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# Structural operational efficiency indices for Emergency Limit Condition (I.OPà.CLE): experimental results

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***ABSTRACT*** The index for evaluation of operational efficiency of limit condition of emergency (I.OPà.CLE), developed by the Italian Department of Civil Protection in 2013, is a probabilistic method aimed to assess the operational efficiency of a municipal contingency plan in case of earthquake occurrence. If the physical elements of this system, assimilated to a network, are not able to resist the earthquake, the whole emergency management can be seriously hindered. The system and the element characteristics are provided by the analysis of the limit condition of emergency (LCE). The method, described in previous papers by the same authors, relies on the formulation of synthetic indices expressing the probability for the emergency system and its relevant components to preserve the operational capability for seismic scenario events with different return periods. The paper describes the results of an experimental application of I.OPà.CLE on a sample of 30 analyses of LCE. Each LCE was analyzed in two different layouts: the original one, as conceived by each municipality or appointed institution, and a minimal one, as obtained by reducing the number of physical components to the essential ones. In total 60 I.OPà.CLE analyses were carried out. The former part of the paper deals with the description of LCE analyses of the sample and their physical components, also by a cross comparison through original and minimal systems. In the second part the results achieved by processing I.OPà.CLE are presented and discussed, so as to draw some final considerations in terms of operational efficiency for the two considered configurations.

**Key words:** emergency plan, emergency road network, redundancy, statistical analysis

## 1. Introduction

Over the last years, the emergency planning has become a topic of growing interest in Italy, which benefits of an increasing attention by the scientific community.

This is also due to the considerable efforts made by the Civil Protection Department (DPC) in underpinning applied research addressed to civil protection (Dolce, 2008; Dolce and Di Bucci, 2015). Specific research work is being addressed to road network systems (Bensi *et al.*, 2014; Cavalieri *et al.*, 2016), as well as to seismic performance of critical structures, such as hospitals, schools, bridges, tunnels, and lifelines (water, electricity and gas supply among others) whose failure after an earthquake can seriously hinder the management of the emergency (Borzi *et al.*, 2013, 2014; Weatherill, 2014; Masi *et al.*, 2015). These research fields, extremely detailed in each sector, provided a solid ground to focus on seismic performance of specific assets and to formulate their potential interactions to be applied at urban or territorial scale.

The development of the analysis of the limit condition for the emergency (LCE) of an urban settlement fits into this framework. It was issued in 2010 by the Italian DPC in the context of Italian National Seismic Prevention Program, as operational tool for supporting and improving the emergency planning at municipality level and to establish priorities for seismic vulnerability reduction of critical buildings. The LCE analysis is defined as a specific "*condition of an urban settlement, which is associated with such physical and functional damage as to interrupt most of its functions, including dwellings, while preserving its strategic functions for the emergency management, as well as their needed internal connections and access routes from outside the urban system*" (Dolce, 2012; INU, 2013; Commissione tecnica per la Microzonazione sismica, 2014).

The analysis is conceived as a speedy data collection method capable to describe the essential physical elements of a contingency plan. Thus, it is potentially applicable to any of nearly 8,000 Italian municipalities.

In 2013, DPC developed a further method specific for the evaluation of the operational efficiency of a contingency plan. The index for evaluation of the operational efficiency of limit condition emergency (I.OPà.CLE) is specifically tailored for the minimum set of information required by the LCE analysis. The method, whose formulation is described by the authors in previous works (Dolce *et al.*, 2013, 2017, 2018), is meant to evaluate the operational efficiency of the physical system defined by LCE, providing a quantitative measure of the probability to preserve its efficiency after an earthquake of a given intensity. Being potentially applicable to any municipality of the country, the method is fairly simplified though satisfactorily reliable with respect to the scale of analysis. Seismic events with different return periods can be considered, usually: $T$=98 and $T$=475 years, respectively associated with exceedance probabilities of 40% and 10% in 50 years. Besides, I.OPà.CLE also considers the initial condition of the system, before any earthquake occurrence ($T$=0). The seismic hazard of each municipality is assessed in terms of macroseismic intensity according to the Mercalli-Cancani-Sieberg scale (MCS) (Albarello and Mucciarelli, 2002; D'Amico and Albarello, 2008). The seismic vulnerability of buildings and other structures involved in the analysis relies on the EMS'98 vulnerability classification (Grünthal, 1998).

