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Resilience-enabling interventions based on building typology approach for earthquake applications

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Historic urban centers in seismic regions face heightened vulnerability due to ageing construction systems, heritage constraints, and increasing demands for energy efficiency and climate resilience. This paper presents a typology-driven analysis of earthquake-induced damage in the historic center of Camerino (Italy), based on post-event AeDES (Agibilità e Danno nell'Emergenza Sismica - Usability and Damage in Seismic Emergency) assessment data from the 2016–2017 Central Italy earthquake sequence. Six seismic building typologies, previously identified through hierarchical clustering, are examined with a focus on the distribution, severity, and spatial extension of structural and non-structural damages across key components, including vertical structures, floors, stairs, roofs, partitions, and secondary elements. The results reveal distinct cluster-specific vulnerability patterns, showing that seismic risk is not only associated with the occurrence of damage but critically with its extent and recurrence across building components, with some typologies exhibiting widespread yet localized medium and heavy damage, while others demonstrate greater resilience or consistent but limited damage extension. By linking these detailed damage profiles to the suitability of energy-related and seismic retrofit interventions, the study highlights the added value of component-level damage analysis for prioritizing targeted, and heritage-compatible interventions.

Keywords: building typology, Camerino, historical center, earthquake, clustering, energy interventions.

1. Introduction

A large share of the European building stock remains vulnerable to natural hazards [1, 2], particularly in historic urban centers where buildings were constructed before the introduction of modern seismic and energy performance standards [3-5]. This vulnerability is amplified by the combined effects of seismic activity, climate-related stressors, and ageing construction systems, which disproportionately affect historic masonry buildings and dense urban fabrics [6]. In such contexts, improving resilience requires approaches that can simultaneously address structural safety, energy performance, and heritage constraints.

Building typology [7] has emerged as a key analytical tool for addressing this challenge, enabling the systematic classification of buildings based on shared structural, architectural, and functional characteristics. Typology-based approaches support risk-informed decision-making by identifying groups of buildings with similar vulnerability profiles and retrofit needs [8]. Previous studies have demonstrated strong correlations between typological classes and observed damage patterns following seismic events, as well as differences in retrofit feasibility and performance across building types [9]. As a result, typologies are increasingly used to prioritize interventions and guide adaptation strategies in heterogeneous and historically significant urban areas [10, 11].

Recent advances in data availability and analytical methods have facilitated the development of data-driven building typologies using clustering and machine learning techniques [12, 13]. Such approaches have been applied to cadastral data, energy performance indicators, and post-event damage assessments to support large-scale vulnerability analysis [14, 15]. However, despite their growing use, relatively limited attention has been paid to the internal distribution of damage types and severity levels within identified building clusters, particularly in historic contexts exposed to seismic risk. Understanding not only whether buildings are damaged, but also how damage is distributed across structural and non-structural components, is critical for defining targeted and proportionate retrofit strategies.

The present work builds upon a broader methodological study, which developed a building-typology framework to support climate-proofing and energy retrofit interventions for the built environment, using the historic center of Camerino as a case study. That study introduced the overall typological classification methodology, integrating structural, non-structural, and exposure-related variables to identify building clusters relevant to both seismic and climatic hazards. Building on the previously identified seismic typologies, this contribution shifts the focus from typology identification to cluster-specific damage profiling, examining the distribution of earthquake-induced damage types and severity levels across structural and non-structural components. Six seismic building typologies are analyzed, highlighting how vulnerability is influenced by factors such as building height, use, construction or renovation period.

By systematically analyzing damage distributions within each cluster using post-earthquake assessment data, this study provides a refined understanding of typological vulnerability in Camerino’s historic center. The resulting damage profiles are then used to evaluate the suitability of energy-related and seismic retrofit interventions [16] for each building group, taking into account the constraints imposed by heritage value and seismic regulations [17, 18]. The proposed approach demonstrates how typology-driven clustering, combined with detailed damage analysis, can enhance risk-informed decision-making and support the prioritization of focused adaptation and retrofit strategies in historically sensitive urban environments.

2. Methods: Cluster-specific distributions of damage levels

The dataset employed in the study are originated from AeDES forms (Agibilità e Danno nell'Emergenza Sismica - Usability and Damage in Seismic Emergency) following the 2016–2017 Central Italy earthquake sequence, standardized at the national level and developed by the Department of Civil Protection in collaboration with ReLUIS (Italian Network of University Laboratories of Earthquake Engineering, The digitalization and systematic analysis of these forms through a dedicated database structure enables the transformation of field observations into actionable intelligence for reconstruction planning and resilience building.

