00
Wall 15		0.00	0.00		
(0.40 cm; 84768 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick	
		damaged area [m2]	failed area [m2]	damaged area [m2]	failed area [m2]
Wall 1		0	0		
Wall 2				0	0
Wall 3				0	0
Wall 4				0	0
Wall 5				0	0
Wall 6				0	0
Wall 7				0	0
Wall 8				0	0
Wall 9				0	0
Wall 10				5.5194	0
Wall 11				0	0
Wall 12		9.0312	0		
Wall 13		22.599	0		
Wall 14				21.1584	0
Wall 15		0	0		
slight (point at 0.48cm, 92745 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick	
		damaged area [m2]	failed area [m2]	damaged area [m2]	failed area [m2]
Wall 1		0	0		
Wall 2				0	0
Wall 3				0	0
Wall 4				0	0
Wall 5				0	0
Wall 6				0	0
Wall 7				0	0
Wall 8				0	0
Wall 9				0	0
Wall 10				5.5194	0
Wall 11				0	0
Wall 12		12.414	0		
Wall 13		30.051	0		
Wall 14				35.268813	0
Wall 15		2.916	0		

(0.56 cm; 103951 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick	
		damaged area [m2]	failed area [m2]	damaged area [m2]	failed area [m2]
Wall 1		0	0		
Wall 2				0.5916	0
Wall 3				0	0
Wall 4				0	0
Wall 5				0	0
Wall 6				0	0
Wall 7				0	0
Wall 8				0	0
Wall 9				0	0
Wall 10				5.5194	0
Wall 11				12.447	0
Wall 12		12.414	0		
Wall 13		45.279	0		
Wall 14				45.22611	0
Wall 15		2.916	0		
moderate (point at 0.80cm, 120796 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick	
		damaged area [m2]	failed area [m2]	damaged area [m2]	failed area [m2]
Wall 1		0	0		
Wall 2				1.1832	0
Wall 3				0	0
Wall 4				0	0
Wall 5				0	0
Wall 6				0	0
Wall 7				0	0
Wall 8				0	0
Wall 9				0	0
Wall 10				5.5194	0
Wall 11				12.447	0
Wall 12		13.6416	0		
Wall 13		63.747	0		
Wall 14				97.514646	0
Wall 15		2.916	0		
extensive (point at 1.12cm, 129542 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick	
		damaged area [m2]	failed area [m2]	damaged area [m2]	failed area [m2]
Wall 1		0	0		
Wall 2				1.7748	0
Wall 3				0	0
Wall 4				0	0
Wall 5				0	0
Wall 6				0	0
Wall 7				0	0
Wall 8				0	0
Wall 9				0	0
Wall 10				6.111	0
Wall 11				12.447	0
Wall 12		14.8692	0		
Wall 13		78.489	0		
Wall 14				98.667543	0
Wall 15		8.748	0		

max. force (point at 1.44cm, 135996 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick	
		damaged area [m2]	failed area [m2]	damaged area [m2]	failed area [m2]
Wall 1		0	0		
Wall 2				7.33959	0
Wall 3				0	0
Wall 4				0	0
Wall 5				0	0
Wall 6				0	0
Wall 7				0	0
Wall 8				0	0
Wall 9				0	0
Wall 10				6.111	0
Wall 11				12.447	0
Wall 12		18.9864	0.6552		
Wall 13		82.62	0		
Wall 14				103.341	0
Wall 15		14.58	0.3456		
failure (point at 1.52cm, 123625 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick	
		damaged area [m2]	failed area [m2]	damaged area [m2]	failed area [m2]
Wall 1		0	0		
Wall 2				7.33959	0
Wall 3				0	0
Wall 4				0	0
Wall 5				0	0
Wall 6				0	0
Wall 7				0	0
Wall 8				0	0
Wall 9				0	0
Wall 10				6.111	0
Wall 11				12.447	0
Wall 12		17.7588	1.8828		
Wall 13		82.62	0		
Wall 14				99.83109	4.67346
Wall 15		14.58	0.3456		
beyond failure (1.76 cm; 127452 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick	
		damaged area [m2]	failed area [m2]	damaged area [m2]	failed area [m2]
Wall 1		0.00	0.00		
Wall 2				7.34	0.00
Wall 3				0.00	0.00
Wall 4				13.45	0.00
Wall 5				0.00	0.00
Wall 6				0.00	0.00
Wall 7				0.00	0.00
Wall 8				0.00	0.00
Wall 9				0.00	0.00
Wall 10				11.68	0.00
Wall 11				12.45	0.00
Wall 12		17.76	1.88		
Wall 13		82.62	0.00		
Wall 14				99.83	5.23
Wall 15		17.50	0.69		

Table 41: CO_2 emissions [kg] for different displacement points and normalisation methods

Normalisation by…	**area 15 ft x 25 ft**		**area 10 ft x 15 ft**		**perimeter 15 ft x 25 ft**		**perimeter 10 ft x 15 ft**		**not normalised (values from PACT)**	
	CO_2 emissions [kg]	**car-km-eq [km]**	**CO_2 emissions [kg]**	**car-km-eq [km]**	**CO_2 emissions [kg]**	**car-km-eq [km]**	**CO_2 emissions [kg]**	**car-km-eq [km]**	**CO_2 emissions [kg]**	**car-km-eq [km]**
(0.40 cm; 847.68 kN)	894	7'232	2'235	18'080	3'082	24'935	4'931	39'897	12'377	100'138
slight damage (0.48 cm; 927.45 kN)	1'319	10'668	3'297	26'671	4'317	34'931	6'908	55'889	16'189	130'979
(0.56 cm; 1039.51 kN)	1'895	15'331	4'737	38'329	5'926	47'948	9'482	76'716	21'003	169'927
moderate damage (0.80 cm, 1207.96 kN)	2'973	24'054	7'433	60'136	8'831	71'447	14'129	114'315	29'446	238'236
extensive damage (1.12 cm, 1295.42 kN)	3'358	27'172	8'396	67'929	10'345	83'694	16'551	133'911	35'384	286'278
max. force (1.44 cm; 1295.42 kN)	3'823	30'927	9'556	77'317	12'680	102'585	20'287	164'137	46'006	372'217
failure (1.52 cm; 1359.96 kN)	4'035	32'648	10'088	81'619	13'708	110'906	21'933	177'450	50'358	407'427

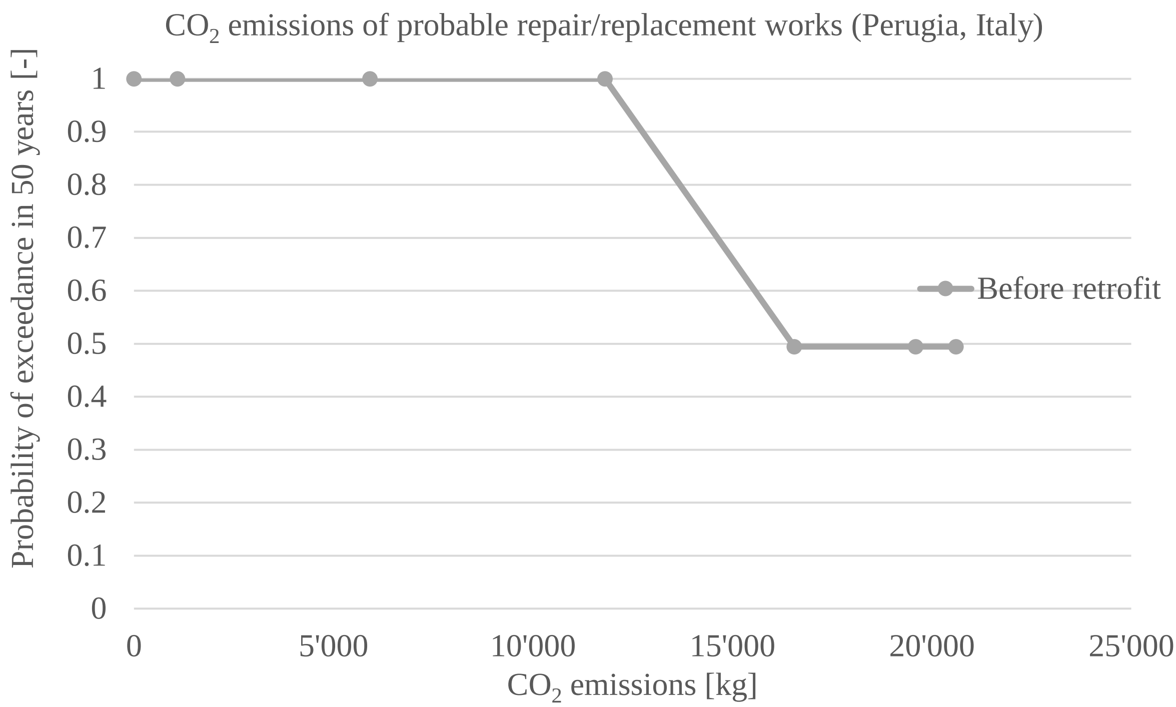


Figure 45: CO_2 emissions of probable repair works for different displacements and related probabilities of exceedance (loss function), Perugia, Italy

Appendix B

Composition and U-values of building elements

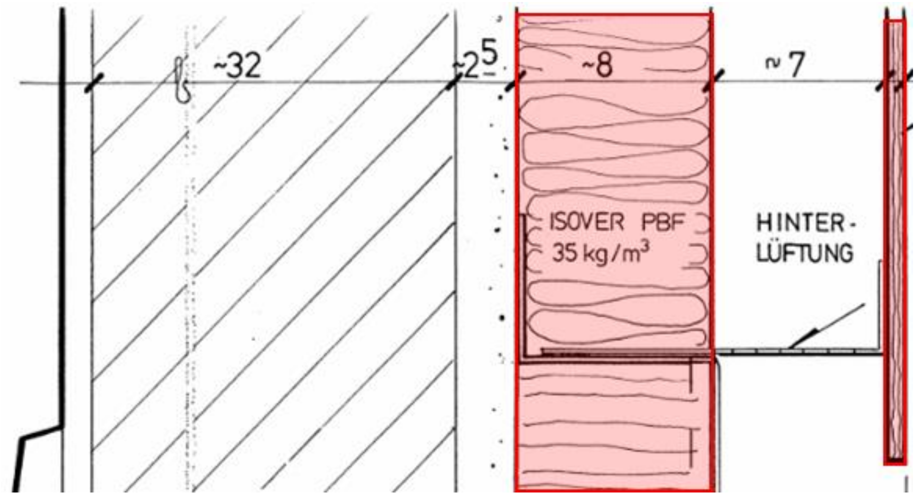


Figure 46: External wall structure (red: thermal insulation measure added in 1986) [88]

Table 42: Structure of exterior walls and correlated U-values

Material	Thickness [mm]	Thermal conductivity [W/(mK)]
Isover (applied in 1986)	80	0.04
Plaster	25	0.51
Brick, Engineering	320	0.81
U-value [W/(m^{2}K)]	0.41 >	MuKEn: 0.25

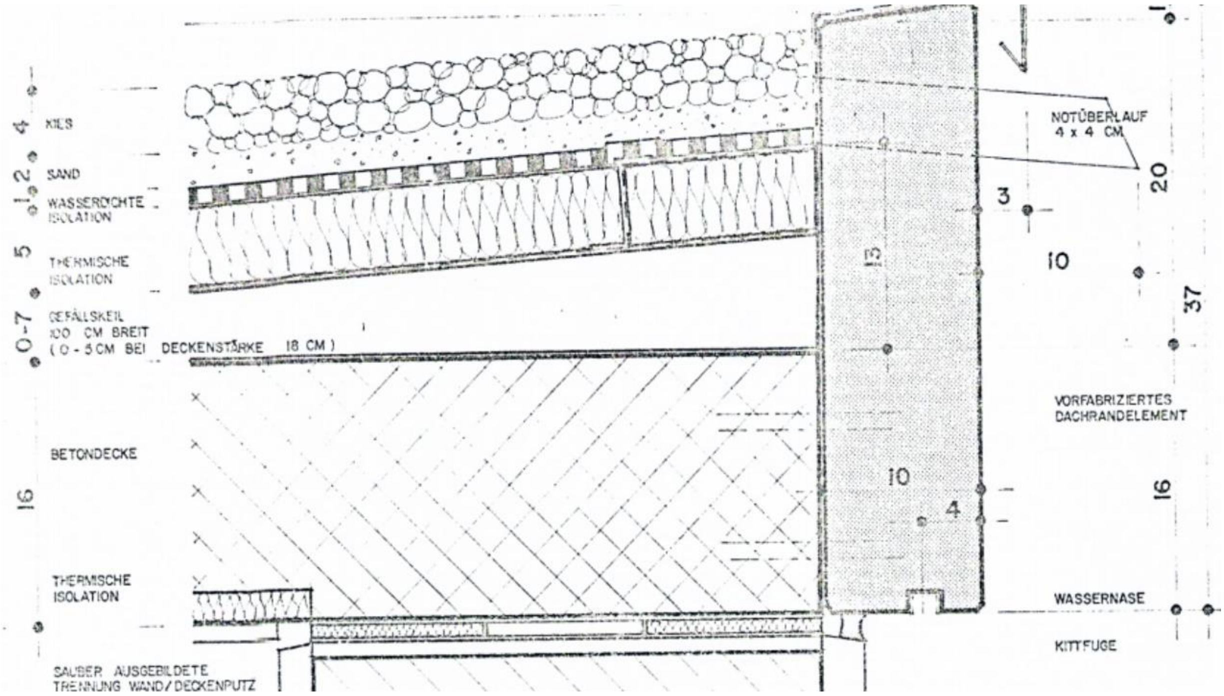


Figure 47: Roof structure [88]

Table 43: Structure of the roof and correlated U-values

Material	Thickness [mm]	Thermal conductivity [W/(mK)]
Sand	40	0.335
Sand	20	0.335
Roofing felt	10	0.5
Isover	50	0.04
Concrete, cast in situ	140	1.046
Isover	20	0.04
Plaster	12.5	0.51
U-value [W/(m^{2}K)]	0.47 >	MuKEn: 0.25

Estimation of the U-value of the windows according to typical windows of the 1970s in Switzerland [69].

Table 44: Structure of the windows and correlated U-values

Material		
Double-glazed window, absorbent coating		
U-value [W/(m^{2}K)]	3.20 >	MuKEn: 1.0

Table 45: Structure of interior walls and correlated U-values

Material	**Thickness [mm]**	**Thermal conductivity [W/(mK)]**
Plaster	12.5	0.51
Concrete masonry units	100	1.3
Plaster	12.5	0.51
U-value [W/(m^{2}K)]	7.94	

Table 46: Structure of the floor slabs and correlated U-values

Material	**Thickness [mm]**	**Thermal conductivity [W/(mK)]**
Isover	30	0.04
Concrete, cast in situ	210	1.046
U-value [W/(m^{2}K)]	1.05	

Table 47: Structure of the ground floor slab and correlated U-values

Material	**Thickness [mm]**	**Thermal conductivity [W/(mK)]**
Concrete, cast in situ	300	1.046
U-value [W/(m^{2}K)]	3.49 >	MuKEn: 0.28

Table 48: Structure of the doors and correlated U-values

Material		
Wooden door, massive wood core		
U-value [W/(m^{2}K)]	2.61 >	MuKEn: 1.2

Appendix C

Embodied CO_2 for retrofit alternatives

Table 49: Embodied CO_2 for seismic intervention with CFRP strips (seismic, Alternative 1)

Seismic intervention	Material	kg CO_2/ m^2 wall	Wall surface [m^2]	Total kg CO_2
Alternative 1: CFRP strips	CFRP	11.3	30.8	347
	Adhesive	14.5	30.8	447
	Concrete	4.6	30.8	143
		0.5	30.8	15
	TOTAL	31		952

Table 50: Embodied CO_2 for seismic intervention with NSM steel reinforcement (seismic, Alternative 3)

		kg CO_2/ m^2 wall	Wall surface [m^2]	Total kg CO_2
Alternative 3: NSM steel reinforcement	Steel reinforcement	3.9	30.8	117
		kg CO_2/ m^2 wall	Wall surface [m^2]	Total kg CO_2
	Adhesive	9.1	30.8	279
	TOTAL	13		396

(Rebars steel B500B, Horizontal: 10mm@400mm, Vertical: 10mm@600mm)

Table 51: Embodied CO_2 for thermal intervention on external walls with straw panels+clay plaster (thermal, Alternative 1)

Thermal intervention		**kg CO_2/ m^2**	**Bound Biogeneous Carbon [kgC/ m^2 wall]**	**Surface external walls [m^2]**	**Total [kg CO_2]**	**Total Biogeneous Carbon [kgC]**
Alternative 1: External Walls, inside	Straw panel	1.7	-6.3	547.8	905	-3467
	Lime plaster	0.4	0.0	547.8	240	0
	Reinforcement fabric	1.9	0.0	547.8	1039	0
	Clay plaster	0.2	0.0	547.8	96	0
	Reinforcement fabric jute	0.1	0.0	547.8	55	-24
	TOTAL	4			2336	-3491

Table 52: Embodied CO_2 for thermal intervention on external walls with straw panels (thermal, Alternative 2)

Thermal intervention		**kg CO_2/ m^2**	**Bound Biogeneous Carbon [kgC/ m^2 wall]**	**Surface external walls [m^2]**	**Total [kg CO_2]**	**Total Biogeneous Carbon [kgC]**
Alternative 2: External Walls, outside	Straw panel	1.7	-6.3	547.8	905	-3467

Table 53: Embodied CO_2 for thermal intervention on external walls with fiberglass mats (thermal, Alternative 3)

Thermal intervention		**kg CO_2/ m^2**	**Bound Biogeneous Carbon [kgC/ m^2 wall]**	**Total [kg CO_2/ m^2]**	**Surface external walls, [m^2]**	**Total [kg CO_2]**
Alternative 3: External Walls, Isover	Glass wool	5.3	0.0	5.3	547.8	2892

Table 54: Embodied CO_2 for thermal intervention on roof with fiberglass mats (thermal, roof)

Thermal intervention		**kg CO_2/ m^2**	**Bound Biogeneous Carbon [kgC/ m^2 wall]**	**Surface roof [m^2]**	**Total [kg CO_2]**
Roof	Glass wool	4.0	0.0	186.8	740

Table 55: Embodied CO_2 for thermal intervention on windows (thermal, windows)

Thermal intervention		**kg CO_2/ m^2**	**Bound Biogeneous Carbon [kgC/m^2 wall]**	**Surface windows [m^2]**	**Total [kg CO_2]**	**Total Biogeneous Carbon [kgC]**
Windows	Wooden windows frame	36.4	-7.5	18.4	670	-138
	Triple-glazing	78.4	0	76.7	6016	
	TOTAL	115			6686	-138

Appendix D

Seismic performance after seismic retrofit on 30.8 m²:

Table 56: Results of the seismic performance analysis in 3Muri after seismic retrofit with CFRP strips (area of application: 30.8 m²)

Analysis	Seismic direction	Seismic load	Eccentricity [cm]	Capacity d_m [cm]	Demand d_t [cm]	Compliance factor α
1	X +	Uniform	0	2.32	3.21	0.72
2	X +	Static forces	0	2.56	3.78	0.68
3	X -	Uniform	0	2.40	3.17	0.76
4	X -	Static forces	0	2.48	3.76	0.66
5	Y +	Uniform	0	1.28	1.36	0.94
6	Y +	Static forces	0	1.99	1.67	1.19
7	Y -	Uniform	0	1.20	1.19	1.01
8	Y -	Static forces	0	2.57	1.49	1.72
9	X +	Uniform	53.8	2.32	3.22	0.72
10	X +	Uniform	-53.8	2.32	3.22	0.72
11	X +	Static forces	53.8	2.48	3.77	0.66
12	X +	Static forces	-53.8	2.48	3.77	0.66
13	X -	Uniform	53.8	2.16	3.17	0.68
14	X -	Uniform	-53.8	2.40	3.18	0.75
15	X -	Static forces	53.8	2.48	3.76	0.66
16	X -	Static forces	-53.8	2.48	3.72	0.67
17	Y +	Uniform	89.6	0.80	1.25	0.64
18	Y +	Uniform	-89.6	1.36	1.51	0.90
19	Y +	Static forces	89.6	1.36	1.54	0.88
20	Y +	Static forces	-89.6	2.31	1.84	1.26
21	Y -	Uniform	89.6	0.72	1.11	0.65
22	Y -	Uniform	-89.6	1.28	1.36	0.94
23	Y -	Static forces	89.6	1.28	1.36	0.94
24	Y -	Static forces	-89.6	2.25	1.72	1.31

Table 57: Results of the seismic performance analysis in 3Muri after seismic retrofit with NSM steel reinforcement (area of application: 30.8 m²)