Coherently with LCE, I.OPà.CLE is applicable to a minimal system, which is assimilated to a network of arcs and nodes, whose physical elements are all and at the same time indispensable for the emergency management. The method follows a bottom-up approach, first analysing individual elements of the contingency system, then passing to the analysis of its subsystems and finally proceeding to the analysis of the system as a whole.

For each physical element (or component) of the LCE analysis (strategic buildings = ESs, emergency areas = AEs, road network segments = RAs, structural units = USs, structural aggregates = ASs), a probabilistic efficiency index is processed by I.OPà.CLE, using the data collected by LCE analysis (Dolce *et al.*, 2018). These elements are, then, each other associated with respect to their functions, so that three different subsystems are defined by I.OPà.CLE:

- subsystem strategic functions (FSs): consisting of one or more critical (or strategic) buildings strictly needed for the emergency management (i.e. coordination centres, hospitals, fire brigade stations, etc.). These elements are considered as strategic nodes of the network.

- subsystem emergency areas and sheltering elements (AREs): including both emergency areas (with storage and sheltering functions) and buildings purposed to recovery. These elements are also considered as strategic nodes of the network.

- subsystem of infrastructural connectivity (CO): including the total number of infrastructural links (or connections) feasible through the emergency road network, defined by consecutive edges, each other joining strategic nodes.

An operational efficiency index is, then, formulated for each of the above subsystems and for the emergency system as a whole (system operational index). Relying on the postulation that the physical components are all strictly indispensable for the contingency management, they are assumed to work in series. This implies that probabilistic efficiency of the first two subsystems is based on the product among the operational indices of their physical components. A specific model is being formulated for infrastructural connectivity, whose calculation relies on the probabilistic analysis of the road network (Dolce *et al.*, 2018). Fig.1 provides a synthesis of all indices calculated by I.OPà.CLE, for the three return periods mentioned ($T$=0, $T$=98, $T$=475 years). Since operational efficiency indices express the probability (of the system, subsystem or individual element) to keep their operability under the considered earthquake, they are all ranging between 0 and 1. Values equal to 1 mean perfect operational efficiency, while smaller values stands for progressively lower performances.

The experimental application of I.OPà.CLE described in the present paper has been carried out on a diversified sample of LCE analyses, in order to allow for some comparative elaborations between different systems. A former step in the experimental phase has been to understand if the chosen examples are *minimal systems*, as required by LCE, or rather if they show functional or infrastructural redundancies. In order to do so, the experimental sample is formerly described in terms of elements included, municipality size, population served and so on. Municipalities are kept anonymous and then simply identified by progressive case-numbers.

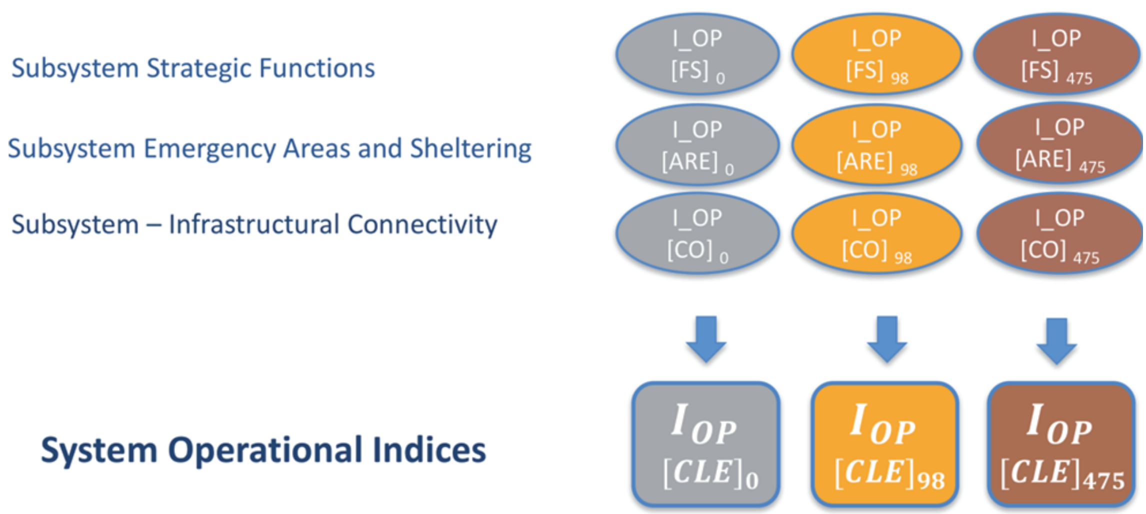



Fig. 1 - Scheme of the indices calculated by I.OPà.CLE.