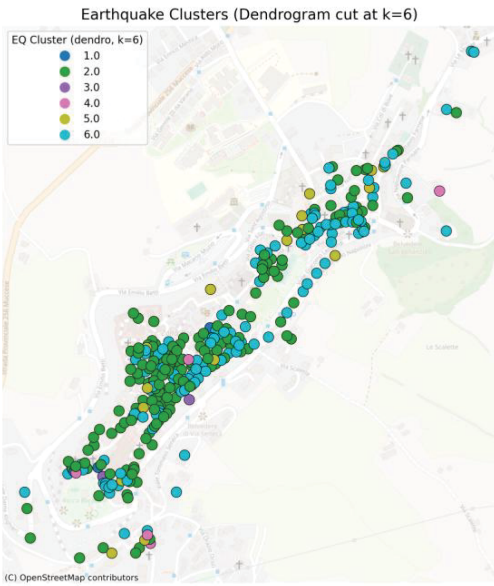

Figure 1. Spatial distribution of clusters.

In addition to the core clustering analysis, the distribution of earthquake-induced damage types and severity levels within each building cluster were examined. For every identified cluster, the frequencies and extents of nominal (e.g., coverings, chimneys) and structural damages (e.g., vertical structures, floors, stairs, roof, partitions, pre-existing conditions) were calculated. This allowed authors to profile the typical damage patterns associated with each building typology and provided a more detailed understanding of cluster-specific vulnerability. These results directly support the prioritization of retrofit interventions and highlight which building groups are most at risk from seismic events in Camerino. The variables used for cluster-specific damage assessment (per cluster):

Structural Damage Variables (by component & damage level)

- Vertical Structures (originally titled in AeDES database: Damage Vertical Structures):
  - F1-1 Very Heavy Damage Vertical Structures
  - F1-1 Medium Damage Vertical Structures
  - F1-1 Slight Damage Vertical Structures
- Floors (originally titled in AeDES database: Damage Floors):
  - F1-2 Very Heavy Damage Floors
  - F1-2 Medium Damage Floors
  - F1-2 Slight Damage Floors
- Stairs (originally titled in AeDES database: Damage Stairs):
  - F1-3 Very Heavy Damage Stairs
  - F1-3 Medium Damage Stairs
  - F1-3 Slight Damage Stairs
- Roof (originally titled in AeDES database: Damage Roof):
  - F1-4 Very Heavy Damage Roof
  - F1-4 Medium Damage Roof
  - F1-4 Slight Damage Roof
- Partition (originally titled in AeDES database: Damage Partition):
  - F1-5 Very Heavy Damage Partition
  - F1-5 Medium Damage Partition
  - F1-5 Slight Damage Partition
- Pre-existing (originally titled in AeDES database: Pre-existing Damage):
  - F1-6 Pre-existing Very Heavy Damage
  - F1-6 Pre-existing Medium Damage
  - F1-6 Pre-existing Slight Damage

Nominal Damage Variables

- Damage Coverings (originally titled in AeDES database: Damage Coverings)
- Damage Tiles Chimneys (originally titled in AeDES database: Damage Tiles Chimneys)
- Damage Eaves (originally titled in AeDES database: Damage Eaves)
- Damage Objects (originally titled in AeDES database: Damage Objects)
- Damage Hydraulic (originally titled in AeDES database: Damage Hydraulic)
- Damage Electric/gas (originally titled in AeDES database: Damage Electric/gas)

The following tables present the percentage distributions of damages for each cluster. Table 1 summarizes the incidence of non-structural damages, such as coverings, chimneys, eaves, objects, hydraulic, and electric/gas systems. The most severe profile is evident in Cluster 2, where nearly all buildings (over 90%) experienced covering damage, and substantial shares showed issues with chimneys (42%) and objects (48%). This indicates a widespread failure of secondary elements, amplifying usability losses. Cluster 1, though very small, also performed poorly, with

100% of buildings showing covering damage and one-third presenting object damage. In contrast, Clusters 4 and 5 show minimal vulnerability, with only isolated cases of coverings or objects damaged. Cluster 6 presents an intermediate condition, with around two-thirds of buildings sustaining covering damage and smaller but non-negligible shares affected in other categories.