Analysis	Seismic direction	Seismic load	Eccentricity [cm]	Capacity d_m [cm]	Demand d_t [cm]	Compliance factor α
1	X +	Uniform	0	2.32	3.17	0.73
2	X +	Static forces	0	2.56	3.79	0.68
3	X -	Uniform	0	2.16	3.12	0.69
4	X -	Static forces	0	2.48	3.77	0.66
5	Y +	Uniform	0	1.28	1.36	0.94
6	Y +	Static forces	0	1.99	1.67	1.19
7	Y -	Uniform	0	1.20	1.20	1.00
8	Y -	Static forces	0	2.57	1.49	1.72
9	X +	Uniform	53.8	2.32	3.18	0.73
10	X +	Uniform	-53.8	2.16	3.17	0.68
11	X +	Static forces	53.8	2.48	3.77	0.66
12	X +	Static forces	-53.8	2.48	3.79	0.65
13	X -	Uniform	53.8	2.40	3.13	0.77
14	X -	Uniform	-53.8	2.08	3.13	0.66
15	X -	Static forces	53.8	2.48	3.77	0.66
16	X -	Static forces	-53.8	2.48	3.73	0.66
17	Y +	Uniform	89.6	0.80	1.25	0.64
18	Y +	Uniform	-89.6	1.36	1.52	0.89
19	Y +	Static forces	89.6	1.36	1.54	0.88
20	Y +	Static forces	-89.6	2.31	1.84	1.26
21	Y -	Uniform	89.6	0.80	1.10	0.73
22	Y -	Uniform	-89.6	1.36	1.36	1.00
23	Y -	Static forces	89.6	1.36	1.36	1.00
24	Y -	Static forces	-89.6	2.65	1.73	1.53

Appendix E

Table 58: After seismic retrofit with CFRP strips (30.8 m^2): calculation of damaged or failed walls (perimeter and area) for the estimation of CO_2 emissions from repair/replacement works

(0.08 cm; 20630 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick		standard walls 8" (=0.2032 m) to 12" (=0.3048) thick [-]		standard walls 4" (=0.1016 m) to 6" (=0.1524 m) thick [-]	
		damaged perimeter [m]	failed area [m2]	damaged perimeter [m]	failed area [m2]	damaged standard walls [-]	failed standard walls [-]	damaged standard walls [-]	failed standard walls [-]
Wall 1		0.00	0.00			0.00	0.00	0.00	0.00
Wall 2				0.00	0.00	0.00	0.00	0.00	0.00
Wall 3				0.00	0.00	0.00	0.00	0.00	0.00
Wall 4				0.00	0.00	0.00	0.00	0.00	0.00
Wall 5				0.00	0.00	0.00	0.00	0.00	0.00
Wall 6				0.00	0.00	0.00	0.00	0.00	0.00
Wall 7				0.00	0.00	0.00	0.00	0.00	0.00
Wall 8				0.00	0.00	0.00	0.00	0.00	0.00
Wall 9				0.00	0.00	0.00	0.00	0.00	0.00
Wall 10				0.00	0.00	0.00	0.00	0.00	0.00
Wall 11				0.00	0.00	0.00	0.00	0.00	0.00
Wall 12		10.08	1.55			0.66	0.11	0.00	0.00
Wall 13		8.52	0.00			0.56	0.00	0.00	0.00
Wall 14				9.30	1.18	0.00	0.00	0.61	0.08
Wall 15		0.00	0.00			0.00	0.00	0.00	0.00

(0.40 cm; 92501 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick		standard walls 8" (=0.2032 m) to 12" (=0.3048) thick [-]		standard walls 4" (=0.1016 m) to 6" (=0.1524 m) thick [-]	
		damaged perimeter [m]	failed area [m2]	damaged perimeter [m]	failed area [m2]	damaged standard walls [-]	failed standard walls [-]	damaged standard walls [-]	failed standard walls [-]
Wall 1		0.00	0.00			0.00	0.00	0.00	0.00
Wall 2				0.00	0.00	0.00	0.00	0.00	0.00
Wall 3				0.00	0.00	0.00	0.00	0.00	0.00
Wall 4				0.00	0.00	0.00	0.00	0.00	0.00
Wall 5				0.00	0.00	0.00	0.00	0.00	0.00
Wall 6				0.00	0.00	0.00	0.00	0.00	0.00
Wall 7				0.00	0.00	0.00	0.00	0.00	0.00
Wall 8				0.00	0.00	0.00	0.00	0.00	0.00
Wall 9				0.00	0.00	0.00	0.00	0.00	0.00
Wall 10				14.62	0.00	0.00	0.00	0.96	0.00
Wall 11				0.00	0.00	0.00	0.00	0.00	0.00
Wall 12		23.88	0.78			1.57	0.06	0.00	0.00
Wall 13		49.14	0.00			3.22	0.00	0.00	0.00
Wall 14				34.02	1.18	0.00	0.00	2.23	0.08
Wall 15		7.56	0.00			0.50	0.00	0.00	0.00

(0.48 cm; 105985 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick		standard walls 8" (=0.2032 m) to 12" (=0.3048) thick [-]		standard walls 4" (=0.1016 m) to 6" (=0.1524 m) thick [-]	
		damaged perimeter [m]	failed area [m2]	damaged perimeter [m]	failed area [m2]	damaged standard walls [-]	failed standard walls [-]	damaged standard walls [-]	failed standard walls [-]
Wall 1		0.00	0.00			0.00	0.00	0.00	0.00
Wall 2				0.00	0.00	0.00	0.00	0.00	0.00
Wall 3				0.00	0.00	0.00	0.00	0.00	0.00
Wall 4				0.00	0.00	0.00	0.00	0.00	0.00
Wall 5				0.00	0.00	0.00	0.00	0.00	0.00
Wall 6				0.00	0.00	0.00	0.00	0.00	0.00
Wall 7				0.00	0.00	0.00	0.00	0.00	0.00
Wall 8				0.00	0.00	0.00	0.00	0.00	0.00
Wall 9				0.00	0.00	0.00	0.00	0.00	0.00
Wall 10				14.62	0.00	0.00	0.00	0.96	0.00
Wall 11				0.00	0.00	0.00	0.00	0.00	0.00
Wall 12		36.82	0.78			2.42	0.06	0.00	0.00
Wall 13		80.82	0.00			5.30	0.00	0.00	0.00
Wall 14			0.00	55.11	1.18	0.00	0.00	3.62	0.08
Wall 15		7.56	0.00			0.50	0.00	0.00	0.00

(0.56 cm; 117461 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick		standard walls 8" (=0.2032 m) to 12" (=0.3048) thick [-]		standard walls 4" (=0.1016 m) to 6" (=0.1524 m) thick [-]	
		damaged perimeter [m]	failed area [m2]	damaged perimeter [m]	failed area [m2]	damaged standard walls [-]	failed standard walls [-]	damaged standard walls [-]	failed standard walls [-]
Wall 1		0.00	0.00			0.00	0.00	0.00	0.00
Wall 2				0.00	0.59	0.00	0.00	0.00	0.04
Wall 3				0.00	0.00	0.00	0.00	0.00	0.00
Wall 4				0.00	0.00	0.00	0.00	0.00	0.00
Wall 5				0.00	0.00	0.00	0.00	0.00	0.00
Wall 6				0.00	0.00	0.00	0.00	0.00	0.00
Wall 7				0.00	0.00	0.00	0.00	0.00	0.00
Wall 8				0.00	0.00	0.00	0.00	0.00	0.00
Wall 9				0.00	0.00	0.00	0.00	0.00	0.00
Wall 10				14.62	0.00	0.00	0.00	0.96	0.00
Wall 11				14.62	0.00	0.00	0.00	0.96	0.00
Wall 12		46.40	0.78			3.04	0.06	0.00	0.00
Wall 13		103.74	0.00			6.81	0.00	0.00	0.00
Wall 14				85.12	1.18	0.00	0.00	5.59	0.08
Wall 15		7.56	0.00			0.50	0.00	0.00	0.00

(0.80 cm; 137563 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick		standard walls 8" (=0.2032 m) to 12" (=0.3048) thick [-]		standard walls 4" (=0.1016 m) to 6" (=0.1524 m) thick [-]	
		damaged perimeter [m]	failed area [m2]	damaged perimeter [m]	failed area [m2]	damaged standard walls [-]	failed standard walls [-]	damaged standard walls [-]	failed standard walls [-]
Wall 1		0.00	0.00			0.00	0.00	0.00	0.00
Wall 2				9.30	0.00	0.00	0.00	0.61	0.00
Wall 3				0.00	0.00	0.00	0.00	0.00	0.00
Wall 4				0.00	0.00	0.00	0.00	0.00	0.00
Wall 5				0.00	0.00	0.00	0.00	0.00	0.00
Wall 6				0.00	0.00	0.00	0.00	0.00	0.00
Wall 7				0.00	0.00	0.00	0.00	0.00	0.00
Wall 8				0.00	0.00	0.00	0.00	0.00	0.00
Wall 9				0.00	0.00	0.00	0.00	0.00	0.00
Wall 10				14.62	0.00	0.00	0.00	0.96	0.00
Wall 11				14.62	0.00	0.00	0.00	0.96	0.00
Wall 12		52.24	0.78			3.43	0.06	0.00	0.00
Wall 13		149.82	0.00			9.83	0.00	0.00	0.00
Wall 14				139.31	1.18	0.00	0.00	9.14	0.08
Wall 15		7.56	0.00			0.50	0.00	0.00	0.00

(1.12 cm; 147817 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick		standard walls 8" (=0.2032 m) to 12" (=0.3048) thick [-]		standard walls 4" (=0.1016 m) to 6" (=0.1524 m) thick [-]	
		damaged perimeter [m]	failed area [m2]	damaged perimeter [m]	failed area [m2]	damaged standard walls [-]	failed standard walls [-]	damaged standard walls [-]	failed standard walls [-]
Wall 1		0.00	0.00			0.00	0.00	0.00	0.00
Wall 2				18.74	0.00	0.00	0.00	1.23	0.00
Wall 3				0.00	0.00	0.00	0.00	0.00	0.00
Wall 4				0.00	0.00	0.00	0.00	0.00	0.00
Wall 5				0.00	0.00	0.00	0.00	0.00	0.00
Wall 6				0.00	0.00	0.00	0.00	0.00	0.00
Wall 7				0.00	0.00	0.00	0.00	0.00	0.00
Wall 8				0.00	0.00	0.00	0.00	0.00	0.00
Wall 9				0.00	0.00	0.00	0.00	0.00	0.00
Wall 10				17.72	0.00	0.00	0.00	1.16	0.00
Wall 11				14.62	0.00	0.00	0.00	0.96	0.00
Wall 12		69.03	0.78			4.53	0.06	0.00	0.00
Wall 13		190.80	0.00			12.52	0.00	0.00	0.00
Wall 14				156.78	1.18	0.00	0.00	10.29	0.08
Wall 15		15.12	0.00			0.99	0.00	0.00	0.00

(max. force) (1.44 cm; 153467 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick		standard walls 8" (=0.2032 m) to 12" (=0.3048) thick [-]		standard walls 4" (=0.1016 m) to 6" (=0.1524 m) thick [-]	
		damaged perimeter [m]	failed area [m2]	damaged perimeter [m]	failed area [m2]	damaged standard walls [-]	failed standard walls [-]	damaged standard walls [-]	failed standard walls [-]
Wall 1		0.00	0.00			0.00	0.00	0.00	0.00
Wall 2				18.74	0.00	0.00	0.00	1.23	0.00
Wall 3				0.00	0.00	0.00	0.00	0.00	0.00
Wall 4				15.36	0.00	0.00	0.00	1.01	0.00
Wall 5				0.00	0.00	0.00	0.00	0.00	0.00
Wall 6				0.00	0.00	0.00	0.00	0.00	0.00
Wall 7				0.00	0.00	0.00	0.00	0.00	0.00
Wall 8				0.00	0.00	0.00	0.00	0.00	0.00
Wall 9				0.00	0.00	0.00	0.00	0.00	0.00
Wall 10				17.72	0.00	0.00	0.00	1.16	0.00
Wall 11				14.62	0.00	0.00	0.00	0.96	0.00
Wall 12		72.45	0.24			4.75	0.02	0.00	0.00
Wall 13		190.80	0.00			12.52	0.00	0.00	0.00
Wall 14				156.78	1.18	0.00	0.00	10.29	0.08
Wall 15		52.92	0.00			3.47	0.00	0.00	0.00

(failure) (1.52 cm; 152866 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick		standard walls 8" (=0.2032 m) to 12" (=0.3048) thick [-]		standard walls 4" (=0.1016 m) to 6" (=0.1524 m) thick [-]	
		damaged perimeter [m]	failed area [m2]	damaged perimeter [m]	failed area [m2]	damaged standard walls [-]	failed standard walls [-]	damaged standard walls [-]	failed standard walls [-]
Wall 1		0.00	0.00			0.00	0.00	0.00	0.00
Wall 2				18.74	0.00	0.00	0.00	1.23	0.00
Wall 3				0.00	0.00	0.00	0.00	0.00	0.00
Wall 4				15.36	0.00	0.00	0.00	1.01	0.00
Wall 5				0.00	0.00	0.00	0.00	0.00	0.00
Wall 6				0.00	0.00	0.00	0.00	0.00	0.00
Wall 7				0.00	0.00	0.00	0.00	0.00	0.00
Wall 8				0.00	0.00	0.00	0.00	0.00	0.00
Wall 9				0.00	0.00	0.00	0.00	0.00	0.00
Wall 10				17.72	0.00	0.00	0.00	1.16	0.00
Wall 11				14.62	0.00	0.00	0.00	0.96	0.00
Wall 12		75.79	0.24			4.97	0.02	0.00	0.00
Wall 13		190.80	0.00			12.52	0.00	0.00	0.00
Wall 14				156.78	1.18	0.00	0.00	10.29	0.08
Wall 15		52.92	0.69			3.47	0.05	0.00	0.00

(beyond failure) (1.76 cm; 146043 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick		standard walls 8" (=0.2032 m) to 12" (=0.3048) thick [-]		standard walls 4" (=0.1016 m) to 6" (=0.1524 m) thick [-]	
		damaged perimeter [m]	failed area [m2]	damaged perimeter [m]	failed area [m2]	damaged standard walls [-]	failed standard walls [-]	damaged standard walls [-]	failed standard walls [-]
Wall 1		0.00	0.00			0.00	0.00	0.00	0.00
Wall 2				18.74	0.00	0.00	0.00	1.23	0.00
Wall 3				0.00	0.00	0.00	0.00	0.00	0.00
Wall 4				15.36	0.00	0.00	0.00	1.01	0.00
Wall 5				0.00	0.00	0.00	0.00	0.00	0.00
Wall 6				0.00	0.00	0.00	0.00	0.00	0.00
Wall 7				0.00	0.00	0.00	0.00	0.00	0.00
Wall 8				0.00	0.00	0.00	0.00	0.00	0.00
Wall 9				0.00	0.00	0.00	0.00	0.00	0.00
Wall 10				26.14	0.00	0.00	0.00	1.71	0.00
Wall 11				14.62	0.00	0.00	0.00	0.96	0.00
Wall 12		88.07	0.24			5.78	0.02	0.00	0.00
Wall 13		190.80	0.00			12.52	0.00	0.00	0.00
Wall 14				184.77	0.85	0.00	0.00	12.12	0.06
Wall 15		52.92	0.69			3.47	0.05	0.00	0.00

Table 59: After seismic retrofit with CFRP strips (30.8 m^2): calculation of damaged or failed walls (area) for the estimation of costs from repair/replacement works

(0.08 cm; 20630 daN)	Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick	
	damaged area [m2]	failed area [m2]	damaged area [m2]	failed area [m2]
Wall 1	0.00	0.00		
Wall 2			0.00	0.00
Wall 3			0.00	0.00
Wall 4			0.00	0.00
Wall 5			0.00	0.00
Wall 6			0.00	0.00
Wall 7			0.00	0.00
Wall 8			0.00	0.00
Wall 9			0.00	0.00
Wall 10			0.00	0.00
Wall 11			0.00	0.00
Wall 12	2.46	1.55		
Wall 13	4.21	0.00		
Wall 14			1.77	1.18
Wall 15	0.00	0.00		
(0.40 cm; 92501 daN)	Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick	
	damaged area [m2]	failed area [m2]	damaged area [m2]	failed area [m2]
Wall 1	0.00	0.00		
Wall 2			0.00	0.00
Wall 3			0.00	0.00
Wall 4			0.00	0.00
Wall 5			0.00	0.00
Wall 6			0.00	0.00
Wall 7			0.00	0.00
Wall 8			0.00	0.00
Wall 9			0.00	0.00
Wall 10			5.52	0.00
Wall 11			0.00	0.00
Wall 12	5.66	0.78		
Wall 13	22.60	0.00		
Wall 14			20.57	1.18
Wall 15	2.92	0.00		
(0.48 cm; 105985 daN)	Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick	
	damaged area [m2]	failed area [m2]	damaged area [m2]	failed area [m2]
Wall 1	0.00	0.00		
Wall 2			0.00	0.00
Wall 3			0.00	0.00
Wall 4			0.00	0.00
Wall 5			0.00	0.00
Wall 6			0.00	0.00
Wall 7			0.00	0.00
Wall 8			0.00	0.00
Wall 9			0.00	0.00
Wall 10			5.52	0.00
Wall 11			0.00	0.00
Wall 12	8.79	0.78		
Wall 13	36.21	0.00		
Wall 14		0.00	34.68	1.18
Wall 15	2.92	0.00		

(0.56 cm; 117461 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick	
		damaged area [m2]	failed area [m2]	damaged area [m2]	failed area [m2]
Wall 1		0.00	0.00		
Wall 2				0.00	0.59
Wall 3				0.00	0.00
Wall 4				0.00	0.00
Wall 5				0.00	0.00
Wall 6				0.00	0.00
Wall 7				0.00	0.00
Wall 8				0.00	0.00
Wall 9				0.00	0.00
Wall 10				5.52	0.00
Wall 11				12.45	0.00
Wall 12		11.50	0.78		
Wall 13		45.28	0.00		
Wall 14				54.03	1.18
Wall 15		2.92	0.00		

(0.80 cm; 137563 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick	
		damaged area [m2]	failed area [m2]	damaged area [m2]	failed area [m2]
Wall 1		0.00	0.00		
Wall 2				1.77	0.00
Wall 3				0.00	0.00
Wall 4				0.00	0.00
Wall 5				0.00	0.00
Wall 6				0.00	0.00
Wall 7				0.00	0.00
Wall 8				0.00	0.00
Wall 9				0.00	0.00
Wall 10				5.52	0.00
Wall 11				12.45	0.00
Wall 12		13.44	0.78		
Wall 13		63.75	0.00		
Wall 14				88.09	1.18
Wall 15		2.92	0.00		

(1.12 cm; 147817 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick	
		damaged area [m2]	failed area [m2]	damaged area [m2]	failed area [m2]
Wall 1		0.00	0.00		
Wall 2				7.34	0.00
Wall 3				0.00	0.00
Wall 4				0.00	0.00
Wall 5				0.00	0.00
Wall 6				0.00	0.00
Wall 7				0.00	0.00
Wall 8				0.00	0.00
Wall 9				0.00	0.00
Wall 10				6.11	0.00
Wall 11				12.45	0.00
Wall 12		17.66	0.78		
Wall 13		82.62	0.00		
Wall 14				97.51	1.18
Wall 15		5.83	0.00		

(max. force) (1.44 cm; 153467 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick	
		damaged area [m2]	failed area [m2]	damaged area [m2]	failed area [m2]
Wall 1		0.00	0.00		
Wall 2				7.34	0.00
Wall 3				0.00	0.00
Wall 4				13.45	0.00
Wall 5				0.00	0.00
Wall 6				0.00	0.00
Wall 7				0.00	0.00
Wall 8				0.00	0.00
Wall 9				0.00	0.00
Wall 10				6.11	0.00
Wall 11				12.45	0.00
Wall 12		18.32	0.24		
Wall 13		82.62	0.00		
Wall 14				97.51	1.18
Wall 15		20.41	0.00		

(failure) (1.52 cm; 152866 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick	
		damaged area [m2]	failed area [m2]	damaged area [m2]	failed area [m2]
Wall 1		0.00	0.00		
Wall 2				7.34	0.00
Wall 3				0.00	0.00
Wall 4				13.45	0.00
Wall 5				0.00	0.00
Wall 6				0.00	0.00
Wall 7				0.00	0.00
Wall 8				0.00	0.00
Wall 9				0.00	0.00
Wall 10				6.11	0.00
Wall 11				12.45	0.00
Wall 12		20.34	0.24		
Wall 13		82.62	0.00		
Wall 14				97.51	1.18
Wall 15		20.41	0.69		

(beyond failure) (1.76 cm; 146043 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick	
		damaged area [m2]	failed area [m2]	damaged area [m2]	failed area [m2]
Wall 1		0.00	0.00		
Wall 2				7.34	0.00
Wall 3				0.00	0.00
Wall 4				13.45	0.00
Wall 5				0.00	0.00
Wall 6				0.00	0.00
Wall 7				0.00	0.00
Wall 8				0.00	0.00
Wall 9				0.00	0.00
Wall 10				10.45	0.00
Wall 11				12.45	0.00
Wall 12		24.46	0.24		
Wall 13		82.62	0.00		
Wall 14				108.03	0.85
Wall 15		20.41	0.69		

Table 60: After seismic retrofit with NSM steel reinforcement (30.8 m^2): calculation of damaged or failed walls (perimeter and area) for the estimation of CO_2 emissions from repair/replacement works