## 2. Sample characteristics and elements

I.OPà.CLE was applied to a sample of the LCE analyses relevant to 30 municipalities distributed across the Italian territory, as shown in the map of Fig. 2. Municipalities were chosen in order to guarantee a fair assortment in terms of macroseismic intensities for the two considered events and of size, by considering three dimensional classes, as follows:
- 15 municipalities in the 1st dimensional class (lower than 10,000 people);
- 10 municipalities in the 2nd dimensional class (between 10,000 and 50,000 people);
- 5 municipalities in the 3rd dimensional class (over 50,000 people).

The pie charts of Fig. 2 compare the distribution of the three dimensional classes in all Italian municipalities (top) to that in the considered sample (bottom). The experimental sample consists of a lower percentage of small municipalities (1st class) compared to the domestic distribution (50 vs. 85%) and a higher percentage of medium and big municipalities, e.g. 2nd and 3rd class (33 vs. 13% and 17 vs. 2%). However the latter ones were particularly useful in understanding if the dimensional class can somehow affect the operational efficiency of the contingency systems.

The histograms of Fig. 3 show the distribution of population and dwellings of the sampled municipalities with respect to the corresponding macroseismic intensities for the two events considered by I.OPà.CLE. They provide an estimate of hazard and exposure of each municipality: for 98-year return period events, 37% of the municipalities are associated with MCS intensity VI, and the complementary fraction (63%) with VII. The biggest municipalities in the sample (cases 28, 29, 30) are associated with intensity VI. Generally speaking, this return period is related to minor emergencies, which any municipality should be potentially capable to cope with. For events