Table 1. Damage variables' percentages per cluster.

Cluster Nr.	Damage Coverings (%)	Damage Tiles Chimneys (%)	Damage Eaves (%)
1	100	0	0
2	90.8	41.8	13
3	50	0	0
4	20	20	0
5	18.8	0	0
6	64.8	17.6	4
Cluster Nr.	**Damage Objects (%)**	**Damage Hydraulic (%)**	**Damage Electric/gas (%)**
1	33.3	0	0
2	47.8	7.1	6.5
3	0	0	0
4	0	0	0
5	18.8	0	0
6	24	1.6	0

For the rest of the tables, it is important to be highlighted from AeDES database, that the encoding appearing in columns (0,1,2,3) is the level of three types of damage extension (Slight, Medium, Very Heavy), with 0 meaning no damage or negligible damage, 1 meaning extension >2/3, 2 meaning 1/3< extension<2/3 and 3 meaning extension<1/3. Vertical structures (Table 2) show that Cluster 2 and Cluster 6 have the widest distribution of vertical structure damages. Many buildings fall under code 0 (no/negligible damage), yet sizeable shares show code 3 (damage <1/3) and code 2 (damage 1/3–2/3), indicating partial but significant impacts. Cluster 3 is unique, as all buildings are classified under code 0 for medium/heavy damage but still show code 3 slight damage, meaning universal yet localised impairment. Clusters 1 and 4 display a combination of codes 1 and 3, suggesting that even when vertical structures are affected, the extension of both heavy and slight damages is limited. This confirms the structural fragility of certain clusters despite relatively small portions of the element being compromised.

Table 2. Damage extension percentage for Vertical Structures per cluster.

Damage Vertical Structures	Cluster Nr.	0	1	2	3
Slight Damage Extension (%) by Cluster	1	66.7	0	0	33.3
	2	71.2	0.5	6.5	21.7
	3	0	0	0	100
	4	40	0	20	40
	5	56.2	0	6.2	37.5
	6	40.8	0	12	47.2
Medium Damage Extension (%) by Cluster	1	33.3	0	0	66.7
	2	39.1	10.3	26.1	24.5
	3	100	0	0	0
	4	60	0	20	20
	5	93.8	0	0	6.2
	6	64	0	1.6	34.4
Very Heavy Damage Extension (%) by Cluster	1	33.3	0	0	66.7
	2	36.4	2.2	21.2	40.2
	3	100	0	0	0
	4	100	0	0	0
	5	100	0	0	0
	6	99.2	0	0	0.8

Damage to floors (Table 3) follows a similar trend to vertical structures. Clusters 2 and 6 again exhibit broader variation, with a mix of codes 0, 2, and 3 across slight, medium, and very heavy categories. This suggests that while some buildings were unaffected, others sustained both moderate and localized severe damage. Cluster 3 is once more distinct, as all buildings show floor damage under code 0 for medium/heavy but code 3 for slight, pointing to universal but limited extension damage. Clusters 4 and 5 present mostly code 0 outcomes.

Table 3. Damage extension percentage for Floors per cluster.

Damage Floors	Cluster Nr.	0	1	2	3
Slight Damage Extension (%) by Cluster	1	66.7	0	0	33.3
	2	69	0.5	4.3	26.1
	3	50	0	0	50
	4	80	0	0	20
	5	81.2	0	0	18.8
	6	55.2	0	3.2	41.6
Medium Damage Extension	1	66.7	0	0	33.3
	2	52.7	3.3	15.2	28.8
	3	100	0	0	0

(%) by Cluster	4	100	0	0	0
	5	100	0	0	0
	6	92.8	0	0	7.2
Very Heavy Damage Extension (%) by Cluster	1	66.7	0	0	33.3
	2	75.5	1.1	4.3	19
	3	100	0	0	0
	4	100	0	0	0
	5	100	0	0	0
	6	100	0	0	0

Stair damage (Table 4) is less frequent overall, though patterns align with the vertical structure results. Cluster 2 shows the widest spectrum, with some buildings registering code 1 (extension >2/3) for medium damage and others code 3 (localized impacts). Clusters 1 and 6 show mixed outcomes, including slight and medium damage with code 3 extensions, while Clusters 4 and 5 remain largely undamaged (code 0). Notably, Cluster 3 records universal damage under code 3 slight, pointing again to limited but consistent structural vulnerability.

Table 4. Damage extension percentage for Stairs per cluster.