(0.08 cm; 20473 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick		standard walls 8" (=0.2032 m) to 12" (=0.3048) thick [-]		standard walls 4" (=0.1016 m) to 6" (=0.1524 m) thick [-]	
		damaged perimeter [m]	failed area [m2]	damaged perimeter [m]	failed area [m2]	damaged standard walls [-]	failed standard walls [-]	damaged standard walls [-]	failed standard walls [-]
Wall 1		0.00	0.00			0.00	0.00	0.00	0.00
Wall 2				0.00	0.00	0.00	0.00	0.00	0.00
Wall 3				0.00	0.00	0.00	0.00	0.00	0.00
Wall 4				0.00	0.00	0.00	0.00	0.00	0.00
Wall 5				0.00	0.00	0.00	0.00	0.00	0.00
Wall 6				0.00	0.00	0.00	0.00	0.00	0.00
Wall 7				0.00	0.00	0.00	0.00	0.00	0.00
Wall 8				0.00	0.00	0.00	0.00	0.00	0.00
Wall 9				0.00	0.00	0.00	0.00	0.00	0.00
Wall 10				0.00	0.00	0.00	0.00	0.00	0.00
Wall 11				0.00	0.00	0.00	0.00	0.00	0.00
Wall 12		10.08	1.55			0.66	0.11	0.00	0.00
Wall 13		8.52	0.00			0.56	0.00	0.00	0.00
Wall 14				9.30	1.18	0.00	0.00	0.61	0.08
Wall 15		0.00	0.00			0.00	0.00	0.00	0.00
(0.40 cm; 92199 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick		standard walls 8" (=0.2032 m) to 12" (=0.3048) thick [-]		standard walls 4" (=0.1016 m) to 6" (=0.1524 m) thick [-]	
		damaged perimeter [m]	failed area [m2]	damaged perimeter [m]	failed area [m2]	damaged standard walls [-]	failed standard walls [-]	damaged standard walls [-]	failed standard walls [-]
Wall 1		0.00	0.00			0.00	0.00	0.00	0.00
Wall 2				0.00	0.00	0.00	0.00	0.00	0.00
Wall 3				0.00	0.00	0.00	0.00	0.00	0.00
Wall 4				0.00	0.00	0.00	0.00	0.00	0.00
Wall 5				0.00	0.00	0.00	0.00	0.00	0.00
Wall 6				0.00	0.00	0.00	0.00	0.00	0.00
Wall 7				0.00	0.00	0.00	0.00	0.00	0.00
Wall 8				0.00	0.00	0.00	0.00	0.00	0.00
Wall 9				0.00	0.00	0.00	0.00	0.00	0.00
Wall 10				11.52	0.00	0.00	0.00	0.76	0.00
Wall 11				0.00	0.00	0.00	0.00	0.00	0.00
Wall 12		23.88	0.78			1.57	0.06	0.00	0.00
Wall 13		49.14	0.00			3.22	0.00	0.00	0.00
Wall 14				34.02	1.18	0.00	0.00	2.23	0.08
Wall 15		0.00	0.00			0.00	0.00	0.00	0.00
(0.48 cm; 106885 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick		standard walls 8" (=0.2032 m) to 12" (=0.3048) thick [-]		standard walls 4" (=0.1016 m) to 6" (=0.1524 m) thick [-]	
		damaged perimeter [m]	failed area [m2]	damaged perimeter [m]	failed area [m2]	damaged standard walls [-]	failed standard walls [-]	damaged standard walls [-]	failed standard walls [-]
Wall 1		0.00	0.00			0.00	0.00	0.00	0.00
Wall 2				0.00	0.00	0.00	0.00	0.00	0.00
Wall 3				0.00	0.00	0.00	0.00	0.00	0.00
Wall 4				0.00	0.00	0.00	0.00	0.00	0.00
Wall 5				0.00	0.00	0.00	0.00	0.00	0.00
Wall 6				0.00	0.00	0.00	0.00	0.00	0.00
Wall 7				0.00	0.00	0.00	0.00	0.00	0.00
Wall 8				0.00	0.00	0.00	0.00	0.00	0.00
Wall 9				0.00	0.00	0.00	0.00	0.00	0.00
Wall 10				14.62	0.00	0.00	0.00	0.96	0.00
Wall 11				0.00	0.00	0.00	0.00	0.00	0.00
Wall 12		30.98	0.78			2.03	0.06	0.00	0.00
Wall 13		88.38	0.00			5.80	0.00	0.00	0.00
Wall 14			0.00	55.11	1.18	0.00	0.00	3.62	0.08
Wall 15		7.56	0.00			0.50	0.00	0.00	0.00

(0.56 cm; 120575 daN)	Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick		standard walls 8" (=0.2032 m) to 12" (=0.3048) thick [-]		standard walls 4" (=0.1016 m) to 6" (=0.1524 m) thick [-]	
	damaged perimeter [m]	failed area [m2]	damaged perimeter [m]	failed area [m2]	damaged standard walls [-]	failed standard walls [-]	damaged standard walls [-]	failed standard walls [-]
Wall 1	0.00	0.00			0.00	0.00	0.00	0.00
Wall 2			0.00	0.59	0.00	0.00	0.00	0.04
Wall 3			0.00	0.00	0.00	0.00	0.00	0.00
Wall 4			0.00	0.00	0.00	0.00	0.00	0.00
Wall 5			0.00	0.00	0.00	0.00	0.00	0.00
Wall 6			0.00	0.00	0.00	0.00	0.00	0.00
Wall 7			0.00	0.00	0.00	0.00	0.00	0.00
Wall 8			0.00	0.00	0.00	0.00	0.00	0.00
Wall 9			0.00	0.00	0.00	0.00	0.00	0.00
Wall 10			14.62	0.00	0.00	0.00	0.96	0.00
Wall 11			14.62	0.00	0.00	0.00	0.96	0.00
Wall 12	46.40	0.78			3.04	0.06	0.00	0.00
Wall 13	103.74	0.00			6.81	0.00	0.00	0.00
Wall 14			85.12	1.18	0.00	0.00	5.59	0.08
Wall 15	7.56	0.00			0.50	0.00	0.00	0.00

(0.80 cm; 140445 daN)	Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick		standard walls 8" (=0.2032 m) to 12" (=0.3048) thick [-]		standard walls 4" (=0.1016 m) to 6" (=0.1524 m) thick [-]	
	damaged perimeter [m]	failed area [m2]	damaged perimeter [m]	failed area [m2]	damaged standard walls [-]	failed standard walls [-]	damaged standard walls [-]	failed standard walls [-]
Wall 1	0.00	0.00			0.00	0.00	0.00	0.00
Wall 2			0.00	0.00	0.00	0.00	0.00	0.00
Wall 3			0.00	0.00	0.00	0.00	0.00	0.00
Wall 4			0.00	0.00	0.00	0.00	0.00	0.00
Wall 5			0.00	0.00	0.00	0.00	0.00	0.00
Wall 6			0.00	0.00	0.00	0.00	0.00	0.00
Wall 7			0.00	0.00	0.00	0.00	0.00	0.00
Wall 8			0.00	0.00	0.00	0.00	0.00	0.00
Wall 9			0.00	0.00	0.00	0.00	0.00	0.00
Wall 10			14.62	0.00	0.00	0.00	0.96	0.00
Wall 11			14.62	0.00	0.00	0.00	0.96	0.00
Wall 12	52.24	0.78			3.43	0.06	0.00	0.00
Wall 13	166.74	0.00			10.94	0.00	0.00	0.00
Wall 14			148.04	1.18	0.00	0.00	9.71	0.08
Wall 15	7.56	0.00			0.50	0.00	0.00	0.00

(1.12 cm; 150821 daN)	Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick		standard walls 8" (=0.2032 m) to 12" (=0.3048) thick [-]		standard walls 4" (=0.1016 m) to 6" (=0.1524 m) thick [-]	
	damaged perimeter [m]	failed area [m2]	damaged perimeter [m]	failed area [m2]	damaged standard walls [-]	failed standard walls [-]	damaged standard walls [-]	failed standard walls [-]
Wall 1	0.00	0.00			0.00	0.00	0.00	0.00
Wall 2			6.20	0.00	0.00	0.00	0.41	0.00
Wall 3			0.00	0.00	0.00	0.00	0.00	0.00
Wall 4			0.00	0.00	0.00	0.00	0.00	0.00
Wall 5			0.00	0.00	0.00	0.00	0.00	0.00
Wall 6			0.00	0.00	0.00	0.00	0.00	0.00
Wall 7			0.00	0.00	0.00	0.00	0.00	0.00
Wall 8			0.00	0.00	0.00	0.00	0.00	0.00
Wall 9			0.00	0.00	0.00	0.00	0.00	0.00
Wall 10			14.62	0.00	0.00	0.00	0.96	0.00
Wall 11			14.62	0.00	0.00	0.00	0.96	0.00
Wall 12	58.95	0.78			3.87	0.06	0.00	0.00
Wall 13	190.80	0.00			12.52	0.00	0.00	0.00
Wall 14			148.04	1.18	0.00	0.00	9.71	0.08
Wall 15	15.12	0.00			0.99	0.00	0.00	0.00

(max. force) (1.44 cm; 148614 daN)	Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick		standard walls 8" (=0.2032 m) to 12" (=0.3048) thick [-]		standard walls 4" (=0.1016 m) to 6" (=0.1524 m) thick [-]	
	damaged perimeter [m]	failed area [m2]	damaged perimeter [m]	failed area [m2]	damaged standard walls [-]	failed standard walls [-]	damaged standard walls [-]	failed standard walls [-]
Wall 1	0.00	0.00			0.00	0.00	0.00	0.00
Wall 2			15.64	0.00	0.00	0.00	1.03	0.00
Wall 3			0.00	0.00	0.00	0.00	0.00	0.00
Wall 4			15.36	0.00	0.00	0.00	1.01	0.00
Wall 5			0.00	0.00	0.00	0.00	0.00	0.00
Wall 6			0.00	0.00	0.00	0.00	0.00	0.00
Wall 7			0.00	0.00	0.00	0.00	0.00	0.00
Wall 8			0.00	0.00	0.00	0.00	0.00	0.00
Wall 9			0.00	0.00	0.00	0.00	0.00	0.00
Wall 10			14.62	0.00	0.00	0.00	0.96	0.00
Wall 11			14.62	0.00	0.00	0.00	0.96	0.00
Wall 12	59.01	0.78			3.87	0.06	0.00	0.00
Wall 13	190.80	0.00			12.52	0.00	0.00	0.00
Wall 14			148.04	1.18	0.00	0.00	9.71	0.08
Wall 15	45.36	0.35			2.98	0.02	0.00	0.00

(failure) (1.52 cm; 144811 daN)	Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick		standard walls 8" (=0.2032 m) to 12" (=0.3048) thick [-]		standard walls 4" (=0.1016 m) to 6" (=0.1524 m) thick [-]	
	damaged perimeter [m]	failed area [m2]	damaged perimeter [m]	failed area [m2]	damaged standard walls [-]	failed standard walls [-]	damaged standard walls [-]	failed standard walls [-]
Wall 1	0.00	0.00			0.00	0.00	0.00	0.00
Wall 2			15.64	0.00	0.00	0.00	1.03	0.00
Wall 3			0.00	0.00	0.00	0.00	0.00	0.00
Wall 4			15.36	0.00	0.00	0.00	1.01	0.00
Wall 5			0.00	0.00	0.00	0.00	0.00	0.00
Wall 6			0.00	0.00	0.00	0.00	0.00	0.00
Wall 7			0.00	0.00	0.00	0.00	0.00	0.00
Wall 8			0.00	0.00	0.00	0.00	0.00	0.00
Wall 9			0.00	0.00	0.00	0.00	0.00	0.00
Wall 10			14.62	0.00	0.00	0.00	0.96	0.00
Wall 11			14.62	0.00	0.00	0.00	0.96	0.00
Wall 12	65.71	0.24			4.31	0.02	0.00	0.00
Wall 13	190.80	0.00			12.52	0.00	0.00	0.00
Wall 14			153.36	1.18	0.00	0.00	10.06	0.08
Wall 15	45.36	0.35			2.98	0.02	0.00	0.00

(beyond failure) (1.76 cm; 145203 daN)	Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick		standard walls 8" (=0.2032 m) to 12" (=0.3048) thick [-]		standard walls 4" (=0.1016 m) to 6" (=0.1524 m) thick [-]	
	damaged perimeter [m]	failed area [m2]	damaged perimeter [m]	failed area [m2]	damaged standard walls [-]	failed standard walls [-]	damaged standard walls [-]	failed standard walls [-]
Wall 1	0.00	0.00			0.00	0.00	0.00	0.00
Wall 2			15.64	0.00	0.00	0.00	1.03	0.00
Wall 3			0.00	0.00	0.00	0.00	0.00	0.00
Wall 4			15.36	0.00	0.00	0.00	1.01	0.00
Wall 5			0.00	0.00	0.00	0.00	0.00	0.00
Wall 6			0.00	0.00	0.00	0.00	0.00	0.00
Wall 7			0.00	0.00	0.00	0.00	0.00	0.00
Wall 8			0.00	0.00	0.00	0.00	0.00	0.00
Wall 9			0.00	0.00	0.00	0.00	0.00	0.00
Wall 10			23.04	0.00	0.00	0.00	1.51	0.00
Wall 11			14.62	0.00	0.00	0.00	0.96	0.00
Wall 12	68.28	2.73			4.48	0.20	0.00	0.00
Wall 13	190.80	0.00			12.52	0.00	0.00	0.00
Wall 14			170.72	0.85	0.00	0.00	11.20	0.06
Wall 15	45.36	0.69			2.98	0.05	0.00	0.00

Table 61: After seismic retrofit with NSM steel reinforcement (30.8 m²): calculation of damaged or failed walls (area) for the estimation of costs from repair/replacement works

(0.08 cm; 20473 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick	
		damaged area [m2]	failed area [m2]	damaged area [m2]	failed area [m2]
Wall 1		0.00	0.00		
Wall 2				0.00	0.00
Wall 3				0.00	0.00
Wall 4				0.00	0.00
Wall 5				0.00	0.00
Wall 6				0.00	0.00
Wall 7				0.00	0.00
Wall 8				0.00	0.00
Wall 9				0.00	0.00
Wall 10				0.00	0.00
Wall 11				0.00	0.00
Wall 12		2.46	1.55		
Wall 13		4.21	0.00		
Wall 14				1.77	1.18
Wall 15		0.00	0.00		
(0.40 cm; 92199 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick	
		damaged area [m2]	failed area [m2]	damaged area [m2]	failed area [m2]
Wall 1		0.00	0.00		
Wall 2				0.00	0.00
Wall 3				0.00	0.00
Wall 4				0.00	0.00
Wall 5				0.00	0.00
Wall 6				0.00	0.00
Wall 7				0.00	0.00
Wall 8				0.00	0.00
Wall 9				0.00	0.00
Wall 10				4.93	0.00
Wall 11				0.00	0.00
Wall 12		5.66	0.78		
Wall 13		22.60	0.00		
Wall 14				20.57	1.18
Wall 15		0.00	0.00		
(0.48 cm; 106885 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick	
		damaged area [m2]	failed area [m2]	damaged area [m2]	failed area [m2]
Wall 1		0.00	0.00		
Wall 2				0.00	0.00
Wall 3				0.00	0.00
Wall 4				0.00	0.00
Wall 5				0.00	0.00
Wall 6				0.00	0.00
Wall 7				0.00	0.00
Wall 8				0.00	0.00
Wall 9				0.00	0.00
Wall 10				5.52	0.00
Wall 11				0.00	0.00
Wall 12		6.85	0.78		
Wall 13		39.12	0.00		
Wall 14			0.00	34.68	1.18
Wall 15		2.92	0.00		

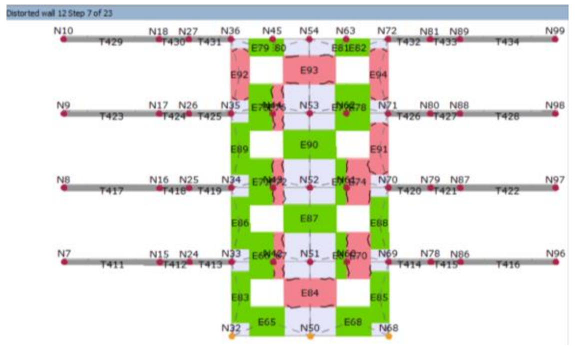
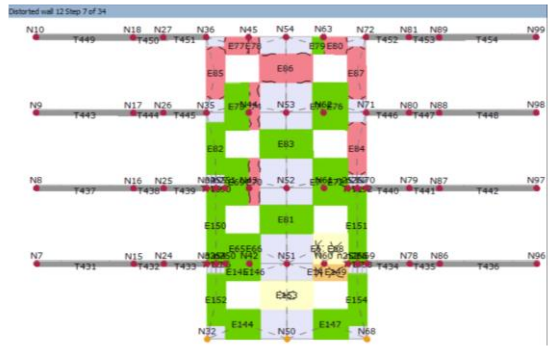
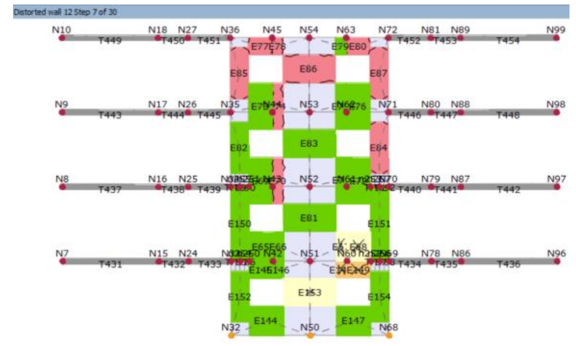
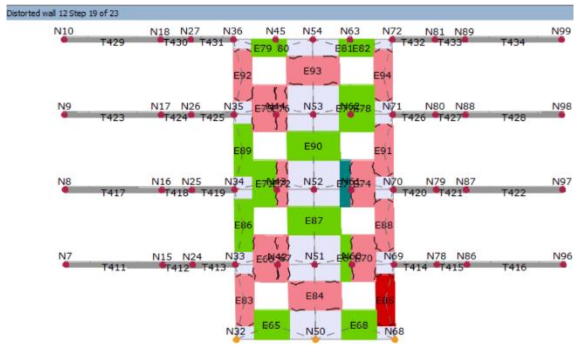
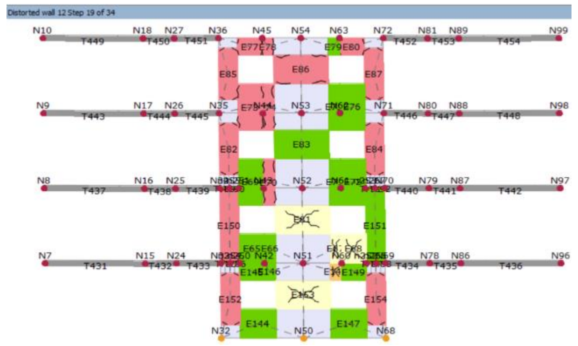
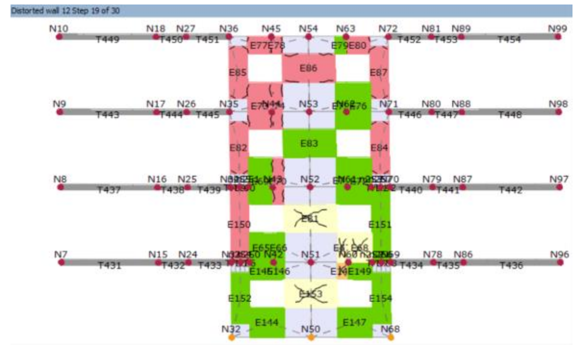
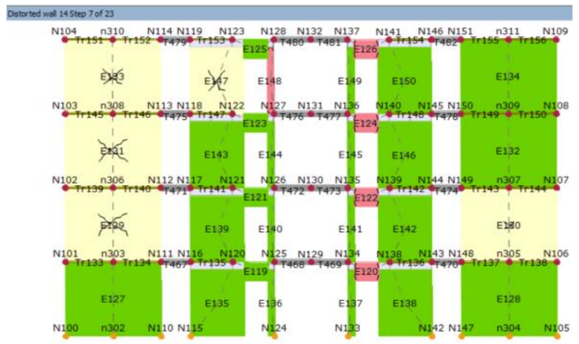
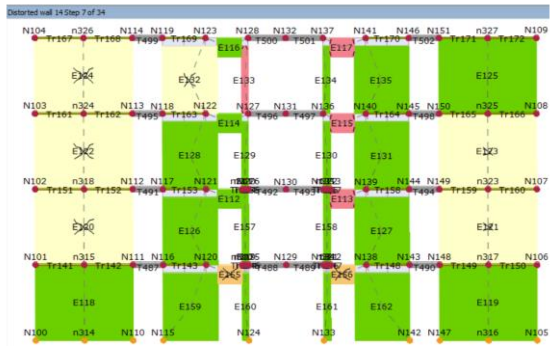
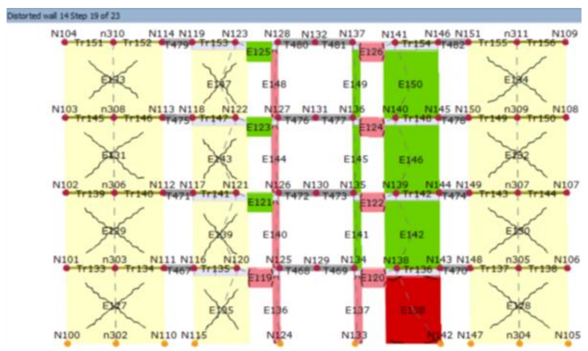
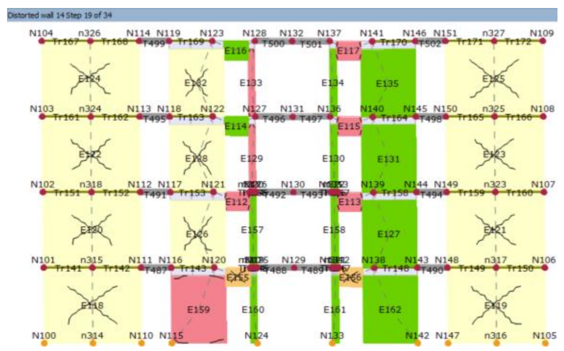
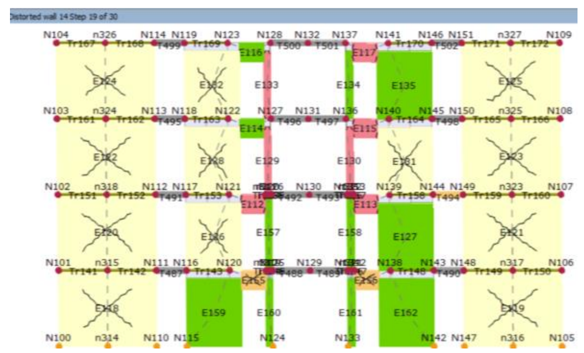
(0.56 cm; 120575 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick	
		damaged area [m2]	failed area [m2]	damaged area [m2]	failed area [m2]
Wall 1		0.00	0.00		
Wall 2				0.00	0.59
Wall 3				0.00	0.00
Wall 4				0.00	0.00
Wall 5				0.00	0.00
Wall 6				0.00	0.00
Wall 7				0.00	0.00
Wall 8				0.00	0.00
Wall 9				0.00	0.00
Wall 10				5.52	0.00
Wall 11				12.45	0.00
Wall 12		11.50	0.78		
Wall 13		45.28	0.00		
Wall 14				54.03	1.18
Wall 15		2.92	0.00		
(0.80 cm; 140445 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick	
		damaged area [m2]	failed area [m2]	damaged area [m2]	failed area [m2]
Wall 1		0.00	0.00		
Wall 2				0.00	0.00
Wall 3				0.00	0.00
Wall 4				0.00	0.00
Wall 5				0.00	0.00
Wall 6				0.00	0.00
Wall 7				0.00	0.00
Wall 8				0.00	0.00
Wall 9				0.00	0.00
Wall 10				5.52	0.00
Wall 11				12.45	0.00
Wall 12		13.44	0.78		
Wall 13		72.01	0.00		
Wall 14				92.80	1.18
Wall 15		2.92	0.00		
(1.12 cm; 150821 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick	
		damaged area [m2]	failed area [m2]	damaged area [m2]	failed area [m2]
Wall 1		0.00	0.00		
Wall 2				1.18	0.00
Wall 3				0.00	0.00
Wall 4				0.00	0.00
Wall 5				0.00	0.00
Wall 6				0.00	0.00
Wall 7				0.00	0.00
Wall 8				0.00	0.00
Wall 9				0.00	0.00
Wall 10				5.52	0.00
Wall 11				12.45	0.00
Wall 12		15.21	0.78		
Wall 13		82.62	0.00		
Wall 14				92.80	1.18
Wall 15		5.83	0.00		