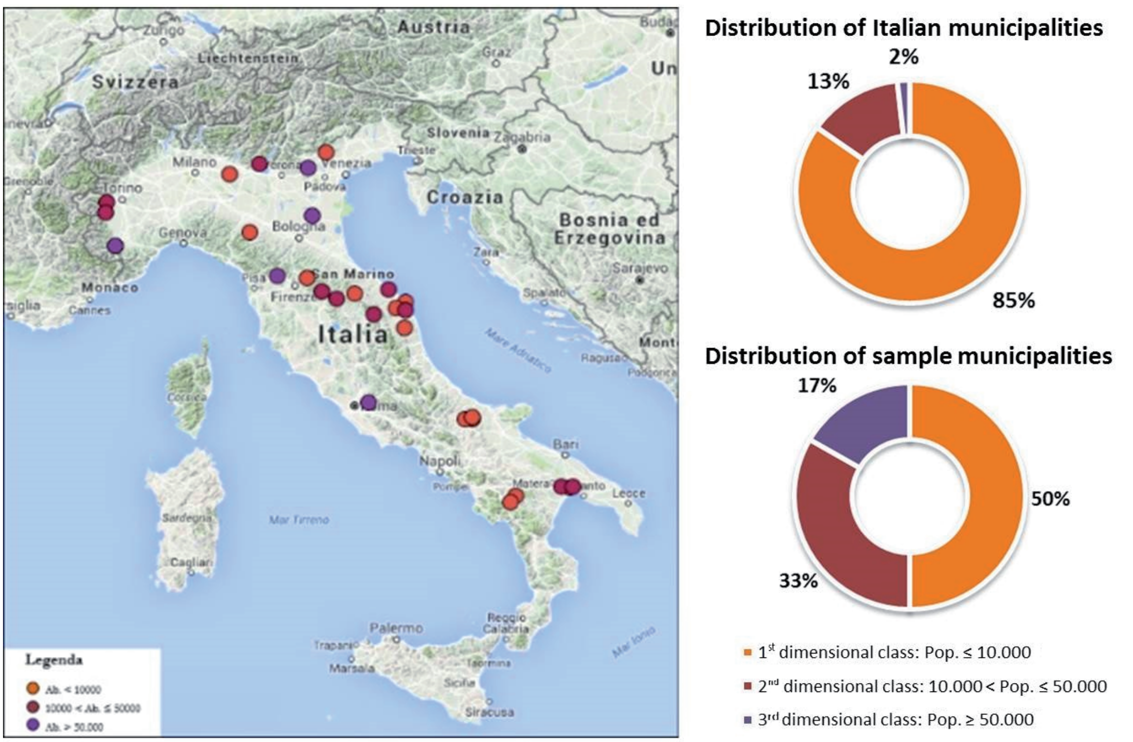



Fig. 2 - Municipalities and associated LCE considered in the sample.

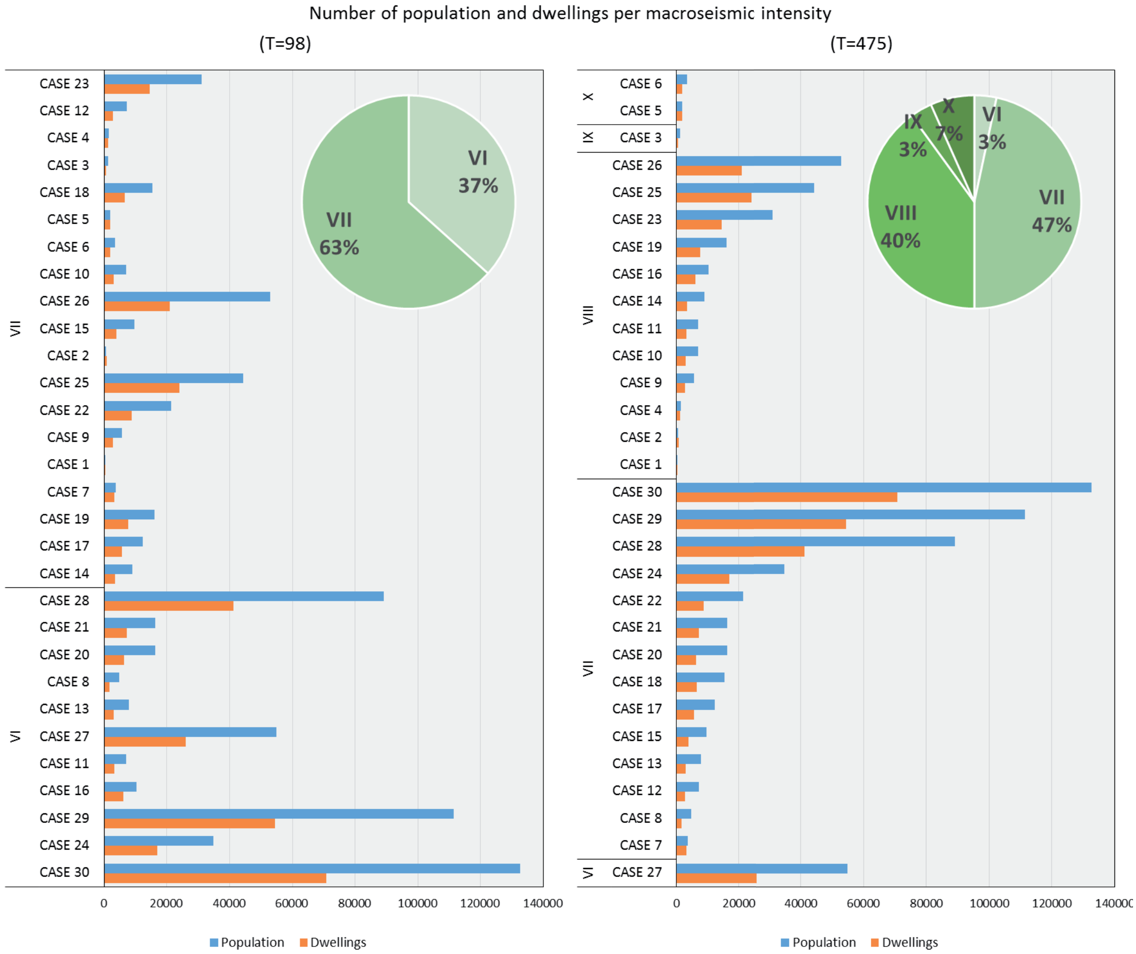



Fig. 3 - Population and dwelling number in the observed sample for the two macroseismic intensities associated with return periods *T*=98 (left) e *T*=475 (right).