Damage Stairs	Cluster Nr.	0	1	2	3
Slight Damage Extension (%) by Cluster	1	66.7	0	0	33.3
	2	71.2	1.1	3.8	23.9
	3	50	0	0	50
	4	100	0	0	0
	5	100	0	0	0
	6	72	0	5.6	22.4
Medium Damage Extension (%) by Cluster	1	33.3	0	33.3	33.3
	2	62.5	7.6	12	17.9
	3	100	0	0	0
	4	80	0	0	20
	5	100	0	0	0
	6	92.8	0	0	7.2
Very Heavy Damage Extension (%) by Cluster	1	100	0	0	0
	2	84.2	2.7	7.1	6
	3	100	0	0	0
	4	100	0	0	0
	5	100	0	0	0
	6	99.2	0	0	0.8

Roof damage (Table 5) is widespread across clusters, particularly Clusters 2 and 6, where most buildings exhibit codes 2 or 3 for medium and heavy damage, reflecting non-negligible yet contained impacts. Clusters 1 and 3 again reveal universal roof damage but are consistently coded as 3, meaning heavy but very localised. In contrast, Cluster 5 is the most resilient group, with most buildings coded as 0 (no damage) and only a small minority experiencing slight, localised impairment.

Table 5. Damage extension percentage for Roof per cluster.

Damage Roof	Cluster Nr.	0	1	2	3
Slight Damage Extension (%) by Cluster	1	66.7	0	0	33.3
	2	67.4	2.2	3.3	27.2
	3	50	0	0	50
	4	80	0	0	20
	5	93.8	0	0	6.2
	6	79.2	0.8	0.8	19.2
Medium Damage Extension (%) by Cluster	1	66.7	0	0	33.3
	2	92.9	0.5	2.7	3.8
	3	100	0	0	0
	4	100	0	0	0
	5	100	0	0	0
	6	100	0	0	0
Very Heavy Damage Extension (%) by Cluster	1	100	0	0	0
	2	89.7	1.6	2.7	6
	3	100	0	0	0
	4	100	0	0	0
	5	100	0	0	0
	6	100	0	0	0

Pre-existing damage patterns (Table 6) reveal that most clusters contained buildings with code 0 (no/negligible pre-damage), particularly Clusters 2, 5, and 6. However, in all clusters where pre-existing damage was noted, it consistently appeared as code 3, meaning limited extension (<1/3 of the component). This suggests that although prior vulnerabilities were present, they were typically restricted to small areas.

Table 6. Pre-existing Damage Extension Percentage per cluster.

Damage Pre-Existing	Cluster Nr.	0	1	2	3
Slight Damage Extension (%) by Cluster	1	66.7	0	0	33.3
	2	94	0	0	6
	3	0	0	0	100
	4	80	0	0	20
	5	87.5	0	0	12.5
	6	84.8	0	1.6	13.6
Medium Damage Extension	1	100	0	0	0
	2	98.9	0	0.5	0.5
	3	100	0	0	0

(%) by Cluster	4	100	0	0	0
	5	100	0	0	0
	6	99.2	0	0	0.8
Very Heavy Damage Extension (%) by Cluster	1	100	0	0	0
	2	100	0	0	0
	3	100	0	0	0
	4	100	0	0	0
	5	100	0	0	0
	6	100	0	0	0

Partitions (Table 7) display some of the most varied damage distributions. Cluster 6 shows a high proportion of buildings under codes 2 and 3, indicating both medium and heavy damage, usually affecting smaller fractions of the element. Cluster 2 also demonstrates significant vulnerability, with noticeable percentages in codes 2 and 3 across different severities. By contrast, Clusters 4 and 5 exhibit relatively localized damage, while Cluster 3 once again shows universal impairment, but limited in extension.

Table 7. Damage extension' percentage for Partition per cluster.