(max. force) (1.44 cm; 148614 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick	
		damaged area [m2]	failed area [m2]	damaged area [m2]	failed area [m2]
Wall 1		0.00	0.00		
Wall 2				6.75	0.00
Wall 3				0.00	0.00
Wall 4				13.45	0.00
Wall 5				0.00	0.00
Wall 6				0.00	0.00
Wall 7				0.00	0.00
Wall 8				0.00	0.00
Wall 9				0.00	0.00
Wall 10				5.52	0.00
Wall 11				12.45	0.00
Wall 12		15.86	0.78		
Wall 13		82.62	0.00		
Wall 14				92.80	1.18
Wall 15		17.50	0.35		

(failure) (1.52 cm; 144811 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick	
		damaged area [m2]	failed area [m2]	damaged area [m2]	failed area [m2]
Wall 1		0.00	0.00		
Wall 2				6.75	0.00
Wall 3				0.00	0.00
Wall 4				13.45	0.00
Wall 5				0.00	0.00
Wall 6				0.00	0.00
Wall 7				0.00	0.00
Wall 8				0.00	0.00
Wall 9				0.00	0.00
Wall 10				5.52	0.00
Wall 11				12.45	0.00
Wall 12		17.88	0.24		
Wall 13		82.62	0.00		
Wall 14				93.40	1.18
Wall 15		17.50	0.35		

(beyond failure) (1.76 cm; 145203 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick	
		damaged area [m2]	failed area [m2]	damaged area [m2]	failed area [m2]
Wall 1		0.00	0.00		
Wall 2				6.75	0.00
Wall 3				0.00	0.00
Wall 4				13.45	0.00
Wall 5				0.00	0.00
Wall 6				0.00	0.00
Wall 7				0.00	0.00
Wall 8				0.00	0.00
Wall 9				0.00	0.00
Wall 10				9.86	0.00
Wall 11				12.45	0.00
Wall 12		18.99	2.73		
Wall 13		82.62	0.00		
Wall 14				102.71	0.85
Wall 15		17.50	0.69		

Table 62: Damage states of walls 12 and 14 (partially retrofitted walls) before and after seismic retrofits

Displacement	Before retrofit	After CFRP strips retrofit (30.8 m^2):	After NSM steel reinforcement retrofit (30.8 m^2):
0.56 cm			
1.52 cm			
0.56 cm			
1.52 cm			

Appendix F

U-values after thermal retrofit:

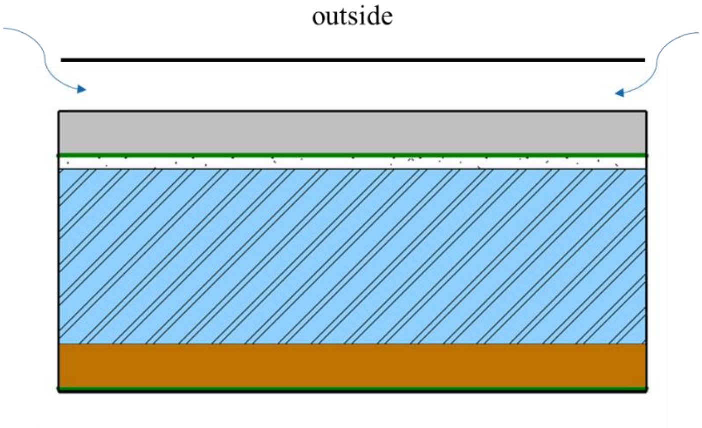


Figure 48: Wall composition after thermal retrofit (Alternative 1). From inside to outside: clay-gypsum plaster, straw panel, masonry brick, plaster, fiberglass mats, rear ventilated façade

Table 63: Structure of exterior walls and correlated U-values after the thermal retrofit (Alternative 1)

Material	Thickness [mm]	Thermal conductivity [W/(mK)]
Isover	80	0.04
Plaster	25	0.51
Brick, Engineering	320	0.81
Straw panel	**80**	**0.0405**
Gypsum plaster	**3**	**0.51**
Clay plaster	**3**	**0.75**
U-value [W/(m^{2}K)]	0.2270 <	MuKEn: 0.25

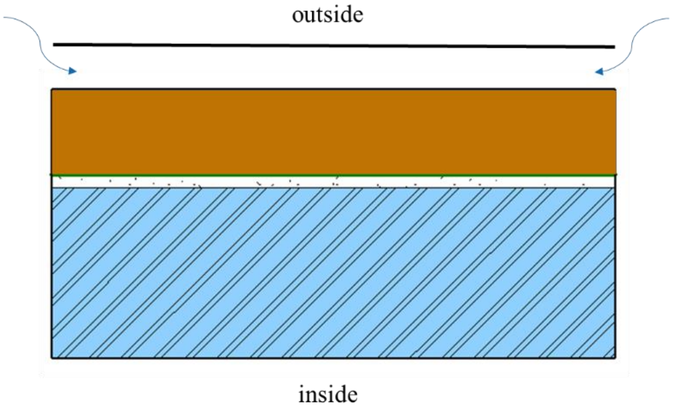


Figure 49: Wall composition after thermal retrofit (Alternative 2). From inside to outside: masonry brick, plaster, straw panel, rear ventilated façade

Table 64: Structure of exterior walls and correlated U-values after the thermal retrofit (Alternative 2)

Material	Thickness [mm]	Thermal conductivity [W/(mK)]
Straw panel	**160**	**0.0405**
Plaster	25	0.51
Brick, Engineering	320	0.81
U-value [W/(m^2K)]	0.2275 <	MuKEn: 0.25

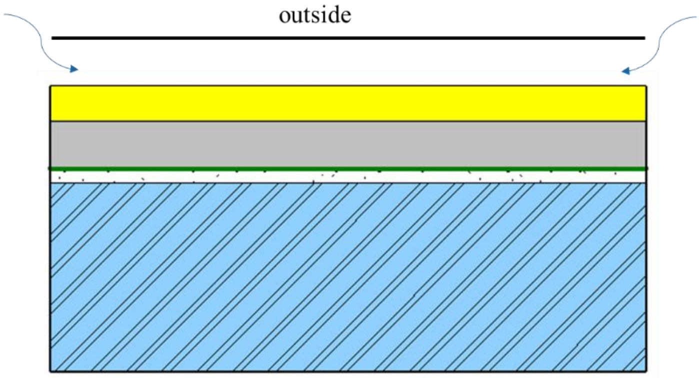


Figure 50: Wall composition after thermal retrofit (Alternative 3). From inside to outside: masonry brick, plaster, fiberglass (existing+new layer), rear ventilated façade

Table 65: Structure of exterior walls and correlated U-values after the thermal retrofit (Alternative 3)

Material	Thickness [mm]	Thermal conductivity [W/(mK)]
Isover, new layer	**59.5**	**0.03**
Isover	**80**	**0.04**
Plaster	25	0.51
Brick, Engineering	320	0.81
U-value [W/(m^{2}K)]	0.2271 <	MuKEn: 0.25

Table 66: Structure of the roof and correlated U-values after the thermal retrofit

Material	Thickness [mm]	Thermal conductivity [W/(mK)]
Sand	40	0.335
Sand	20	0.335
Roofing felt	10	0.5
Isover, new layer	**60**	**0.03**
Isover	50	0.04
Concrete, cast in situ	140	1.046
Isover	20	0.04
Plaster	12.5	0.51
U-value [W/(m^{2}K)]	0.2447 <	MuKEn: 0.25

Table 67: Structure of the windows and correlated U-values after the thermal retrofit

Material		
Triple-glazed window		
U-value [W/(m^{2}K)]	0.5678 <	MuKEn: 1.0

Appendix G

Time estimation

Sources of procedures:

Thermal intervention
Window replacement [89]
Installation watertight seal [90]

NSM steel reinforcement
Installation NSM reinforcement [60]

CFRP strips
Installation CFRP strips [91]

Table 68: Schedule for thermal intervention (Alternative 2 applied on walls, windows, roof)

ID	Task Mode	Task Name	Duration	Start	Finish	Predecessors	Successors	Resource Names
1		Site installation, preparation of works	2 days	Mon 01.08.22	Tue 02.08.22		2	Worker Team
2		Scaffold installation	2 days	Wed 03.08.2	Thu 04.08.22	1	6;4;5;3;8	Worker Team
3		Temporary roof railing installation	0.5 days	Fri 05.08.22	Fri 05.08.22	2	13	Worker Team[40%]
4		Dismounting of window sills	0.2 days	Thu 08.09.22	Thu 08.09.22	2	19	Worker Team[20%]
5		Replacement of windows (3.25h/window, 42 windows)	16.8 days	Fri 02.09.22	Mon 26.09.22	2	19	Worker Team[40%]
6		Dismounting of rear ventilated façade panels	2 days	Fri 05.08.22	Mon 08.08.22	2	7	Worker Team[40%]
7		Dismounting Isover fiberglass insulatic	2 days	Tue 09.08.22	Wed 10.08.2	6	9	Worker Team[40%]
8		Cut straw insulation panels to fit	1 day	Fri 05.08.22	Fri 05.08.22	2	9	Worker Team[20%]
9		Affixing of straw insulation panels with mineral adhesive and	5 days	Tue 16.08.22	Mon 22.08.22	7;8	10	Worker Team
10		Affixing of straw insulation panels with dowels	2 days	Tue 23.08.22	Wed 24.08.22	9	11	Worker Team
11		Mounting of rear ventilated façade panels	4 days	Fri 02.09.22	Wed 07.09.22	10	19;12	Worker Team[60%]
12		Installation of window sills	0.5 days	Thu 08.09.22	Thu 08.09.22	11	19	Worker Team[20%]
13		Removal of gravel and sand layers from roof	1 day	Thu 11.08.22	Thu 11.08.22	3	14	Worker Team[80%]
14		Removal of watertight roof seal	2 days	Fri 12.08.22	Mon 15.08.2	13	15	Worker Team[60%]
15		Installation of fiberglass insulation ma	3 days	Thu 25.08.22	Mon 29.08.2	14	16	Worker Team[60%]
16		Installation of watertight roof seal	2 days	Tue 30.08.22	Wed 31.08.2	15	17	Worker Team[60%]
17		Filling up with sand and gravel layer on the roof	1 day	Thu 01.09.22	Thu 01.09.22	16	18	Worker Team[60%]
18		Temporary roof railing dismounting	0.5 days	Thu 08.09.22	Thu 08.09.22	17	19	Worker Team[20%]
19		Scaffold dismounting	1.5 days	Mon 26.09.2	Wed 28.09.2	11;18;5;4;12	20	Worker Team
20		Site cleaning, conclusion of works	2 days	Wed 28.09.2	Fri 30.09.22	19		Worker Team

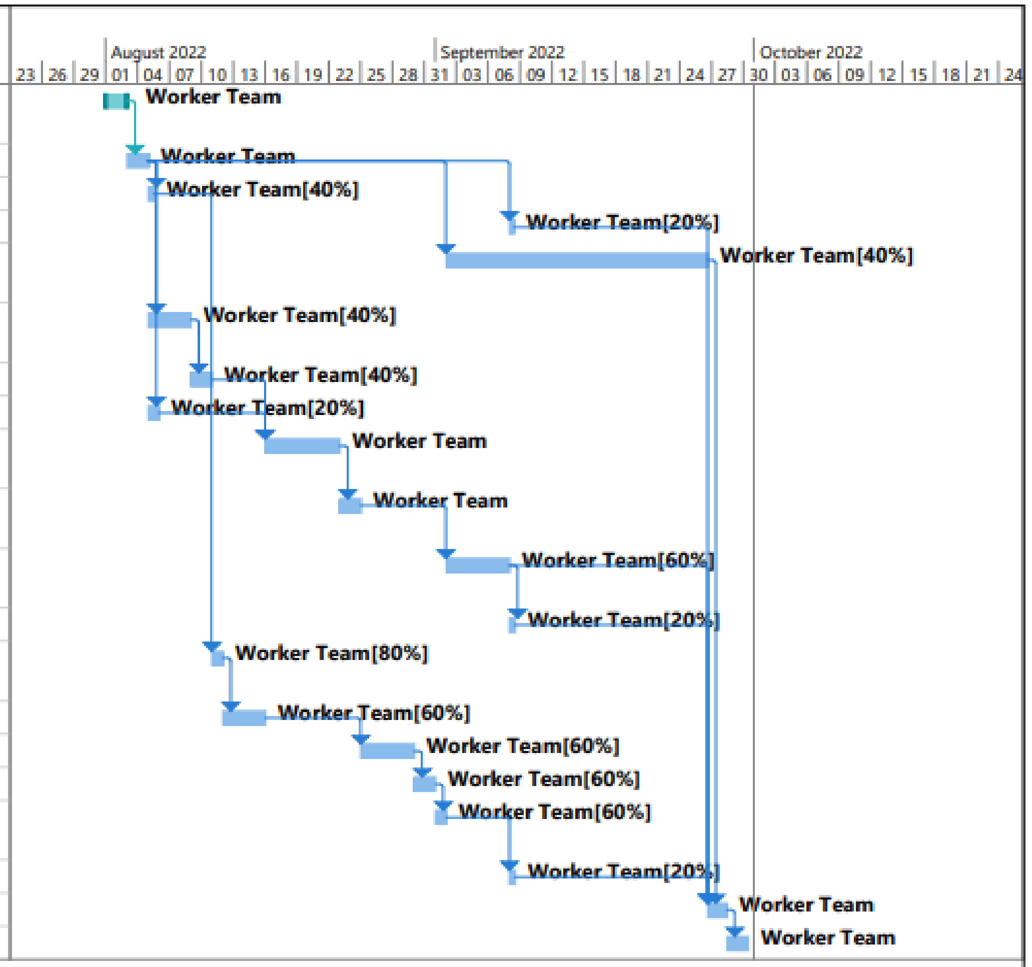
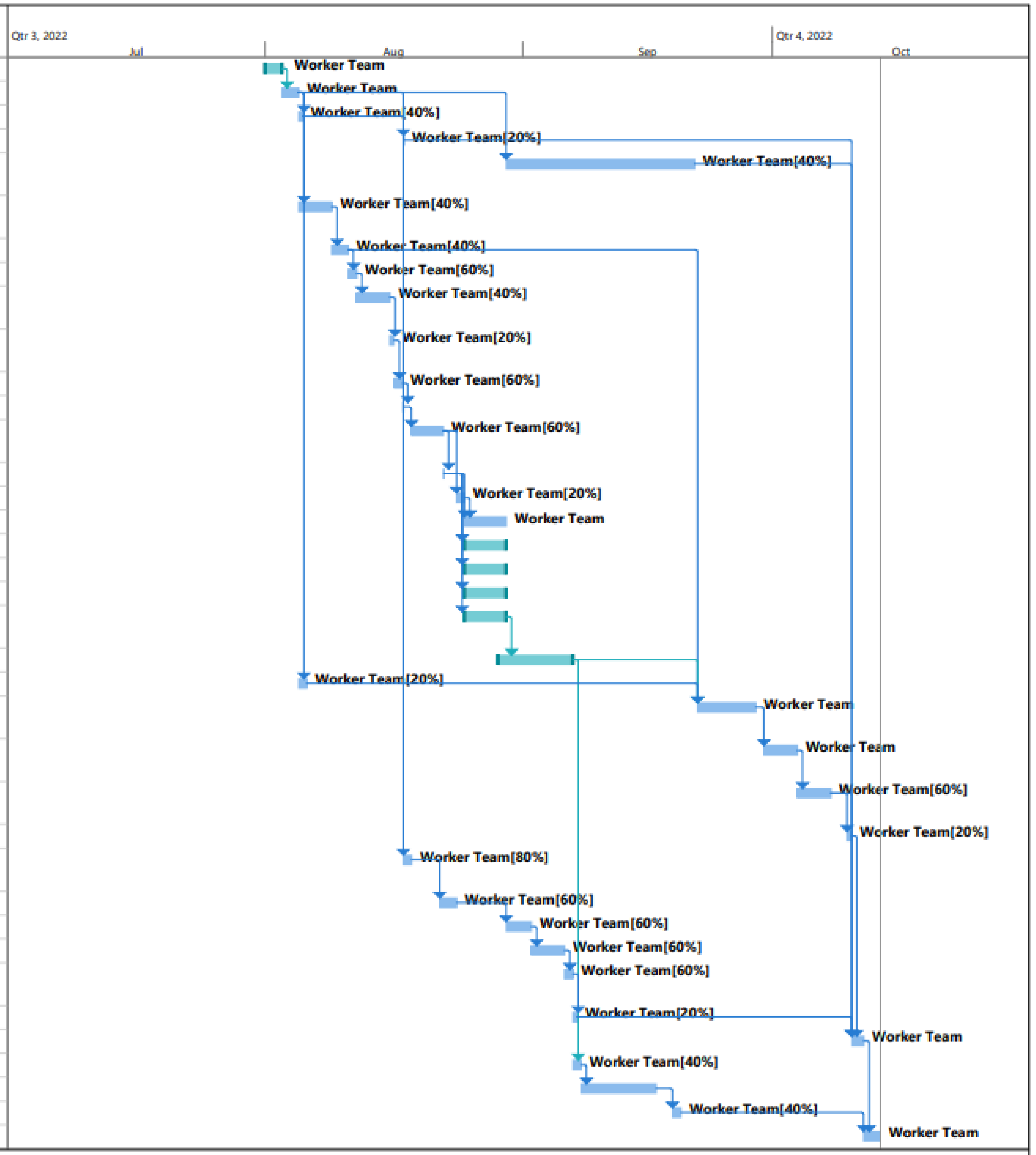


Table 69: Schedule for combined thermal (Alternative 2 applied on walls, windows, roof) and seismic (CFRP strips, 30.8 m²) intervention