with return period *T*=475 years, macroseismic intensities sensibly increase. As a matter of fact, most of the municipalities are associated with VII and VIII degrees (47 and 40% respectively), while just a small rate is over and under these intensities. It is worth noticing that the biggest municipalities in the sample match with intensity VII, 15 medium-sized ones with intensity VIII and 3 of these with IX and X intensities (cases 3, 5, 6).

For the sake of clarity, it is rather unlikely that emergencies triggered by events like these could be entirely managed at municipal level. Rather, they should require the involvement of external resources, deployed by upper administration levels, like the regional or the national ones. However, evaluation through I.OPà.CLE also for this return period (*T*=475 years), can provide helpful hints on potential criticalities which could hinder the emergency management at any level.

## 3. Functional and infrastructural redundancy

Coherently with LCE definition, all strategic components of the LCE contingency system are assumed to be strictly necessary for preserving the functionality of its fundamental functions (emergency coordination, sanitary relief, operational intervention). Despite in real cases some functional interdependencies can be recognized, at this stage of the work no mutual functional dependence was considered by I.OPà.CLE. A typical example of interdependence is the presence of subsidiary components in the emergency plan, tackling exactly the same functions (to make an example 2 hospitals), so as to assure the continuity of the service in case of damage occurred to one of them (one hospital is damaged, the other one keeps safe so that the sanitary relief is somehow preserved). As being a limit condition, the contingency system described by LCE should be conceived as sub-multiple of the real one, so that no subsidiary element should be included in any LCE analysis. In other terms, this condition would not admit, conceptually, any type of functional redundancy on AEs and FSs, these being strategic nodes of the virtual network.

For this purpose, with reference to the LCE sample under observation, a former significant indicator is represented by the number of strategic nodes found out in each system and subsystem above mentioned (corresponding to AE and FS) compared with the size of the municipality. While, on average, the number of strategic nodes of the sample is 13, some differences can be appreciated with respect to the municipality dimensional class. In fact, municipalities of the 1$^{st}$ and 2$^{nd}$ classes include, on average, 10 and 15 strategic nodes respectively (AEs or FSs ether), while in larger municipalities (3$^{rd}$ dimensional class) the mean is 17. However, since the number of AEs is very variable with respect to the urban layout, it can be more useful to refer this amount to FSs only (including hospitals, municipalities, fire brigade station, coordination centres, and so on). In this case, on average, there are six FSs per municipality (and corresponding nodes of the network), more specifically 5 and 7 for the 1$^{st}$ and 2$^{nd}$ dimensional classes and 8 for the 3$^{rd}$ one. Fig. 4 highlights that the number of FSs increases less than linearly with the municipality population. However, the significant dispersion of the chart, especially for largest municipalities, confirms the lack of a uniform rule in the design of the LCE analyses under investigation. A similar trend, even with larger dispersion, can be observed for AEs. To sum up, the emergency systems of the sample, especially those of small-medium municipalities, seem to be averagely far from minimal endowment and, consequently, not fully compliant with LCE requirements.

When considering the analysis of infrastructural networks, on the contrary, infrastructural redundancies are necessarily processed by I.OPà.CLE, in order to make a proper probabilistic calculation of CO subsystem. In particular, the probability of success of any infrastructural connection between two generic strategic nodes, depends on the total probability of the possible alternative routes existing for that specific link, enabling the mutual connection of the two nodes (Dolce *et al.*, 2018).