Damage Partition	Cluster Nr.	0	1	2	3
Slight Damage Extension (%) by Cluster	1	66.7	0	0	33.3
	2	70.7	2.2	8.7	18.5
	3	50	0	0	50
	4	40	0	0	60
	5	62.5	6.2	0	31.2
	6	27.2	0.8	18.4	53.6
Medium Damage Extension (%) by Cluster	1	0	0	33.3	66.7
	2	34.8	11.4	28.3	25.5
	3	50	0	0	50
	4	40	0	0	60
	5	100	0	0	0
	6	74.4	0.8	5.6	19.2
Very Heavy Damage Extension (%) by Cluster	1	100	0	0	0
	2	69.6	1.6	11.4	17.4
	3	100	0	0	0
	4	100	0	0	0
	5	100	0	0	0
	6	99.2	0	0	0.8

Overall, the distribution of damage levels across clusters highlights distinct typological vulnerabilities in Camerino's building stock. While many buildings in several clusters remained undamaged or showed only negligible impairment (code 0), others consistently exhibited code 3 damage patterns, meaning that very heavy, medium, or slight damage was present but limited to less than one-third of the component. This indicates a recurring trend of localized yet widespread damage across multiple structural elements. Clusters 2 and 6 emerge as the most vulnerable, with high shares of medium and heavy damage spanning vertical structures, floors, stairs, and roofs, confirming their susceptibility to seismic impacts. Conversely, Clusters 4 and 5 show greater resilience, with most damage either absent or confined to minor portions of the components. Cluster 3 stands out as a unique case, where damage was universal but always restricted to limited extensions, pointing to structural fragility without total failure. Taken together, these patterns underline that vulnerability in Camerino is not only a function of whether damage occurs but also of its extent and distribution across building components, a factor that must be carefully considered when prioritising retrofit interventions.

3. Results: Earthquake-related interventions

This section examines the relevance of interventions in reducing earthquake-related vulnerabilities across the six clusters. The ranking highlights both structural and non-structural measures, with higher suitability assigned to clusters showing the greatest fragility. While clusters with severe usability losses benefit most from envelope strengthening, insulation, and monitoring systems, more resilient groups are prioritized for complementary actions such as shading, urban greening, and efficiency upgrades.

Notes on Ratings:

- ★★★★★ = Highly suitable and directly impactful for this cluster's typical building/environment.
- ★★★★☆ = Strongly suitable; likely positive but may need adaptation.
- ★★★☆☆ = Moderately suitable or feasible, with some limitations.
- ★★☆☆☆ = Marginal relevance; possible but not a primary solution.
- ★☆☆☆☆ = Not directly applicable or feasible for heat hazard/urban context.

For clusters with the highest structural vulnerability and unusable status, such as Clusters 1 and 2, interventions emphasizing deep envelope retrofitting, advanced insulation, fire-resistant materials, smart building monitoring, and cooling solutions (both passive and active) receive the highest ratings (see Appendix, Table 8). These clusters also benefit from broader urban greening and community-based resilience actions. Clusters 3 and 4, which include taller or newer buildings that remain partially or fully usable, are rated highly for solutions that further reduce heat stress, improve indoor environmental quality, and integrate smart and renewable energy technologies. Meanwhile, the more resilient low-rise and single-storey clusters (5 and 6), though generally less impacted, are prioritized for interventions that sustain their performance, such as urban shading, nature-based cooling, and low-intrusion efficiency upgrades.

4. Conclusions

This study presented a focused, cluster-based analysis of earthquake-induced damage in the historic center of Camerino, using a systematically digitized dataset derived from AeDES post-earthquake assessment forms following the 2016–2017 Central Italy seismic sequence. Building upon a broader, methodological framework, this contribution specifically examined the distribution, severity, and spatial extension of both structural and non-structural damages within each identified building typology. By analyzing damage frequencies and extension levels across vertical structures, floors, stairs, roofs, partitions, and secondary elements, the study demonstrated that seismic vulnerability is not solely defined by the occurrence of damage, but critically by its extent and recurrence across building components. The results revealed distinct typological behaviors: Clusters 2 and 6 emerged as the most vulnerable groups, with widespread yet often localized medium and heavy damages across multiple structural elements, while Clusters 4 and 5 showed greater resilience with predominantly negligible or isolated impairments. Cluster 3 represented a unique condition, exhibiting universal damage presence but consistently limited extension, indicating latent structural fragility without extensive failure.

Beyond damage characterization, the findings directly supported the prioritization and differentiation of retrofit and resilience-enhancing interventions. By linking cluster-specific damage profiles to the suitability of structural, technological, and nature-based solutions, the analysis enables more targeted decision-making for reconstruction and climate-resilient upgrading in historically sensitive urban environments. Highly vulnerable clusters benefit most from deeper envelope retrofitting, monitoring systems, and structural strengthening measures, while more resilient typologies are better suited for complementary actions such as shading, urban greening, and low-intrusion efficiency upgrades. The added value of detailed, component-level damage analysis in transforming post-earthquake field data into actionable intelligence was demonstrated. The approach reinforces the role of typology-driven assessments as a robust basis for prioritizing interventions, optimizing resource allocation, and enhancing seismic and climate resilience in historic city centers.