ID	Task Mode	Task Name	Duration	Start	Finish	Predecessors	Successors
1		Site installation, preparation of works	2 days	Mon 01.08.22	Tue 02.08.22		2
2		Scaffold installation	2 days	Wed 03.08.22	Thu 04.08.22	1	6;4;5;3;22
3		Temporary roof railing installation	0.5 days	Fri 05.08.22	Fri 05.08.22	2	27
4		Dismounting of window sills	0.2 days	Wed 17.08.22	Wed 17.08.22	2	33
5		Replacement of windows (3.25h/window, 42 windows)	16.8 days	Tue 30.08.22	Wed 21.09.22	2	33
6		Dismounting of rear ventilated façade panels	2 days	Fri 05.08.22	Mon 08.08.22	2	7
7		Dismounting Isover fiberglass insulatic	2 days	Tue 09.08.22	Wed 10.08.22	6	23;8
8		Removal of coating/plaster	1 day	Thu 11.08.22	Thu 11.08.22	7	9
9		Polishing of masonry wall and removal of angles	2 days	Fri 12.08.22	Mon 15.08.22	8	10
10		Cleaning masonry wall surface with compressed air and dry wall surface	0.5 days	Tue 16.08.22	Tue 16.08.22	9	11
11		Application of primer adhesive	1 day	Tue 16.08.22	Wed 17.08.22	10	12
12		Touch dry time of primer adhesive	0.25 days	Wed 17.08.22	Wed 17.08.22	11	13
13		Filling up of joints and irregularities with putty	1.5 days	Thu 18.08.22	Mon 22.08.22	12	14;15
14		Touch dry time of levelling adhesive	0.25 days	Mon 22.08.22	Mon 22.08.22	13	16;17;18;19;20
15		Cutting of CFRP strips	1 day	Wed 24.08.22	Wed 24.08.22	13	16
16		Mixing of epoxy adhesive	3 days	Thu 25.08.22	Mon 29.08.22	14;15	
17		Application of impregnation adhesive	3 days	Thu 25.08.22	Mon 29.08.22	14	
18		Installation of CFRP strips	3 days	Thu 25.08.22	Mon 29.08.22	14	
19		Levelling of CFRP surface strips	3 days	Thu 25.08.22	Mon 29.08.22	14	
20		Application of impregnation adhesive (epoxy) on CFRP	3 days	Thu 25.08.22	Mon 29.08.22	14	21
21		Curing of impregnation adhesive	7 days	Mon 29.08.22	Tue 06.09.22	20	23;34
22		Cut straw insulation panels to fit	1 day	Fri 05.08.22	Fri 05.08.22	2	23
23		Affixing of straw insulation panels with mineral adhesive and	5 days	Thu 22.09.22	Wed 28.09.22	7;21;22	24
24		Affixing of straw insulation panels with dowels	2 days	Fri 30.09.22	Mon 03.10.22	23	25
25		Mounting of rear ventilated façade panels	4 days	Tue 04.10.22	Fri 07.10.22	24	33;26
26		Installation of window sills	0.5 days	Mon 10.10.22	Mon 10.10.22	25	33
27		Removal of gravel and sand layers from roof	1 day	Wed 17.08.22	Thu 18.08.22	3	28
28		Removal of watertight roof seal	2 days	Mon 22.08.22	Tue 23.08.22	27	29
29		Installation of fiberglass insulation ma	3 days	Tue 30.08.22	Thu 01.09.22	28	30
30		Installation of watertight roof seal	2 days	Fri 02.09.22	Mon 05.09.22	29	31
31		Filling up with sand and gravel layer on the roof	1 day	Tue 06.09.22	Tue 06.09.22	30	32
32		Temporary roof railing dismounting	0.5 days	Wed 07.09.22	Wed 07.09.22	31	33
33		Scaffold dismounting	1.5 days	Mon 10.10.22	Tue 11.10.22	25;32;5;4;26	37
34		Interior wall plastering	1 day	Wed 07.09.22	Wed 07.09.22	21	35
35		Curing of plaster	7 days	Thu 08.09.22	Fri 16.09.22	34	36
36		Interior wall painting	1 day	Mon 19.09.22	Mon 19.09.22	35	37
37		Site cleaning, conclusion of works	2 days	Wed 12.10.22	Thu 13.10.22	36;33	



Project: Schedule_Thermal inter
Date: Wed 01.06.22

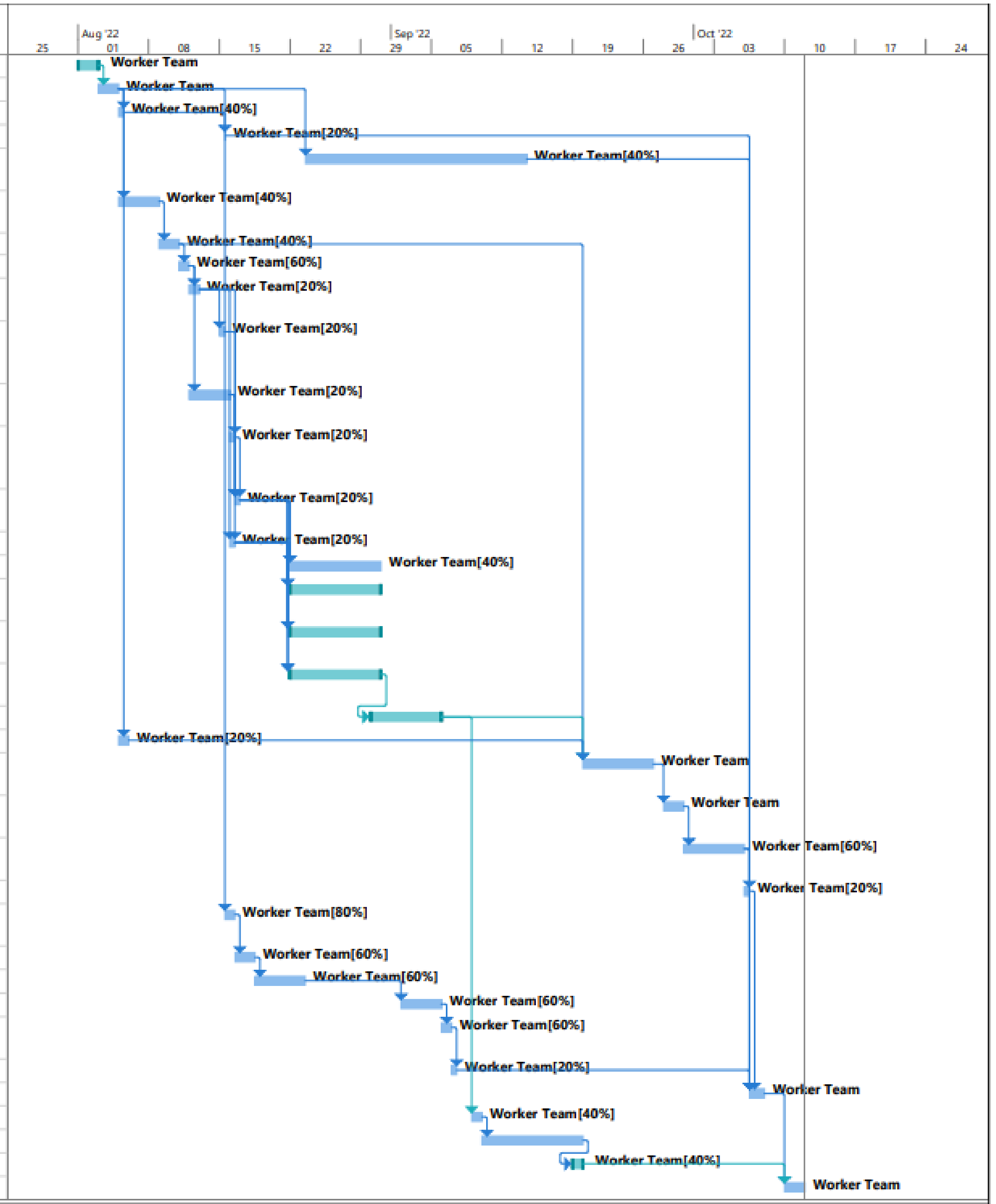
Task		Project Summary		Manual Task		Start-only	
Split		Inactive Task		Duration-only		Finish-only	
Milestone		Inactive Milestone		Manual Summary Rollup		External Tasks	
Summary		Inactive Summary		Manual Summary		External Milestone	

Deadline
Progress
Manual Progress

Page 1

Table 70: Schedule for combined thermal (Alternative 2 applied on walls, windows, roof) and seismic (NSM steel reinforcement, 30.8 m^2) intervention

ID	Task Mode	Task Name	Duration	Start	Finish	Predecessors	Successors	Resource Names
1		Site installation, preparation of works	2 days	Mon 01.08.22	Tue 02.08.22		2	Worker Team
2		Scaffold installation	2 days	Wed 03.08.22	Thu 04.08.22	1	6;4;5;3;20	Worker Team
3		Temporary roof railing installation	0.5 days	Fri 05.08.22	Fri 05.08.22	2	25	Worker Team[40%]
4		Dismounting of window sills	0.2 days	Mon 15.08.22	Mon 15.08.22	2	31	Worker Team[20%]
5		Replacement of windows (3.25h/window, 42 windows)	16.8 days	Tue 23.08.22	Wed 14.09.22	2	31	Worker Team[40%]
6		Dismounting of rear ventilated façade panels	2 days	Fri 05.08.22	Mon 08.08.22	2	7	Worker Team[40%]
7		Dismounting Isover fiberglass insulatic	2 days	Tue 09.08.22	Wed 10.08.22	6	21;8	Worker Team[40%]
8		Removal of coating/plaster	1 day	Thu 11.08.22	Thu 11.08.22	7	9;11	Worker Team[60%]
9		Horizontal saw cutting of grooves through bed joints	1 day	Fri 12.08.22	Fri 12.08.22	8	13;14;10	Worker Team[20%]
10		Drill holes at vertical wall ends at heigths of horizontal grooves (anchorage for steel rebars)	0.5 days	Mon 15.08.22	Mon 15.08.22	9	13	Worker Team[20%]
11		Vertical saw cutting through bricks and head joints	2 days	Fri 12.08.22	Mon 15.08.22	8	13;14;12	Worker Team[20%]
12		Drill holes at horizontal wall ends at locations of vertical grooves (anchorage for steel rebars)	0.5 days	Tue 16.08.22	Tue 16.08.22	11	13	Worker Team[20%]
13		Cleaning of grooves and holes with compressed air	0.5 days	Tue 16.08.22	Tue 16.08.22	9;10;11;12	18;16;17;15	Worker Team[20%]
14		Cleaning of reinforcement bars	0.5 days	Tue 16.08.22	Tue 16.08.22	9;11	18;16;17;15	Worker Team[20%]
15		Mixing of epoxy resin	7 days	Mon 22.08.22	Tue 30.08.22	13;14		Worker Team[40%]
16		Partial filling of grooves and holes with epoxy	7 days	Mon 22.08.22	Tue 30.08.22	13;14		
17		Placing and pressing steel reinforcement into the grooves	7 days	Mon 22.08.22	Tue 30.08.22	13;14		
18		Filling and surface finishing of grooves (remove excess epoxy)	7 days	Mon 22.08.22	Tue 30.08.22	13;14	19	
19		Curing of epoxy resin	5 days	Tue 30.08.22	Mon 05.09.22	18	32;21	
20		Cut straw insulation panels to fit	1 day	Fri 05.08.22	Fri 05.08.22	2	21	Worker Team[20%]
21		Affixing of straw insulation panels with mineral adhesive and	5 days	Tue 20.09.22	Mon 26.09.22	7;20;19	22	Worker Team
22		Affixing of straw insulation panels with dowels	2 days	Wed 28.09.22	Thu 29.09.22	21	23	Worker Team
23		Mounting of rear ventilated façade panels	4 days	Fri 30.09.22	Wed 05.10.22	22	31;24	Worker Team[60%]
24		Installation of window sills	0.5 days	Thu 06.10.22	Thu 06.10.22	23	31	Worker Team[20%]
25		Removal of gravel and sand layers from roof	1 day	Mon 15.08.22	Tue 16.08.22	3	26	Worker Team[80%]
26		Removal of watertight roof seal	2 days	Tue 16.08.22	Thu 18.08.22	25	27	Worker Team[60%]
27		Installation of fiberglass insulation ma	3 days	Thu 18.08.22	Tue 23.08.22	26	28	Worker Team[60%]
28		Installation of watertight roof seal	2 days	Fri 02.09.22	Mon 05.09.22	27	29	Worker Team[60%]
29		Filling up with sand and gravel layer on the roof	1 day	Tue 06.09.22	Tue 06.09.22	28	30	Worker Team[60%]
30		Temporary roof railing dismounting	0.5 days	Wed 07.09.22	Wed 07.09.22	29	31	Worker Team[20%]
31		Scaffold dismounting	1.5 days	Thu 06.10.22	Fri 07.10.22	23;30;5;4;24	35	Worker Team
32		Interior wall plastering	1 day	Fri 09.09.22	Fri 09.09.22	19	33	Worker Team[40%]
33		Curing of plaster	7 days	Sat 10.09.22	Mon 19.09.22	32	34	
34		Interior wall painting	1 day	Mon 19.09.22	Mon 19.09.22	33	35	Worker Team[40%]
35		Site cleaning, conclusion of works	2 days	Mon 10.10.22	Tue 11.10.22	34;31		Worker Team



Project: Schedule_Thermal inter
Date: Wed 01.06.22

Task, Split, Milestone, Summary, Project Summary, Inactive Task, Inactive Milestone, Inactive Summary, Manual Task, Duration-only, Manual Summary Rollup, Manual Summary, Start-only, Finish-only, External Tasks, External Milestone, Deadline, Progress, Manual Progress

Page 1

Appendix H

Cost estimation

Sources of prices:

Thermal intervention	
Disposal of building materials	[92]
Scaffold installation	[93]
Temporary roof railing installation + rental	[94]
Windows installation	[95]
Windows disposal	[95]
Straw insulation panels	[96]
Cement mortar	[97]
Dowels	[98]
Insulation panel fiberglass (Isover)	[99]
Watertight seal	[100]
Sand	[101]

NSM steel reinforcement	
Epoxy resin	[102]
Steel rebar	[103]
Interior plaster	[104]
Interior wall paint	[105]

CFRP strips	
Primer adhesive	[106]
Putty	[107]
Impregnation epoxy	[108]
CFRP textile	[109]

Table 71: Cost estimation for thermal intervention (Alternative 2 applied on walls, windows, roof)

Work Breakdown Structure						Unit cost		Extent		Quantity	Total material + rental [CHF]	Unit price [CHF/h]	Duration [d]	Duration [h]	Quantity workers	Total [CHF]	Total material + rental + work [CHF]	Remarks
1	Thermal retrofit	1.1	Preparation	1.1.1	Site installation, preparation of works	-		-		-	-	90	2.00	16	5	7'200	7'200	
				1.1.2	Scaffold installation + rental	35	CHF/m2	547	m2	1	19'145	90	2.00	16	5	7'200	26'345	35 CHF/m2* 547m2
				1.1.3	Temporary roof railing installation + rental	45	CHF/m			22	990	90	0.50	4	2	720	1'710	45 CHF/element*60.3m/2.8m/element
		1.2	Windows	1.2.1	Dismounting of window sills						-	90	0.20	2	1	144	144	
				1.2.2	Replacement of windows (3.25h/window, 42 windows)	800	CHF/windo			42	33'600	90	16.80	134	2	24'192	57'792	Triple glazing window + disposal 120 CHF/window
		1.3	Facade	1.3.1	Dismounting of rear ventilated façade panels						-	90	2.00	16	2	2'880	2'880	
				1..3.2	Dismounting Isover fiberglass insulation	85	CHF/m3	44	m3	44	3'740	90	2.00	16	2	2'880	6'620	Disposal 85CHF/m3 547 m2*0.08m
				1.3.3	Cut straw insulation panels to fit						-	90	1.00	8	1	720	720	
				1.3.4	Affixing of straw insulation panels with mineral adhesive and reinforcing mortar	25	CHF/m2	547	m2		13'675	90	5.00	40	5	18'000	31'675	straw insulation panels: 20 CHF/m2
				1.3.5	Affixing of straw insulation panels with dowels	1	CHF/piece			2'200	2'200	90	2.00	16	5	7'200	9'400	dowels: 1 CHF/piece
				1.3.6	Mounting of rear ventilated façade panels						-	90	4.00	32	3	8'640	8'640	
				1.3.7	Installation of window sills						-	90	0.50	4	1	360	360	
		1.4	Roof	1.4.1	Removal of gravel and sand layers from roof	42	CHF/m3	12	m3	12	504	90	1.00	8	4	2'880	3'384	Disposal 42 CHF/m3 199 m2*0.06m
				1.4.2	Removal of watertight roof seal	85	CHF/m3	2	m3	2	170	90	2.00	16	3	4'320	4'490	Disposal 85 CHF/m3 199 m2*0.01m
				1.4.3	Installation of fiberglass insulation mats	25	CHF/m2	199	m2	199	4'975	90	3.00	24	5	10'800	15'775	
				1.4.4	Installation of watertight roof seal	9	CHF/m2	199	m2	199	4'975	90	2.00	16	3	4'320	9'295	
				1.4.5	Filling up with sand and gravel layer on the roof	0.25	CHF/kg	30'000	kg	30'000	7'500	90	1.00	8	3	2'160	9'660	199 m2*0.06m*2400 kg/m3
				1.4.6	Temporary roof railing dismounting						-	90	0.50	4	1	360	360	
		1.5	Conclusion of works	1.5.1	Scaffold dismounting						-	90	1.50	12	5	5'400	5'400	
				1.5.2	Site cleaning, conclusion of works						-	90	2.00	16	5	7'200	7'200	
Total construction costs (material+rental+work)																	**209'050**	
Indirect costs 10%																	**20'905**	
Engineering 5%																	**10'453**	
Markup (profit 5% + contingency 7%)																	**25'086**	
VAT 7.7%																	**16'097**	
Total																	**281'590**	

Disposal costs

Table 72: Cost estimation for combined thermal (Alternative 2 applied on walls, windows, roof) and seismic (CFRP strips, 30.8 m^2) intervention

Work Breakdown Structure						Unit cost		Extent		Quantity	Total material + rental [CHF]	Hourly cost [CHF/h]	Duration [d]	Duration [h]	Quantity workers	Total work [CHF]	Total material + rental + work [CHF]	Remarks
1	Thermal retrofit	1.1	Preparation	1.1.1	Site installation, preparation of works	-		-		-	-	90	2.00	16	5	7'200	7'200	
				1.1.2	Scaffold installation + rental	35	CHF/m2	547	m2	1	19'145	90	2.00	16	5	7'200	26'345	35 CHF/m2* 547m2
				1.1.3	Temporary roof railing installation + rental	45	CHF/m			22	990	90	0.50	4	2	720	1'710	45 CHF/element*60.3m/2.8m/element
		1.2	Windows	1.2.1	Dismounting of window sills						-	90	0.20	2	1	144	144	
				1.2.2	Replacement of windows (3.25h/window, 42 windows)	800	CHF/window			42	33'600	90	16.80	134	2	24'192	57'792	Triple glazing window + disposal 120 CHF/window
		1.3	Facade	1.3.1	Dismounting of rear ventilated façade panels						-	90	2.00	16	2	2'880	2'880	
				1..3.2	Dismounting Isover fiberglass insulation	85	CHF/m3	44	m3	44	3'740	90	2.00	16	2	2'880	6'620	Disposal 85CHF/m3 547 m2*0.08m
				1.3.3	Cut straw insulation panels to fit						-	90	1.00	8	1	720	720	
				1.3.4	Affixing of straw insulation panels with mineral adhesive and reinforcing mortar	25	CHF/m2	547	m2	547	13'675	90	5.00	40	5	18'000	31'675	straw insulation panels: 20
				1.3.5	Affixing of straw insulation panels with dowels	1	CHF/piece			2'200	2'200	90	2.00	16	5	7'200	9'400	dowels: 1 CHF/piece
				1.3.6	Mounting of rear ventilated façade panels						-	90	4.00	32	3	8'640	8'640	
				1.3.7	Installation of window sills						-	90	0.50	4	1	360	360	
		1.4	Roof	1.4.1	Removal of gravel and sand layers from roof	42	CHF/m3	12	m3	12	504	90	1.00	8	4	2'880	3'384	Disposal 42 CHF/m3 199 m2*0.06m
				1.4.2	Removal of watertight roof seal	85	CHF/m3	2	m3	2	170	90	2.00	16	3	4'320	4'490	Disposal 85 CHF/m3 199 m2*0.01m
				1.4.3	Installation of fiberglass insulation mats	25	CHF/m2	199	m2	199	4'975	90	3.00	24	5	10'800	15'775	
				1.4.4	Installation of watertight roof seal	9	CHF/m2	199	m2	199	4'975	90	2.00	16	3	4'320	9'295	
				1.4.5	Filling up with sand and gravel layer on the roof	0.25	CHF/kg	30'000	kg	30'000	7'500	90	1.00	8	3	2'160	9'660	199 m2*0.06m*2400 kg/m3
				1.4.6	Temporary roof railing dismounting						-	90	0.50	4	1	360	360	
2	Seismic retrofit	2.1	Walls	2.1.1	Removal of coating/plaster	20	CHF/m3	14	m3	14	280	90	1	8	3	2'160	2'440	Disposal 20 CHF/m3 547 m2*0.025m
				2.1.2	Polishing of masonry wall and removal of angles						-	90	2	16	2	2'880	2'880	
				2.1.3	Cleaning masonry wall surface with compressed air and dry wall surface						-	90	0.5	4	1	360	360	
				2.1.4	Application of primer adhesive	4.5	CHF/m2	31	m2	31	140	90	1	8	3	2'160	2'300	8.5CHF/l*0.5l/m2*31m2
				2.1.5	Touch dry time of primer adhesive							90	0.25	2		-	-	
				2.1.6	Filling up of joints and irregularities with putty (levelling adhesive)	60	CHF/m2	31	m2	31	1'860	90	1.5	12	3	3'240	5'100	20CHF/l*3l/m2*31m2
				2.1.7	Touch dry time of levelling adhesive							90	0.25	2		-	-	
				2.1.8	Cutting of CFRP strips							90	1	8	1	720	720	
				2.1.9	Mixing of epoxy adhesive							90	3	24	5	10'800	10'800	
				2.1.10	Application of impregnation adhesive	30	CHF/m2	31	m2	31	930	90	3	24		-	930	30CHF/l*1l/m2*31m2
				2.1.11	Installation of CFRP strips	75	CHF/m2	31	m2	31	2'325	90	3	24		-	2'325	75 CHF/m2*31m2
				2.1.12	Levelling of CFRP surface strips							90	3	24		-	-	
				2.1.13	Application of impregnation adhesive (epoxy) on CFRP	60	CHF/m2	31	m2	31	1'860	90	3	24		-	1'860	30CHF/l*2l/m2*31m2
				2.1.14	Curing of impregnation adhesive							90	7	56		-	-	
3	Conclusion of works	3.1	Conclusion of works	3.1.1	Scaffold dismounting						-	90	1.50	12	5	5'400	5'400	
				3.1.2	Interior wall plastering	1.50	CHF/m2	14	m2	14	28	90	1.00	8	2	1'440	1'468	0.40 CHF/kg * 3.6 kg/m2 * 14 m2
				3.1.3	Curing of plaster							90	7.00	56		-	-	
				3.1.4	Interior wall painting	0.60	CHF/m2	14	m2	14	14	90	1.00	8	2	1'440	1'454	4 CHF/l*0.15 l/m2*14 m2
				1.5.2	Site cleaning, conclusion of works						-	90	2.00	16	5	7'200	7'200	
Total construction costs (material+rental+work)																	241'687	
Indirect costs 10%																	24'169	
Engineering 5%																	12'084	
Markup (profit 5% + contingency 7%)																	29'002	
VAT 7.7%																	18'610	
Total																	325'552	