Fig. 5 illustrates the redundancies of the infrastructural systems expressed as the ratio between the total number of routes existing in each system and the number of relevant infrastructural links per municipality, for the three dimensional classes considered. As one might expect, the infrastructural redundancy is higher in medium and large municipalities (2$^{nd}$ and 3$^{rd}$ class), while it is smaller in smaller ones (1$^{st}$ class). In fact, by increasing the municipality size, its complexity equally increases also in terms of road network and, consequently, of alternative routes. However, there are still few cases (one in 2$^{nd}$ class and two in 3$^{rd}$ class) whose infrastructural networks do not provide alternative routes, being their ratios equal to 1. Typically, a non-redundant configuration is a straight road segment crossed by independent transversal arcs. The mean values of the routes/connections ratio confirm this: while in small municipalities this ratio is equal to 1.5, in medium and large municipalities it is around the double (3.5 and 2.8 respectively for 2$^{nd}$ and 3$^{rd}$ class).

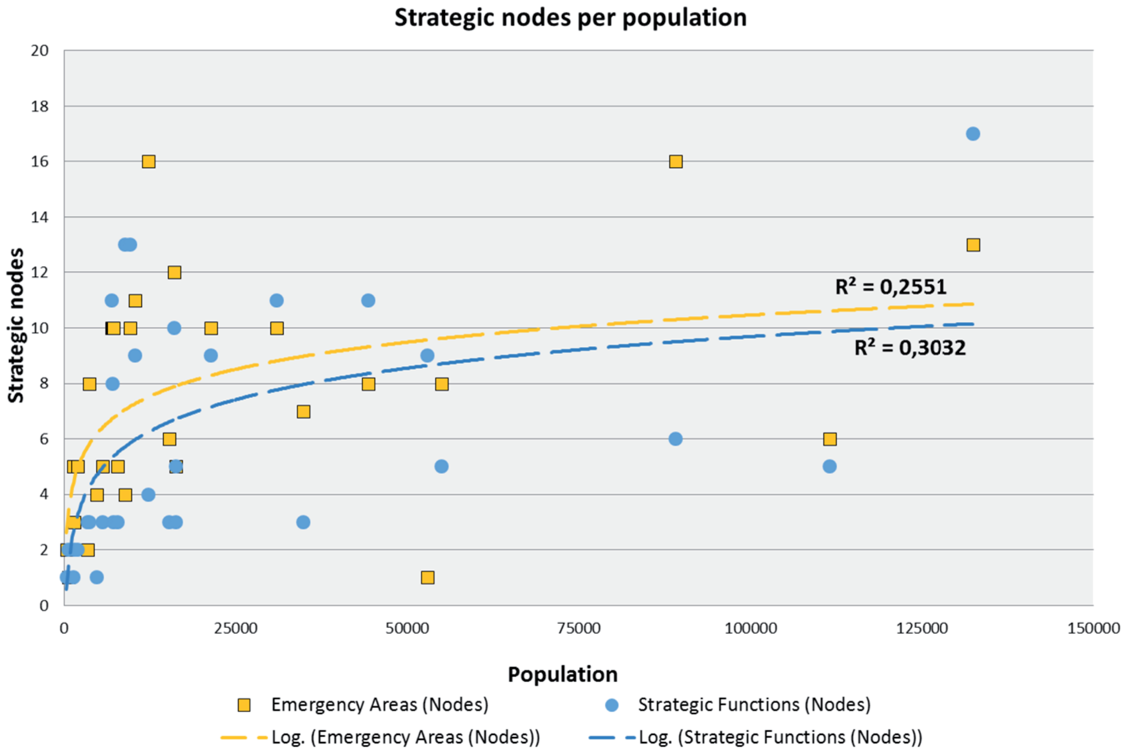



Fig. 4 - Number of strategic elements per population.