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Appendix.

Table 8. Ranking of energy interventions for each cluster.

Solution	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6
Balcony/private garden	★★☆☆☆	★☆☆☆☆	★★★☆☆	★★★★☆	★★★☆☆	★★☆☆☆
Adopted public spaces	★★★☆☆	★★★★★	★★★☆☆	★★★★☆	★★★☆☆	★★★★★
Amenity areas	★★★☆☆	★★★★★	★★★☆☆	★★★★☆	★★★★☆	★★★★★

Parks	★★★☆☆	★★★★★	★★★☆☆	★★★★☆	★★★★☆	★★★★★
Street trees	★★★★☆	★★★★★	★★★☆☆	★★★★★	★★★★☆	★★★★★
Reforestation	★☆☆☆☆	★★★★☆	★☆☆☆☆	★★☆☆☆	★★★☆☆	★★★★☆
Cool/ventilated roofs	★★★★☆	★★★☆☆	★★★★★	★★★★☆	★★★★☆	★★★☆☆
Shading devices	★★★★☆	★★★★☆	★★★★★	★★★★☆	★★★☆☆	★★★★☆
Adequate insulation	★★★★★	★★★★☆	★★★★★	★★★★★	★★★★☆	★★★★☆
Natural ventilation	★★★★☆	★★★☆☆	★★★★☆	★★★★★	★★★★☆	★★★★☆
Fire-resistant materials	★★★★★	★★★★☆	★★★★★	★★★★★	★★★★☆	★★★★☆
Natural daylighting	★★★★☆	★★★☆☆	★★★★☆	★★★★★	★★★★☆	★★★★☆
Building monitoring	★★★★★	★★★☆☆	★★★★★	★★★★☆	★★★☆☆	★★★★☆
Sensors	★★★★★	★★★☆☆	★★★★★	★★★★☆	★★★☆☆	★★★★☆
Renewable energy	★★★★☆	★★★☆☆	★★★★☆	★★★★☆	★★★☆☆	★★★★☆
Energy storage	★★★★☆	★★★☆☆	★★★★☆	★★★★☆	★★★☆☆	★★★★☆
Demand/response	★★★★☆	★★★☆☆	★★★★☆	★★★★☆	★★★☆☆	★★★★☆
Energy communities	★★★★☆	★★★☆☆	★★★★☆	★★★★☆	★★★☆☆	★★★★☆
Light/reflective materials	★★★★☆	★★★☆☆	★★★★★	★★★★☆	★★★★☆	★★★☆☆
Thermal chimneys	★★★☆☆	★★☆☆☆	★★★★☆	★★★★☆	★★★☆☆	★★★★☆
High thermal mass materials	★★★★☆	★★★☆☆	★★★★★	★★★★☆	★★★☆☆	★★★★☆
Active cooling/ventilation	★★★★☆	★★★☆☆	★★★★★	★★★★☆	★★★☆☆	★★★★☆
Geocooling/heat pumps	★★★★☆	★★★☆☆	★★★★☆	★★★★☆	★★★☆☆	★★★★☆
Passive dampers	★★★☆☆	★★★★☆	★★★★☆	★★★☆☆	★★★☆☆	★★★★☆
Jacketing of frame elements	★★★☆☆	★★★★☆	★★★★☆	★★★☆☆	★★★☆☆	★★★★☆
E&M above flood level	★★★☆☆	★★★★☆	★★★☆☆	★★★☆☆	★★★☆☆	★★★★☆
EM-DAT disaster DB	★★☆☆☆	★★★☆☆	★★★☆☆	★★★☆☆	★★★☆☆	★★★☆☆
myclimateservices.eu	★★★☆☆	★★★☆☆	★★★☆☆	★★★☆☆	★★★☆☆	★★★☆☆
OBREC	★☆☆☆☆	★☆☆☆☆	★☆☆☆☆	★☆☆☆☆	★☆☆☆☆	★☆☆☆☆
QoAir (UHI sensors)	★★★★☆	★★★★★	★★★★☆	★★★★★	★★★★☆	★★★★★
Fire protection units	★★☆☆☆	★★★★☆	★★★☆☆	★★★☆☆	★★★☆☆	★★★★☆

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