Disposal costs

Table 73: Cost estimation for combined thermal (Alternative 2 applied on walls, windows, roof) and seismic (NSM steel reinforcement, 30.8 m²) intervention

Work Breakdown Structure						Unit cost		Extent		Quantity	Total material + rental [CHF]	Unit price [CHF/h]	Duration [d]	Duration [h]	Quantity workers	Total [CHF]	Total material + rental + work	Remarks
1	Thermal retrofit	1.1	Preparation	1.1.1	Site installation, preparation of works	-		-		-	-	90	2.00	16	5	7'200	7'200	
				1.1.2	Scaffold installation + rental	35	CHF/m2	547	m2	1	19'145	90	2.00	16	5	7'200	26'345	35 CHF/m2* 547m2
				1.1.3	Temporary roof railing installation + rental	45	CHF/m			22	990	90	0.50	4	2	720	1'710	CHF/element*60.3m/2.8m/element
		1.2	Windows	1.2.1	Dismounting of window sills						-	90	0.20	2	1	144	144	
				1.2.2	Replacement of windows (3.25h/window, 42 windows)	800	CHF/window			42	33'600	90	16.80	134	2	24'192	57'792	ndow + disposal 120 CHF/window
		1.3	Facade	1.3.1	Dismounting of rear ventilated façade panels						-	90	2.00	16	2	2'880	2'880	
				1..3.2	Dismounting Isover fiberglass insulation	85	CHF/m3	44	m3	44	3'740	90	2.00	16	2	2'880	6'620	Disposal 85CHF/m3 547 m2*0.08m
				1.3.3	Cut straw insulation panels to fit						-	90	1.00	8	1	720	720	
				1.3.4	Affixing of straw insulation panels with mineral adhesive and reinforcing mortar	25	CHF/m2	547	m2	547	13'675	90	5.00	40	5	18'000	31'675	raw insulation panels: 20 CHF/m2
				1.3.5	Affixing of straw insulation panels with dowels	1	CHF/piece			2'200	2'200	90	2.00	16	5	7'200	9'400	dowels: 1 CHF/piece
				1.3.6	Mounting of rear ventilated façade panels						-	90	4.00	32	3	8'640	8'640	
				1.3.7	Installation of window sills						-	90	0.50	4	1	360	360	
		1.4	Roof	1.4.1	Removal of gravel and sand layers from roof	42	CHF/m3	12	m3	12	504	90	1.00	8	4	2'880	3'384	Disposal 42 CHF/m3 199 m2*0.06m
				1.4.2	Removal of watertight roof seal	85	CHF/m3	2	m3	2	170	90	2.00	16	3	4'320	4'490	Disposal 85 CHF/m3 199 m2*0.01m
				1.4.3	Installation of fiberglass insulation mats	25	CHF/m2	199	m2	199	4'975	90	3.00	24	5	10'800	15'775	
				1.4.4	Installation of watertight roof seal	9	CHF/m2	199	m2	199	4'975	90	2.00	16	3	4'320	9'295	
				1.4.5	Filling up with sand and gravel layer on the roof	0.25	CHF/kg	30'000	kg	30'000	7'500	90	1.00	8	3	2'160	9'660	199 m2*0.06m*2400 kg/m3
				1.4.6	Temporary roof railing dismounting						-	90	0.50	4	1	360	360	
2	Seismic retrofit	2.1	Walls	2.1.1	Removal of coating/plaster	20	CHF/m3	14	m3	14	280	90	1	8	3	2'160	2'440	Disposal 20 CHF/m3 547 m2*0.025m
				2.1.2	Horizontal saw cutting of grooves through bed joints							90	1	8	1	720	720	
				2.1.3	Drill holes at vertical wall ends at heights of horizontal grooves (anchorage for steel rebars)							90	0.5	4	1	360	360	
				2.1.4	Vertical saw cutting through bricks and head joints							90	2	16	1	1'440	1'440	
				2.1.5	Drill holes at horizontal wall ends at locations of vertical grooves (anchorage for steel rebars)							90	0.5	4	1	360	360	
				2.1.6	Cleaning of grooves and holes with compressed air							90	0.5	4	1	360	360	
				2.1.7	Cleaning of reinforcement bars							90	0.5	4	1	360	360	
				2.1.8	Mixing of epoxy resin	75	CHF/l	0.06	m3	0.06	4'650	90	7	56	2	10'080	14'730	70 CHF/l*102 m * 0.04m*0.015
				2.1.9	Partial filling of grooves and holes with epoxy						-	90	7	56			-	
				2.1.10	Placing and pressing steel reinforcement into the grooves	6	CHF/m	102	m	102	612	90	7	56			612	3 CHF/m * 102 m
				2.1.11	Filling and surface finishing of grooves (remove excess epoxy)							90	7	56			-	
				2.1.12	Curing of epoxy resin							90	7	56			-	
3	Conclusion of works	3.1	Conclusion of works	3.1.1	Scaffold dismounting						-	90	1.50	12	5	5'400	5'400	
				3.1.2	Interior wall plastering	1.50	CHF/m2	14	m2	14	28	90	1.00	8	2	1'440	1'468	0.40 CHF/kg * 3.6 kg/m2 * 14 m2
				3.1.3	Curing of plaster								7.00	56		-	-	
				3.1.4	Interior wall painting	0.60	CHF/m2	14	m2	14	14	90	1.00	8	2	1'440	1'454	4 CHF/l*0.15 l/m2*14 m2
				3.1.5	Site cleaning, conclusion of works						-	90	2.00	16	5	7'200	7'200	
Total construction costs (material+rental+work)																	233'354	
Indirect costs 10%																	23'335	
Engineering 5%																	11'668	
Markup (profit 5% + contingency 7%)																	28'002	
VAT 7.7%																	17'968	
Total																	314'328	

Disposal costs

Appendix J

Table 74: After optimised seismic retrofit with NSM steel reinforcement (54.2 m^2): calculation of damaged or failed walls (perimeter and area) for the estimation of CO_2 emissions from repair/replacement works

(0.08 cm; 20669 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick		standard walls 8" (=0.2032 m) to 12" (=0.3048) thick [-]		standard walls 4" (=0.1016 m) to 6" (=0.1524 m) thick [-]	
		damaged perimeter [m]	failed area [m2]	damaged perimeter [m]	failed area [m2]	damaged standard walls [-]	failed standard walls [-]	damaged standard walls [-]	failed standard walls [-]
Wall 1		0.00	0.00			0.00	0.00	0.00	0.00
Wall 2				0.00	0.59	0.00	0.00	0.00	0.04
Wall 3				0.00	0.00	0.00	0.00	0.00	0.00
Wall 4				0.00	0.00	0.00	0.00	0.00	0.00
Wall 5				0.00	0.00	0.00	0.00	0.00	0.00
Wall 6				0.00	0.00	0.00	0.00	0.00	0.00
Wall 7				0.00	0.00	0.00	0.00	0.00	0.00
Wall 8				0.00	0.00	0.00	0.00	0.00	0.00
Wall 9				0.00	0.00	0.00	0.00	0.00	0.00
Wall 10				0.00	0.59	0.00	0.00	0.00	0.04
Wall 11				0.00	0.00	0.00	0.00	0.00	0.00
Wall 12		10.08	1.55			0.66	0.11	0.00	0.00
Wall 13		8.52	0.00			0.56	0.00	0.00	0.00
Wall 14				9.30	1.18	0.00	0.00	0.61	0.08
Wall 15		0.00	0.00			0.00	0.00	0.00	0.00

(0.40 cm; 92213 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick		standard walls 8" (=0.2032 m) to 12" (=0.3048) thick [-]		standard walls 4" (=0.1016 m) to 6" (=0.1524 m) thick [-]	
		damaged perimeter [m]	failed area [m2]	damaged perimeter [m]	failed area [m2]	damaged standard walls [-]	failed standard walls [-]	damaged standard walls [-]	failed standard walls [-]
Wall 1		0.00	0.00			0.00	0.00	0.00	0.00
Wall 2				0.00	0.59	0.00	0.00	0.00	0.04
Wall 3				0.00	0.00	0.00	0.00	0.00	0.00
Wall 4				0.00	0.00	0.00	0.00	0.00	0.00
Wall 5				0.00	0.00	0.00	0.00	0.00	0.00
Wall 6				0.00	0.00	0.00	0.00	0.00	0.00
Wall 7				0.00	0.00	0.00	0.00	0.00	0.00
Wall 8				0.00	0.00	0.00	0.00	0.00	0.00
Wall 9				0.00	0.00	0.00	0.00	0.00	0.00
Wall 10				11.52	0.59	0.00	0.00	0.76	0.04
Wall 11				0.00	0.00	0.00	0.00	0.00	0.00
Wall 12		23.10	0.53			1.52	0.04	0.00	0.00
Wall 13		49.14	0.00			3.22	0.00	0.00	0.00
Wall 14				34.02	1.18	0.00	0.00	2.23	0.08
Wall 15		0.00	0.00			0.00	0.00	0.00	0.00

(0.48 cm; 106856 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick		standard walls 8" (=0.2032 m) to 12" (=0.3048) thick [-]		standard walls 4" (=0.1016 m) to 6" (=0.1524 m) thick [-]	
		damaged perimeter [m]	failed area [m2]	damaged perimeter [m]	failed area [m2]	damaged standard walls [-]	failed standard walls [-]	damaged standard walls [-]	failed standard walls [-]
Wall 1		0.00	0.00			0.00	0.00	0.00	0.00
Wall 2				0.00	0.59	0.00	0.00	0.00	0.04
Wall 3				0.00	0.00	0.00	0.00	0.00	0.00
Wall 4				0.00	0.00	0.00	0.00	0.00	0.00
Wall 5				0.00	0.00	0.00	0.00	0.00	0.00
Wall 6				0.00	0.00	0.00	0.00	0.00	0.00
Wall 7				0.00	0.00	0.00	0.00	0.00	0.00
Wall 8				0.00	0.00	0.00	0.00	0.00	0.00
Wall 9				0.00	0.00	0.00	0.00	0.00	0.00
Wall 10				11.52	0.59	0.00	0.00	0.76	0.04
Wall 11				0.00	0.00	0.00	0.00	0.00	0.00
Wall 12		30.98	0.53			2.03	0.04	0.00	0.00
Wall 13		88.38	0.00			5.80	0.00	0.00	0.00
Wall 14			0.00	55.11	1.18	0.00	0.00	3.62	0.08
Wall 15		7.56	0.00			0.50	0.00	0.00	0.00

(0.56 cm; 120521 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick		standard walls 8" (=0.2032 m) to 12" (=0.3048) thick [-]		standard walls 4" (=0.1016 m) to 6" (=0.1524 m) thick [-]	
		damaged perimeter [m]	failed area [m2]	damaged perimeter [m]	failed area [m2]	damaged standard walls [-]	failed standard walls [-]	damaged standard walls [-]	failed standard walls [-]
Wall 1		0.00	0.00			0.00	0.00	0.00	0.00
Wall 2				0.00	0.59	0.00	0.00	0.00	0.04
Wall 3				0.00	0.00	0.00	0.00	0.00	0.00
Wall 4				0.00	0.00	0.00	0.00	0.00	0.00
Wall 5				0.00	0.00	0.00	0.00	0.00	0.00
Wall 6				0.00	0.00	0.00	0.00	0.00	0.00
Wall 7				0.00	0.00	0.00	0.00	0.00	0.00
Wall 8				0.00	0.00	0.00	0.00	0.00	0.00
Wall 9				0.00	0.00	0.00	0.00	0.00	0.00
Wall 10				14.62	0.59	0.00	0.00	0.96	0.04
Wall 11				14.62	0.00	0.00	0.00	0.96	0.00
Wall 12		46.42	0.78			3.05	0.06	0.00	0.00
Wall 13		103.74	0.00			6.81	0.00	0.00	0.00
Wall 14				85.12	1.18	0.00	0.00	5.59	0.08
Wall 15		7.56	0.00			0.50	0.00	0.00	0.00

(0.80 cm; 140413 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick		standard walls 8" (=0.2032 m) to 12" (=0.3048) thick [-]		standard walls 4" (=0.1016 m) to 6" (=0.1524 m) thick [-]	
		damaged perimeter [m]	failed area [m2]	damaged perimeter [m]	failed area [m2]	damaged standard walls [-]	failed standard walls [-]	damaged standard walls [-]	failed standard walls [-]
Wall 1		0.00	0.00			0.00	0.00	0.00	0.00
Wall 2				6.20	0.00	0.00	0.00	0.41	0.00
Wall 3				0.00	0.00	0.00	0.00	0.00	0.00
Wall 4				0.00	0.00	0.00	0.00	0.00	0.00
Wall 5				0.00	0.00	0.00	0.00	0.00	0.00
Wall 6				0.00	0.00	0.00	0.00	0.00	0.00
Wall 7				0.00	0.00	0.00	0.00	0.00	0.00
Wall 8				0.00	0.00	0.00	0.00	0.00	0.00
Wall 9				0.00	0.00	0.00	0.00	0.00	0.00
Wall 10				14.62	0.59	0.00	0.00	0.96	0.04
Wall 11				14.62	0.00	0.00	0.00	0.96	0.00
Wall 12		52.24	0.78			3.43	0.06	0.00	0.00
Wall 13		166.74	0.00			10.94	0.00	0.00	0.00
Wall 14				148.04	1.18	0.00	0.00	9.71	0.08
Wall 15		7.56	0.00			0.50	0.00	0.00	0.00

(1.12 cm; 150719 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick		standard walls 8" (=0.2032 m) to 12" (=0.3048) thick [-]		standard walls 4" (=0.1016 m) to 6" (=0.1524 m) thick [-]	
		damaged perimeter [m]	failed area [m2]	damaged perimeter [m]	failed area [m2]	damaged standard walls [-]	failed standard walls [-]	damaged standard walls [-]	failed standard walls [-]
Wall 1		0.00	0.00			0.00	0.00	0.00	0.00
Wall 2				6.20	0.59	0.00	0.00	0.41	0.04
Wall 3				0.00	0.00	0.00	0.00	0.00	0.00
Wall 4				0.00	0.00	0.00	0.00	0.00	0.00
Wall 5				0.00	0.00	0.00	0.00	0.00	0.00
Wall 6				0.00	0.00	0.00	0.00	0.00	0.00
Wall 7				0.00	0.00	0.00	0.00	0.00	0.00
Wall 8				0.00	0.00	0.00	0.00	0.00	0.00
Wall 9				0.00	0.00	0.00	0.00	0.00	0.00
Wall 10				14.62	0.59	0.00	0.00	0.96	0.04
Wall 11				14.62	0.00	0.00	0.00	0.96	0.00
Wall 12		58.17	0.53			3.82	0.04	0.00	0.00
Wall 13		190.80	0.00			12.52	0.00	0.00	0.00
Wall 14				148.04	1.18	0.00	0.00	9.71	0.08
Wall 15		15.12	0.00			0.99	0.00	0.00	0.00

(max. force) (1.44 cm; 147321 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick		standard walls 8" (=0.2032 m) to 12" (=0.3048) thick [-]		standard walls 4" (=0.1016 m) to 6" (=0.1524 m) thick [-]	
		damaged perimeter [m]	failed area [m2]	damaged perimeter [m]	failed area [m2]	damaged standard walls [-]	failed standard walls [-]	damaged standard walls [-]	failed standard walls [-]
Wall 1		0.00	0.00			0.00	0.00	0.00	0.00
Wall 2				15.64	0.59	0.00	0.00	1.03	0.04
Wall 3				0.00	0.00	0.00	0.00	0.00	0.00
Wall 4				15.36	0.00	0.00	0.00	1.01	0.00
Wall 5				0.00	0.00	0.00	0.00	0.00	0.00
Wall 6				0.00	0.00	0.00	0.00	0.00	0.00
Wall 7				0.00	0.00	0.00	0.00	0.00	0.00
Wall 8				0.00	0.00	0.00	0.00	0.00	0.00
Wall 9				0.00	0.00	0.00	0.00	0.00	0.00
Wall 10				14.62	0.59	0.00	0.00	0.96	0.04
Wall 11				14.62	0.00	0.00	0.00	0.96	0.00
Wall 12		64.49	0.00			4.23	0.00	0.00	0.00
Wall 13		190.80	0.00			12.52	0.00	0.00	0.00
Wall 14				156.74	1.18	0.00	0.00	10.28	0.08
Wall 15		45.36	0.00			2.98	0.00	0.00	0.00

(failure) (1.52 cm; 157800 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick		standard walls 8" (=0.2032 m) to 12" (=0.3048) thick [-]		standard walls 4" (=0.1016 m) to 6" (=0.1524 m) thick [-]	
		damaged perimeter [m]	failed area [m2]	damaged perimeter [m]	failed area [m2]	damaged standard walls [-]	failed standard walls [-]	damaged standard walls [-]	failed standard walls [-]
Wall 1		0.00	0.00			0.00	0.00	0.00	0.00
Wall 2				15.64	0.59	0.00	0.00	1.03	0.04
Wall 3				0.00	0.00	0.00	0.00	0.00	0.00
Wall 4				15.36	0.00	0.00	0.00	1.01	0.00
Wall 5				0.00	0.00	0.00	0.00	0.00	0.00
Wall 6				0.00	0.00	0.00	0.00	0.00	0.00
Wall 7				0.00	0.00	0.00	0.00	0.00	0.00
Wall 8				0.00	0.00	0.00	0.00	0.00	0.00
Wall 9				0.00	0.00	0.00	0.00	0.00	0.00
Wall 10				14.62	0.59	0.00	0.00	0.96	0.04
Wall 11				14.62	0.00	0.00	0.00	0.96	0.00
Wall 12		67.73	0.00			4.44	0.00	0.00	0.00
Wall 13		190.80	0.00			12.52	0.00	0.00	0.00
Wall 14				156.72	1.18	0.00	0.00	10.28	0.08
Wall 15		45.36	0.35			2.98	0.02	0.00	0.00

(beyond failure) (1.76 cm; 146043 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick		standard walls 8" (=0.2032 m) to 12" (=0.3048) thick [-]		standard walls 4" (=0.1016 m) to 6" (=0.1524 m) thick [-]	
		damaged perimeter [m]	failed area [m2]	damaged perimeter [m]	failed area [m2]	damaged standard walls [-]	failed standard walls [-]	damaged standard walls [-]	failed standard walls [-]
Wall 1		0.00	0.00			0.00	0.00	0.00	0.00
Wall 2				15.64	0.59	0.00	0.00	1.03	0.04
Wall 3				0.00	0.00	0.00	0.00	0.00	0.00
Wall 4				15.36	0.00	0.00	0.00	1.01	0.00
Wall 5				0.00	0.00	0.00	0.00	0.00	0.00
Wall 6				0.00	0.00	0.00	0.00	0.00	0.00
Wall 7				0.00	0.00	0.00	0.00	0.00	0.00
Wall 8				0.00	0.00	0.00	0.00	0.00	0.00
Wall 9				0.00	0.00	0.00	0.00	0.00	0.00
Wall 10				23.04	0.59	0.00	0.00	1.51	0.04
Wall 11				14.62	0.00	0.00	0.00	0.96	0.00
Wall 12		74.14	0.78			4.86	0.06	0.00	0.00
Wall 13		190.80	0.00			12.52	0.00	0.00	0.00
Wall 14				176.04	0.59	0.00	0.00	11.55	0.04
Wall 15		45.36	0.69			2.98	0.05	0.00	0.00

Table 75: After optimised seismic retrofit with NSM steel reinforcement (54.2 m^2): calculation of damaged or failed walls (area) for the estimation of costs from repair/replacement works

(0.08 cm; 20669 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick	
		damaged area [m2]	failed area [m2]	damaged area [m2]	failed area [m2]
Wall 1		0.00	0.00		
Wall 2				0.00	0.59
Wall 3				0.00	0.00
Wall 4				0.00	0.00
Wall 5				0.00	0.00
Wall 6				0.00	0.00
Wall 7				0.00	0.00
Wall 8				0.00	0.00
Wall 9				0.00	0.00
Wall 10				0.00	0.59
Wall 11				0.00	0.00
Wall 12		2.46	1.55		
Wall 13		4.21	0.00		
Wall 14				1.77	1.18
Wall 15		0.00	0.00		

(0.40 cm; 92213 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick	
		damaged area [m2]	failed area [m2]	damaged area [m2]	failed area [m2]
Wall 1		0.00	0.00		
Wall 2				0.00	0.59
Wall 3				0.00	0.00
Wall 4				0.00	0.00
Wall 5				0.00	0.00
Wall 6				0.00	0.00
Wall 7				0.00	0.00
Wall 8				0.00	0.00
Wall 9				0.00	0.00
Wall 10				4.93	0.59
Wall 11				0.00	0.00
Wall 12		5.25	0.53		
Wall 13		22.60	0.00		
Wall 14				20.57	1.18
Wall 15		0.00	0.00		

(0.48 cm; 106856 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick	
		damaged area [m2]	failed area [m2]	damaged area [m2]	failed area [m2]
Wall 1		0.00	0.00		
Wall 2				0.00	0.59
Wall 3				0.00	0.00
Wall 4				0.00	0.00
Wall 5				0.00	0.00
Wall 6				0.00	0.00
Wall 7				0.00	0.00
Wall 8				0.00	0.00
Wall 9				0.00	0.00
Wall 10				4.93	0.59
Wall 11				0.00	0.00
Wall 12		6.85	0.53		
Wall 13		39.12	0.00		
Wall 14			0.00	34.68	1.18
Wall 15		2.92	0.00		

		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick	
(0.56 cm; 120521 daN)					
		damaged area [m2]	failed area [m2]	damaged area [m2]	failed area [m2]
Wall 1		0.00	0.00		
Wall 2				0.00	0.59
Wall 3				0.00	0.00
Wall 4				0.00	0.00
Wall 5				0.00	0.00
Wall 6				0.00	0.00
Wall 7				0.00	0.00
Wall 8				0.00	0.00
Wall 9				0.00	0.00
Wall 10				5.52	0.59
Wall 11				12.45	0.00
Wall 12		11.51	0.78		
Wall 13		45.28	0.00		
Wall 14				54.03	1.18
Wall 15		2.92	0.00		
(0.80 cm; 140413 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick	
		damaged area [m2]	failed area [m2]	damaged area [m2]	failed area [m2]
Wall 1		0.00	0.00		
Wall 2				1.18	0.00
Wall 3				0.00	0.00
Wall 4				0.00	0.00
Wall 5				0.00	0.00
Wall 6				0.00	0.00
Wall 7				0.00	0.00
Wall 8				0.00	0.00
Wall 9				0.00	0.00
Wall 10				5.52	0.59
Wall 11				12.45	0.00
Wall 12		13.44	0.78		
Wall 13		72.01	0.00		
Wall 14				92.80	1.18
Wall 15		2.92	0.00		
(1.12 cm; 150719 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick	
		damaged area [m2]	failed area [m2]	damaged area [m2]	failed area [m2]
Wall 1		0.00	0.00		
Wall 2				1.18	0.59
Wall 3				0.00	0.00
Wall 4				0.00	0.00
Wall 5				0.00	0.00
Wall 6				0.00	0.00
Wall 7				0.00	0.00
Wall 8				0.00	0.00
Wall 9				0.00	0.00
Wall 10				5.52	0.59
Wall 11				12.45	0.00
Wall 12		14.80	0.53		
Wall 13		82.62	0.00		
Wall 14				92.80	1.18
Wall 15		5.83	0.00		

(max. force) (1.44 cm; 147321 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick	
		damaged area [m2]	failed area [m2]	damaged area [m2]	failed area [m2]
Wall 1		0.00	0.00		
Wall 2				6.75	0.59
Wall 3				0.00	0.00
Wall 4				13.45	0.00
Wall 5				0.00	0.00
Wall 6				0.00	0.00
Wall 7				0.00	0.00
Wall 8				0.00	0.00
Wall 9				0.00	0.00
Wall 10				5.52	0.59
Wall 11				12.45	0.00
Wall 12		16.24	0.00		
Wall 13		82.62	0.00		
Wall 14				97.47	1.18
Wall 15		17.50	0.00		
(failure) (1.52 cm; 157800 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick	
		damaged area [m2]	failed area [m2]	damaged area [m2]	failed area [m2]
Wall 1		0.00	0.00		
Wall 2				6.75	0.59
Wall 3				0.00	0.00
Wall 4				13.45	0.00
Wall 5				0.00	0.00
Wall 6				0.00	0.00
Wall 7				0.00	0.00
Wall 8				0.00	0.00
Wall 9				0.00	0.00
Wall 10				5.52	0.59
Wall 11				12.45	0.00
Wall 12		18.12	0.00		
Wall 13		82.62	0.00		
Wall 14				97.46	1.18
Wall 15		17.50	0.35		
(beyond failure) (1.76 cm; 146043 daN)		Walls 8" (= 0.20 m) to 12" (= 0.30) thick		Walls 4" (= 0.10 m) to 6" (= 0.15 m) thick	
		damaged area [m2]	failed area [m2]	damaged area [m2]	failed area [m2]
Wall 1		0.00	0.00		
Wall 2				6.75	0.59
Wall 3				0.00	0.00
Wall 4				13.45	0.00
Wall 5				0.00	0.00
Wall 6				0.00	0.00
Wall 7				0.00	0.00
Wall 8				0.00	0.00
Wall 9				0.00	0.00
Wall 10				9.86	0.59
Wall 11				12.45	0.00
Wall 12		21.09	0.78		
Wall 13		82.62	0.00		
Wall 14				103.32	0.59
Wall 15		17.50	0.69		

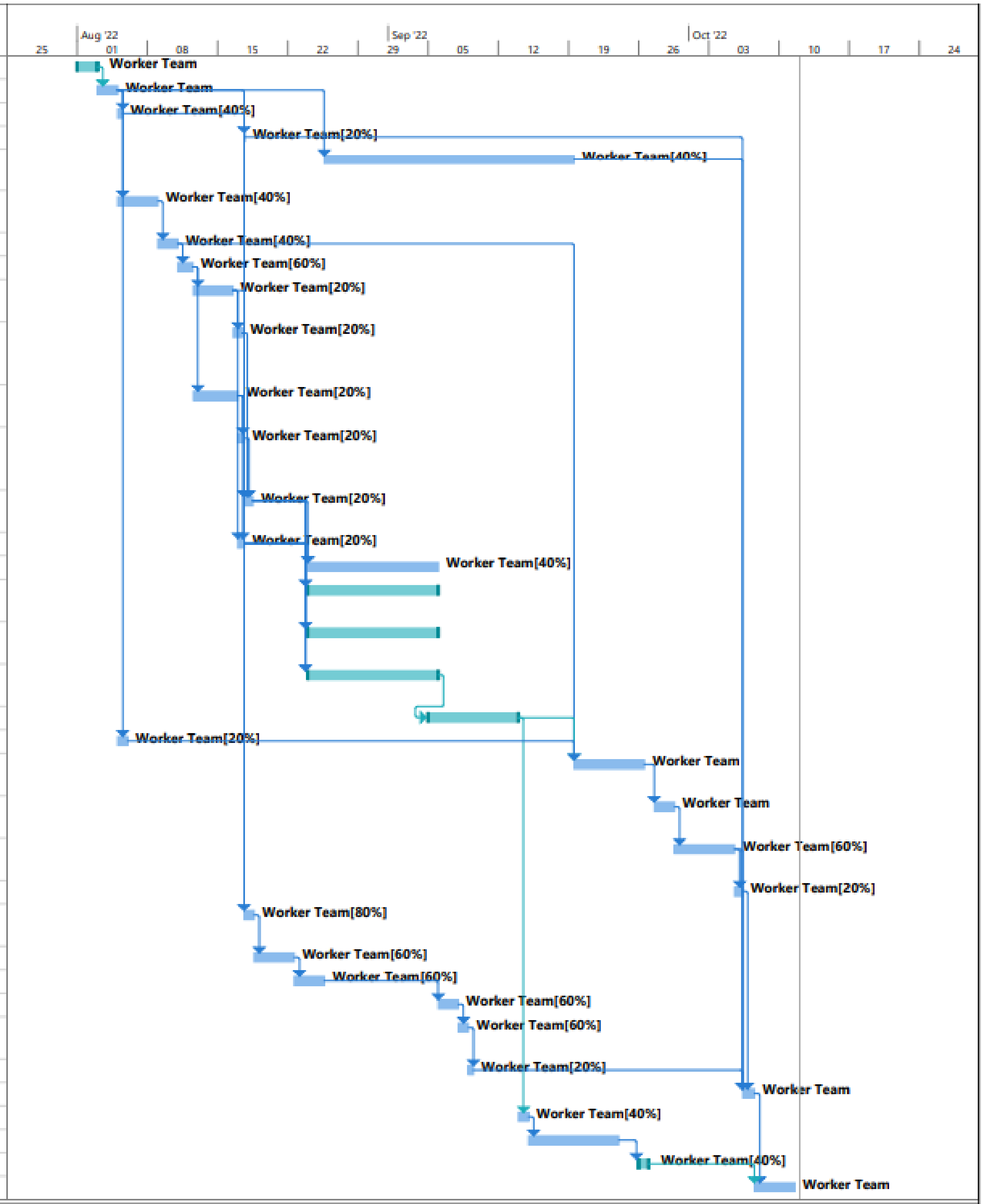
Seismic performance after optimisation of retrofit:

Table 76: Results of the seismic performance analysis in 3Muri after the optimised seismic retrofit with NSM steel reinforcement (area of application: 54.2 m^2)

Analysis	Seismic direction	Seismic load	Eccentricity [cm]	Capacity d_m [cm]	Demand d_t [cm]	Compliance factor α
1	X +	Uniform	0	2.40	3.19	0.75
2	X +	Static forces	0	2.56	3.79	0.68
3	X -	Uniform	0	2.32	3.12	0.74
4	X -	Static forces	0	2.48	3.77	0.66
5	Y +	Uniform	0	2.23	1.30	1.72
6	Y +	Static forces	0	2.39	1.64	1.46
7	Y -	Uniform	0	1.61	1.15	1.40
8	Y -	Static forces	0	2.65	1.49	1.78
9	X +	Uniform	53.8	2.32	3.18	0.73
10	X +	Uniform	-53.8	2.40	3.18	0.75
11	X +	Static forces	53.8	2.48	3.78	0.66
12	X +	Static forces	-53.8	2.48	3.78	0.66
13	X -	Uniform	53.8	2.32	3.13	0.74
14	X -	Uniform	-53.8	2.08	3.13	0.66
15	X -	Static forces	53.8	2.48	3.77	0.66
16	X -	Static forces	-53.8	2.48	3.73	0.66
17	Y +	Uniform	89.6	1.20	1.21	0.99
18	Y +	Uniform	-89.6	2.87	1.49	1.93
19	Y +	Static forces	89.6	1.59	1.52	1.05
20	Y +	Static forces	-89.6	3.11	1.86	1.67
21	Y -	Uniform	89.6	0.88	1.06	0.83
22	Y -	Uniform	-89.6	1.69	1.33	1.27
23	Y -	Static forces	89.6	1.36	1.35	1.01
24	Y -	Static forces	-89.6	2.57	1.72	1.49

Table 77: Schedule for optimised combined thermal (Alternative 2 applied on walls (380 mm straw panel), windows, roof) and seismic (NSM steel reinforcement, 54.2 m^2) intervention

ID	Task Name	Duration	Start	Finish	Predecessors	Successors	Resource Names
1	Site installation, preparation of works	2 days	Mon 01.08.22	Tue 02.08.22		2	Worker Team
2	Scaffold installation	2 days	Wed 03.08.22	Thu 04.08.22	1	6;4;5;3;20	Worker Team
3	Temporary roof railing installation	0.5 days	Fri 05.08.22	Fri 05.08.22	2	25	Worker Team[40%]
4	Dismounting of window sills	0.2 days	Wed 17.08.22	Wed 17.08.22	2	31	Worker Team[20%]
5	Replacement of windows (3.25h/window, 42 windows)	16.8 days	Thu 25.08.22	Mon 19.09.22	2	31	Worker Team[40%]
6	Dismounting of rear ventilated façade panels	2 days	Fri 05.08.22	Mon 08.08.22	2	7	Worker Team[40%]
7	Dismounting Isover fiberglass insulatic	2 days	Tue 09.08.22	Wed 10.08.22	6	21;8	Worker Team[40%]
8	Removal of coating/plaster	1.5 days	Thu 11.08.22	Fri 12.08.22	7	9;11	Worker Team[60%]
9	Horizontal saw cutting of grooves through bed joints	2 days	Fri 12.08.22	Tue 16.08.22	8	13;14;10	Worker Team[20%]
10	Drill holes at vertical wall ends at heigths of horizontal grooves (anchorage for steel rebars)	0.75 days	Tue 16.08.22	Wed 17.08.22	9	13	Worker Team[20%]
11	Vertical saw cutting through bricks and head joints	2.5 days	Fri 12.08.22	Tue 16.08.22	8	13;14;12	Worker Team[20%]
12	Drill holes at horizontal wall ends at locations of vertical grooves (anchorage for steel rebars)	0.75 days	Wed 17.08.22	Wed 17.08.22	11	13	Worker Team[20%]
13	Cleaning of grooves and holes with compressed air	0.75 days	Wed 17.08.22	Thu 18.08.22	9;10;11;12	18;16;17;15	Worker Team[20%]
14	Cleaning of reinforcement bars	0.75 days	Wed 17.08.22	Wed 17.08.22	9;11	18;16;17;15	Worker Team[20%]
15	Mixing of epoxy resin	9 days	Wed 24.08.22	Mon 05.09.22	13;14		Worker Team[40%]
16	Partial filling of grooves and holes with epoxy	9 days	Wed 24.08.22	Mon 05.09.22	13;14		
17	Placing and pressing steel reinforcement into the grooves	9 days	Wed 24.08.22	Mon 05.09.22	13;14		
18	Filling and surface finishing of grooves (remove excess epoxy)	9 days	Wed 24.08.22	Mon 05.09.22	13;14	19	
19	Curing of epoxy resin	7 days	Mon 05.09.22	Tue 13.09.22	18	32;21	
20	Cut straw insulation panels to fit	1 day	Fri 05.08.22	Fri 05.08.22	2	21	Worker Team[20%]
21	Affixing of straw insulation panels with mineral adhesive and	5 days	Mon 19.09.22	Mon 26.09.22	7;20;19	22	Worker Team
22	Affixing of straw insulation panels with dowels	2 days	Tue 27.09.22	Thu 29.09.22	21	23	Worker Team
23	Mounting of rear ventilated façade panels	4 days	Thu 29.09.22	Wed 05.10.22	22	31;24	Worker Team[60%]
24	Installation of window sills	0.5 days	Wed 05.10.22	Thu 06.10.22	23	31	Worker Team[20%]
25	Removal of gravel and sand layers from roof	1 day	Wed 17.08.22	Thu 18.08.22	3	26	Worker Team[80%]
26	Removal of watertight roof seal	2 days	Thu 18.08.22	Mon 22.08.22	25	27	Worker Team[60%]
27	Installation of fiberglass insulation ma	3 days	Mon 22.08.22	Thu 25.08.22	26	28	Worker Team[60%]
28	Installation of watertight roof seal	2 days	Tue 06.09.22	Wed 07.09.22	27	29	Worker Team[60%]
29	Filling up with sand and gravel layer on the roof	1 day	Thu 08.09.22	Thu 08.09.22	28	30	Worker Team[60%]
30	Temporary roof railing dismounting	0.5 days	Fri 09.09.22	Fri 09.09.22	29	31	Worker Team[20%]
31	Scaffold dismounting	1.5 days	Thu 06.10.22	Fri 07.10.22	23;30;5;4;24	35	Worker Team
32	Interior wall plastering	1 day	Wed 14.09.22	Wed 14.09.22	19	33	Worker Team[40%]
33	Curing of plaster	7 days	Thu 15.09.22	Fri 23.09.22	32	34	
34	Interior wall painting	1 day	Mon 26.09.22	Mon 26.09.22	33	35	Worker Team[40%]
35	Site cleaning, conclusion of works	2 days	Fri 07.10.22	Tue 11.10.22	34;31		Worker Team



Project: Schedule_Thermal inter
Date: Wed 01.06.22

Task, Split, Milestone, Summary, Project Summary, Inactive Task, Inactive Milestone, Inactive Summary, Manual Task, Duration-only, Manual Summary Rollup, Manual Summary, Start-only, Finish-only, External Tasks, External Milestone, Deadline, Progress, Manual Progress

Page 1

Table 78: Cost estimation for optimised combined thermal (Alternative 2 applied on walls (380 mm straw panel), windows, roof) and seismic (NSM steel reinforcement, 54.2 m^2) intervention

Work Breakdown Structure						Unit cost		Extent		Quantity	Total material + rental [CHF]	Unit price [CHF/h]	Duration [d]	Duration [h]	Quantity workers	Total [CHF]	Total material + rental + work [CHF]	Remarks
1	Thermal retrofit	1.1	Preparation	1.1.1	Site installation, preparation of works	-		-		-	-	90	2.00	16	5	7'200	7'200	
				1.1.2	Scaffold installation + rental	35	CHF/m2	547	m2	1	19'145	90	2.00	16	5	7'200	26'345	35 CHF/m2* 547m2
				1.1.3	Temporary roof railing installation + rental	45	CHF/m			22	990	90	0.50	4	2	720	1'710	CHF/element*60.3m/2.8m/element
		1.2	Windows	1.2.1	Dismounting of window sills						-	90	0.20	2	1	144	144	
				1.2.2	Replacement of windows (3.25h/window, 42 windows)	800	CHF/window			42	33'600	90	16.80	134	2	24'192	57'792	ndow + disposal 120 CHF/window
		1.3	Facade	1.3.1	Dismounting of rear ventilated façade panels						-	90	2.00	16	2	2'880	2'880	
				1..3.2	Dismounting Isover fiberglass insulation	85	CHF/m3	44	m3	44	3'740	90	2.00	16	2	2'880	6'620	Disposal 85CHF/m3 547 m2*0.08m
				1.3.3	Cut straw insulation panels to fit						-	90	1.00	8	1	720	720	
				1.3.4	Affixing of straw insulation panels with mineral adhesive and reinforcing mortar	25	CHF/m2	547	m2	547	13'675	90	5.00	40	5	18'000	31'675	traw insulation panels: 20 CHF/m2
				1.3.5	Affixing of straw insulation panels with dowels	1	CHF/piece			2'200	2'200	90	2.00	16	5	7'200	9'400	dowels: 1 CHF/piece
				1.3.6	Mounting of rear ventilated façade panels						-	90	4.00	32	3	8'640	8'640	
				1.3.7	Installation of window sills						-	90	0.50	4	1	360	360	
		1.4	Roof	1.4.1	Removal of gravel and sand layers from roof	42	CHF/m3	12	m3	12	504	90	1.00	8	4	2'880	3'384	Disposal 42 CHF/m3 199 m2*0.06m
				1.4.2	Removal of watertight roof seal	85	CHF/m3	2	m3	2	170	90	2.00	16	3	4'320	4'490	Disposal 85 CHF/m3 199 m2*0.01m
				1.4.3	Installation of fiberglass insulation mats	25	CHF/m2	199	m2	199	4'975	90	3.00	24	5	10'800	15'775	
				1.4.4	Installation of watertight roof seal	9	CHF/m2	199	m2	199	4'975	90	2.00	16	3	4'320	9'295	
				1.4.5	Filling up with sand and gravel layer on the roof	0.25	CHF/kg	30'000	kg	30'000	7'500	90	1.00	8	3	2'160	9'660	199 m2*0.06m*2400 kg/m3
				1.4.6	Temporary roof railing dismounting						-	90	0.50	4	1	360	360	
2	Seismic retrofit	2.1	Walls	2.1.1	Removal of coating/plaster	20	CHF/m3	14	m3	14	280	90	1.5	12	3	3'240	3'520	Disposal 20 CHF/m3 547 m2*0.025m
				2.1.2	Horizontal saw cutting of grooves through bed joints							90	2	16	1	1'440	1'440	
				2.1.3	Drill holes at vertical wall ends at heights of horizontal grooves (anchorage for steel rebars)							90	0.75	6	1	540	540	
				2.1.4	Vertical saw cutting through bricks and head joints							90	2.5	20	1	1'800	1'800	
				2.1.5	Drill holes at horizontal wall ends at locations of vertical grooves (anchorage for steel rebars)							90	0.75	6	1	540	540	
				2.1.6	Cleaning of grooves and holes with compressed air							90	0.75	6	1	540	540	
				2.1.7	Cleaning of reinforcement bars							90	0.75	6	1	540	540	
				2.1.8	Mixing of epoxy resin	75	CHF/l	0.1	m3	0	7'500	90	9	72	2	12'960	20'460	70 CHF/l*168 m * 0.04m*0.015
				2.1.9	Partial filling of grooves and holes with epoxy						-	90	9	72			-	
				2.1.10	Placing and pressing steel reinforcement into the grooves	6	CHF/m	168	m	168	1'008	90	9	72			1'008	3 CHF/m * 168 m
				2.1.11	Filling and surface finishing of grooves (remove excess epoxy)							90	9	72			-	
				2.1.12	Curing of epoxy resin							90	7	56			-	
3	Conclusion of works	3.1	Conclusion of works	3.1.1	Scaffold dismounting						-	90	1.50	12	5	5'400	5'400	
				3.1.2	Interior wall plastering	1.50	CHF/m2	39	m2	39	78	90	1.00	8	2	1'440	1'518	0.40 CHF/kg * 3.6 kg/m2 * 39 m2
				3.1.3	Curing of plaster							90	7.00	56		-	-	
				3.1.4	Interior wall painting	0.60	CHF/m2	39	m2	39	39	90	1.00	8	2	1'440	1'479	4 CHF/l*0.15 l/m2*39 m2
				3.1.5	Site cleaning, conclusion of works						-	90	2.00	16	5	7'200	7'200	
Total construction costs (material+rental+work)																	242'435	
Indirect costs 10%																	24'244	
Engineering 5%																	12'122	
Markup (profit 5% + contingency 7%)																	29'092	
VAT 7.7%																	18'667	
Total																	326'560	

Disposal costs

Appendix K

Table 79: Decision-making table: thermal retrofit (wall insulation: Alternative 2 with 160 mm straw insulation panels, roof insulation: fiberglass mats, windows: triple-glazed)

	CO_2 emissions in 50 years [kg]		Costs [CHF]		Time [days]		Safety (difference of actual compliance factor to 1)	
Is-state	seismic: probable repair works is-status	**6'962**	seismic: monetarized CO_2 emissions from probable repair works	1'447	Rental cost of an apartment [CHF/month]	**1'327**	Compliance factor is-status	**0.44**
			thermal: costs from heating demand of building in is-state in 50 years	**152'716**	Number of non-usable apartments during construction works	**6**	Difference compliance factor is-status to ideal compliance factor (1)	0.56
	thermal: heating demand is-status in 50 years	**382'628**	thermal: monetarized CO_2 emissions from heating demand of building in is-state in 50 years	79'548	Limit of acceptable monetary loss from incapacitation of occupancy	**10'000**		
			Seismic: costs of probable repair works in is-state	**11'640**	acceptable time of incapacitation of occupancy derived from limit of acceptable monetary loss [days]	38		
					acceptable time of incapacitation of occupancy due to non-monetary reasons [days]	**60**		
Total		389'590		245'351		38		0.56
Target factor; Total	**0.5**	194'795	**2**	490'702	**0.92**	34.66	**0.7**	0.39
After retrofit	seismic: probable repair works	**6'962**	seismic: commensurable costs	-	effective time of incapacitation of occupancy	**25**	Compliance factor after seismic retrofit	**0.44**
	seismic: retrofit intervention	-	seismic: cost of retrofit intervention	-			$\Delta\alpha_{mean} = \Delta dm_{mean}/\Delta dt_{mean}$	**0.00**
	thermal: heating demand in 50 years	**210'267**	thermal: cost of retrofit intervention	**281'590**			Difference averaged compliance factor to ideal compliance factor (1)	0.56
	thermal: retrofit intervention	**7'661**	seismic: monetarized CO_2 emissions from probable repair works	1'447				
			thermal: costs from heating demand of retrofitted building in 50 years	**83'922**				
			thermal: monetarized CO_2 emissions from heating demand of retrofitted building in 50 years	43'714				
			Seismic: costs of probable repair works retrofitted building	11'640				
			Costs from time of incapacitation of occupancy	6'635				
Total		224'889		428'949		25		0.56

Table 80: Decision-making table: combined thermal (wall insulation: Alternative 2 with 160 mm straw insulation panels, roof insulation: fiberglass mats, windows: triple-glazed) and seismic retrofit (CFRP strips, 30.8 m^2)

	CO2 emissions in 50 years [kg]		Costs [CHF]		Time [days]		Safety (difference of actual compliance factor to 1)	
Is-state	seismic: probable repair works is-status	**6'962**	seismic: monetarized CO2 emissions from probable repair works	1'447	Rental cost of an apartment [CHF/month]	**1'327**	Compliance factor is-status	**0.44**
			thermal: costs from heating demand of building in is-state in 50 years	**152'716**	Number of non-usable apartments during construction works	**6**	Difference compliance factor is-status to ideal compliance factor (1)	0.56
	thermal: heating demand is-status in 50 years	**382'628**	thermal: monetarized CO2 emissions from heating demand of building in is-state in 50 years	79'548	Limit of acceptable monetary loss from incapacitation of occupancy	**10'000**		
			Seismic: costs of probable repair works in is-state	**11'640**	acceptable time of incapacitation of occupancy derived from limit of acceptable monetary loss [days]	38		
					acceptable time of incapacitation of occupancy due to non-monetary reasons [days]	**60**		
Total		389'590		245'351		38		0.56
Target factor; Total	**0.5**	194'795	**2**	490'702	**0.92**	34.66	**0.7**	0.39
After retrofit	seismic: probable repair works	**7'148**	seismic: commensurable costs	**-16'000**	effective time of incapacitation of occupancy	**34**	Compliance factor after seismic retrofit	**0.64**
	seismic: retrofit intervention	**952**	seismic: cost of retrofit intervention	**43'961**			$\Delta\alpha\_mean = \Delta dm\_mean/\Delta dt\_mean$	**0.07**
	thermal: heating demand in 50 years	**210'267**	thermal: cost of retrofit intervention	**281'590**			Difference averaged compliance factor to ideal compliance factor (1)	0.29
	thermal: retrofit intervention	**7'661**	seismic: monetarized CO2 emissions from probable repair works	1'486				
			thermal: costs from heating demand of retrofitted building in 50 years	**83'922**				
			thermal: monetarized CO2 emissions from heating demand of retrofitted building in 50 years	43'714				
			Seismic: costs of probable repair works retrofitted building	**12'577**				
			Costs from time of incapacitation of occupancy	9'024				
Total		226'027		460'275		34		0.29

Table 81: Decision-making table: combined thermal (wall insulation: Alternative 2 with 160 mm straw insulation panels, roof insulation: fiberglass mats, windows: triple-glazed) and seismic retrofit (NSM steel reinforcement, 30.8 m^2)

	CO2 emissions in 50 years [kg]		Costs [CHF]		Time [days]		Safety (difference of actual compliance factor to 1)	
Is-state	seismic: probable repair works is-status	**6'962**	seismic: monetarized CO2 emissions from probable repair works	1'447	Rental cost of an apartment [CHF/month]	**1'327**	Compliance factor is-status	**0.44**
			thermal: costs from heating demand of building in is-state in 50 years	**152'716**	Number of non-usable apartments during construction works	**6**	Difference compliance factor is-status to ideal compliance factor (1)	0.56
	thermal: heating demand is-status in 50 years	**382'628**	thermal: monetarized CO2 emissions from heating demand of building in is-state in 50 years	79'548	Limit of acceptable monetary loss from incapacitation of occupancy	**10'000**		
			Seismic: costs of probable repair works in is-state	**11'640**	acceptable time of incapacitation of occupancy derived from limit of acceptable monetary loss [days]	38		
					acceptable time of incapacitation of occupancy due to non-monetary reasons [days]	**60**		
Total		389'590		245'351		38		0.56
Target factor; Total	**0.5**	194'795	**2**	490'702	**0.92**	34.66	**0.7**	0.39
After retrofit	seismic: probable repair works	**7'059**	seismic: commensurable costs	**-16'000**	effective time of incapacitation of occupancy	**32**	Compliance factor after seismic retrofit	**0.64**
	seismic: retrofit intervention	**396**	seismic: cost of retrofit intervention	**32'737**			Δα_mean = Δdm_mean/Δdt_mean	**0.07**
	thermal: heating demand in 50 years	**210'267**	thermal: cost of retrofit intervention	**281'590**			Difference averaged compliance factor to ideal compliance factor (1)	0.29
	thermal: retrofit intervention	**7'661**	seismic: monetarized CO2 emissions from probable repair works	1'468				
			thermal: costs from heating demand of retrofitted building in 50 years	**83'922**				
			thermal: monetarized CO2 emissions from heating demand of retrofitted building in 50 years	43'714				
			Seismic: costs of probable repair works retrofitted building	12'558				
			Costs from time of incapacitation of occupancy	8'493				
Total		225'383		448'483		32		0.29

Table 82: Decision-making table: optimised thermal retrofit (wall insulation: Alternative 2 with 380 mm straw insulation panels, roof insulation: fiberglass mats, windows: triple-glazed)

	CO2 emissions in 50 years [kg]		Costs [CHF]		Time [days]		Safety (difference of actual compliance factor to 1)	
Is-state	seismic: probable repair works is-status	**6'962**	seismic: monetarized CO2 emissions from probable repair works	1'447	Rental cost of an apartment [CHF/month]	**1'327**	Compliance factor is-status	**0.44**
			thermal: costs from heating demand of building in is-state in 50 years	**152'716**	Number of non-usable apartments during construction works	**6**	Difference compliance factor is-status to ideal compliance factor (1)	0.56
	thermal: heating demand is-status in 50 years	**382'628**	thermal: monetarized CO2 emissions from heating demand of building in is-state in 50 years	79'548	Limit of acceptable monetary loss from incapacitation of occupancy	**10'000**		
			Seismic: costs of probable repair works in is-state	**11'640**	acceptable time of incapacitation of occupancy derived from limit of acceptable monetary loss [days]	38		
					acceptable time of incapacitation of occupancy due to non-monetary reasons [days]	**60**		
Total		389'590		245'351		38		0.56
Target factor; Total	**0.5**	194'795	**2**	490'702	**0.92**	34.66	**0.7**	0.39
After retrofit	seismic: probable repair works	**6'962**	seismic: commensurable costs	**-**	effective time of incapacitation of occupancy	**25**	Compliance factor after seismic retrofit	**0.44**
	seismic: retrofit intervention	**-**	seismic: cost of retrofit intervention	**-**			Δα_mean = Δdm_mean/Δdt_mean	**0.00**
	thermal: heating demand in 50 years	**167'580**	thermal: cost of retrofit intervention	**281'590**			Difference averaged compliance factor to ideal compliance factor (1)	0.56
	thermal: retrofit intervention	**12'483**	seismic: monetarized CO2 emissions from probable repair works	1'447.34				
			thermal: costs from heating demand of retrofitted building in 50 years	**66'885**				
			thermal: monetarized CO2 emissions from heating demand of retrofitted building in 50 years	34'840				
			Seismic: costs of probable repair works retrofitted building	11'640				
			Costs from time of incapacitation of occupancy	6'635				
Total		187'025		403'037		25		0.56

Table 83: Decision-making table: combined thermal optimised (wall insulation: Alternative 2 with 380 mm straw insulation panels, roof insulation: fiberglass mats, windows: triple-glazed) and seismic retrofit (CFRP strips, 30.8 m^2)

	CO2 emissions in 50 years [kg]			Costs [CHF]			Time [days]			Safety (difference of actual compliance factor to 1)		
Is-state	seismic: probable repair works is-status		**6'962**	seismic: monetarized CO2 emissions from probable repair works		1'447	Rental cost of an apartment [CHF/month]		**1'327**	Compliance factor is-status		**0.44**
				thermal: costs from heating demand of building in is-state in 50 years		**152'716**	Number of non-usable apartments during construction works		**6**	Difference compliance factor is-status to ideal compliance factor (1)		0.56
	thermal: heating demand is-status in 50 years		**382'628**	thermal: monetarized CO2 emissions from heating demand of building in is-state in 50 years		79'548	Limit of acceptable monetary loss from incapacitation of occupancy		**10'000**			
				Seismic: costs of probable repair works in is-state		**11'640**	acceptable time of incapacitation of occupancy derived from limit of acceptable monetary loss [days]		38			
							acceptable time of incapacitation of occupancy due to non-monetary reasons [days]		**60**			
Total			389'590			245'351			38			0.56
Target factor; Total		**0.5**	194'795		**2**	490'702		**0.92**	34.66		**0.7**	0.39
After retrofit	seismic: probable repair works		**7'148**	seismic: commensurable costs		**-16'000**	effective time of incapacitation of occupancy		**34**	Compliance factor after seismic retrofit		**0.64**
	seismic: retrofit intervention		**952**	seismic: cost of retrofit intervention		**43'961**				Δα_mean = Δdm_mean/Δdt_mean		**0.07**
	thermal: heating demand in 50 years		**167'580**	thermal: cost of retrofit intervention		**281'590**				Difference averaged compliance factor to ideal compliance factor (1)		0.29
	thermal: retrofit intervention		**12'483**	seismic: monetarized CO2 emissions from probable repair works		1'486.02						
				thermal: costs from heating demand of retrofitted building in 50 years		**66'885**						
				thermal: monetarized CO2 emissions from heating demand of retrofitted building in 50 years		34'840						
				Seismic: costs of probable repair works retrofitted building		**12'577**						
				Costs from time of incapacitation of occupancy		9'024						
Total			188'162			434'363			34			0.29

Table 84: Decision-making table: combined thermal optimised (wall insulation: Alternative 2 with 380 mm straw insulation panels, roof insulation: fiberglass mats, windows: triple-glazed) and seismic retrofit (NSM steel reinforcement, 30.8 m^2)

	CO2 emissions in 50 years [kg]		Costs [CHF]		Time [days]		Safety (difference of actual compliance factor to 1)	
Is-state	seismic: probable repair works is-status	**6'962**	seismic: monetarized CO2 emissions from probable repair works	1'447	Rental cost of an apartment [CHF/month]	**1'327**	Compliance factor is-status	**0.44**
			thermal: costs from heating demand of building in is-state in 50 years	**152'716**	Number of non-usable apartments during construction works	**6**	Difference compliance factor is-status to ideal compliance factor (1)	0.56
	thermal: heating demand is-status in 50 years	**382'628**	thermal: monetarized CO2 emissions from heating demand of building in is-state in 50 years	79'548	Limit of acceptable monetary loss from incapacitation of occupancy	**10'000**		
			Seismic: costs of probable repair works in is-state	**11'640**	acceptable time of incapacitation of occupancy derived from limit of acceptable monetary loss [days]	38		
					acceptable time of incapacitation of occupancy due to non-monetary reasons [days]	**60**		
Total		389'590		245'351		38		0.56
Target factor; Total	**0.5**	194'795	**2**	490'702	**0.92**	34.66	**0.7**	0.39
After retrofit	seismic: probable repair works	**7'059**	seismic: commensurable costs	**-16'000**	effective time of incapacitation of occupancy	**32**	Compliance factor after seismic retrofit	**0.64**
	seismic: retrofit intervention	**396**	seismic: cost of retrofit intervention	**32'737**			$\Delta\alpha_{mean} = \Delta dm_{mean}/\Delta dt_{mean}$	**0.07**
	thermal: heating demand in 50 years	**167'580**	thermal: cost of retrofit intervention	**281'590**			Difference averaged compliance factor to ideal compliance factor (1)	0.29
	thermal: retrofit intervention	**12'483**	seismic: monetarized CO2 emissions from probable repair works	1'467.65				
			thermal: costs from heating demand of retrofitted building in 50 years	**66'885**				
			thermal: monetarized CO2 emissions from heating demand of retrofitted building in 50 years	34'840				
			Seismic: costs of probable repair works retrofitted building	12'558				
			Costs from time of incapacitation of occupancy	8'493				
Total		187'519		422'571		32		0.29

Table 85: Decision-making table: combined thermal (wall insulation: Alternative 2 with 160 mm straw insulation panels, roof insulation: fiberglass mats, windows: triple-glazed) and seismic optimised retrofit (NSM steel reinforcement, 54.2 m²)

	CO2 emissions in 50 years [kg]		Costs [CHF]		Time [days]		Safety (difference of actual compliance factor to 1)	
Is-state	seismic: probable repair works is-status	**6'962**	seismic: monetarized CO2 emissions from probable repair works	1'447	Rental cost of an apartment [CHF/month]	**1'327**	Min. Compliance factor is-status	**0.44**
			thermal: costs from heating demand of building in is-state in 50 years	**152'716**	Number of non-usable apartments during construction works	**6**	Difference compliance factor is-status to ideal compliance factor (1)	0.56
	thermal: heating demand is-status in 50 years	**382'628**	thermal: monetarized CO2 emissions from heating demand of building in is-state	79'548	Limit of acceptable monetary loss from incapacitation of occupancy	**10'000**		
			Seismic: costs of probable repair works in is-state	**11'640**	acceptable time of incapacitation of occupancy derived from limit of acceptable monetary loss [days]	38		
					acceptable time of incapacitation of occupancy due to non-monetary reasons [days]	**60**		
Total		389'590		245'351		38		0.56
Target factor; Total	**0.7**	272'713	**2**	490'702	**1**	37.68	**0.7**	0.39
After retrofit	seismic: probable repair works	**7'866**	seismic: commensurable costs	**-16'000**	effective time of incapacitation of occupancy	**34**	Min. Compliance factor after seismic retrofit	**0.66**
	seismic: retrofit intervention	**704**	seismic: cost of retrofit intervention	**44'970**			Δα_mean = Δdm_mean/Δdt_mean	**0.12**
	thermal: heating demand in 50 years	**210'267**	thermal: cost of retrofit intervention	**281'590**			Difference averaged compliance factor to ideal compliance factor (1)	0.22
	thermal: retrofit intervention	**7'661**	seismic: monetarized CO2 emissions from probable repair works	1'635.32				
			thermal: costs from heating demand of retrofitted building in 50 years	**83'922**				
			thermal: monetarized CO2 emissions from heating demand of retrofitted building in 50 years	43'714				
			Seismic: costs of probable repair works retrofitted building	12'948				
			Costs from time of incapacitation of occupancy	9'024				
Total		226'497		461'803		34		0.22

Table 86: Decision-making table: combined thermal optimised (wall insulation: Alternative 2 with 380 mm straw insulation panels, roof insulation: fiberglass mats, windows: triple-glazed) and seismic optimised retrofit (NSM steel reinforcement, 54.2 m^2)

	CO2 emissions in 50 years [kg]		Costs [CHF]		Time [days]		Safety (difference of actual compliance factor to 1)	
Is-state	seismic: probable repair works is-status	**6'962**	seismic: monetarized CO2 emissions from probable repair works	1'447	Rental cost of an apartment [CHF/month]	**1'327**	Min. Compliance factor is-status	**0.44**
			thermal: costs from heating demand of building in is-state in 50 years	**152'716**	Number of non-usable apartments during construction works	**6**	Difference compliance factor is-status to ideal compliance factor (1)	0.56
	thermal: heating demand is-status in 50 years	**382'628**	thermal: monetarized CO2 emissions from heating demand of building in is-state	79'548	Limit of acceptable monetary loss from incapacitation of occupancy	**10'000**		
			Seismic: costs of probable repair works in is-state	**11'640**	acceptable time of incapacitation of occupancy derived from limit of acceptable monetary loss [days]	38		
					acceptable time of incapacitation of occupancy due to non-monetary reasons [days]	**60**		
Total		389'590		245'351		38		0.56
Target factor; Total	**0.7**	272'713	**2**	490'702	**1**	37.68	**0.7**	0.39
After retrofit	seismic: probable repair works	**7'866**	seismic: commensurable costs	**-16'000**	effective time of incapacitation of occupancy	**34**	Min. Compliance factor after seismic retrofit	**0.66**
	seismic: retrofit intervention	**704**	seismic: cost of retrofit intervention	**44'970**			Δα_mean = Δdm_mean/Δdt_mean	**0.12**
	thermal: heating demand in 50 years	**167'580**	thermal: cost of retrofit intervention	**281'590**			Difference averaged compliance factor to ideal compliance factor (1)	0.22
	thermal: retrofit intervention	**12'483**	seismic: monetarized CO2 emissions from probable repair works	1'635.32				
			thermal: costs from heating demand of retrofitted building in 50 years	**66'885**				
			thermal: monetarized CO2 emissions from heating demand of retrofitted building in 50 years	34'840				
			Seismic: costs of probable repair works retrofitted building	12'948				
			Costs from time of incapacitation of occupancy	9'024				
Total		188'632		435'891		34		0.22