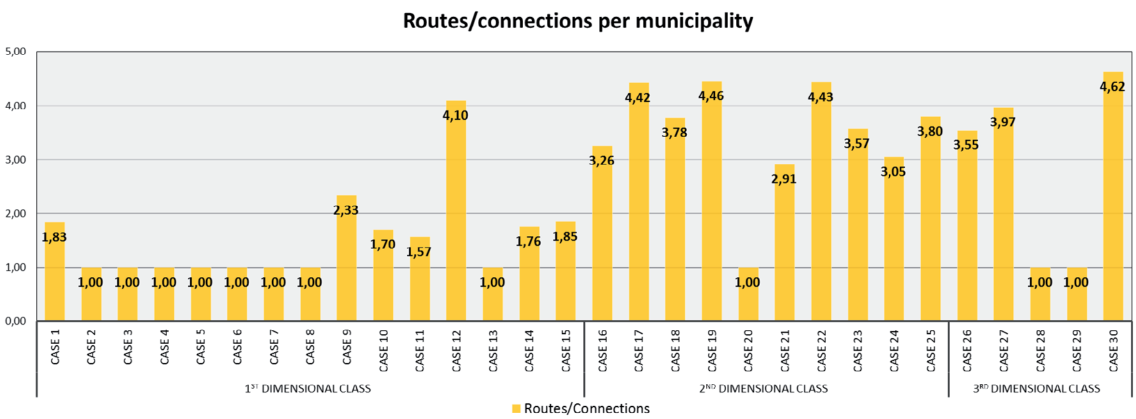



Fig. 5 - Routes/connections ratio per municipality.

However, it is worth to note that the number of strategic nodes (AEs and FSs), is directly correlated with the infrastructural connectivity. In fact, strategic nodes govern, through an exponential trend, the number of resulting infrastructural links of the network (Dolce *et al.*, 2018). Over the whole sample, the average number of infrastructural links per municipality is 93, while the average number of connections is 51, 123 and 158, for the 1st, 2nd, and 3rd class, respectively.

Fig. 6 shows the different relationships between the number of infrastructural connections and the three considered dimensional classes.

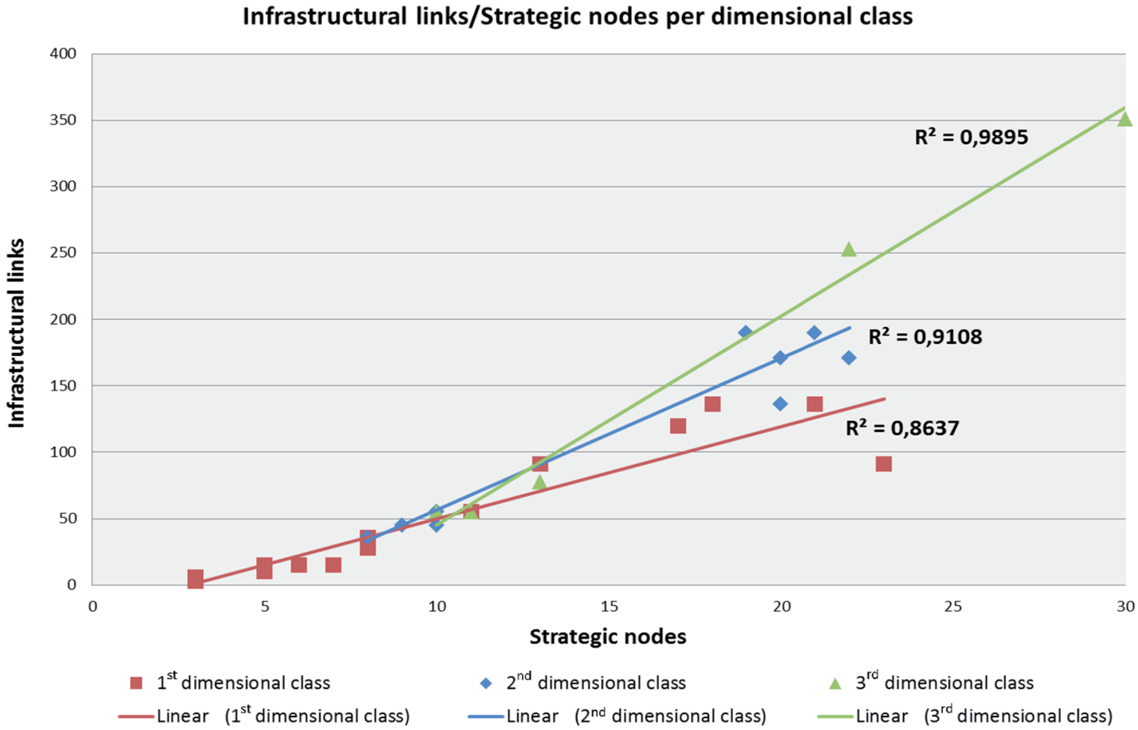


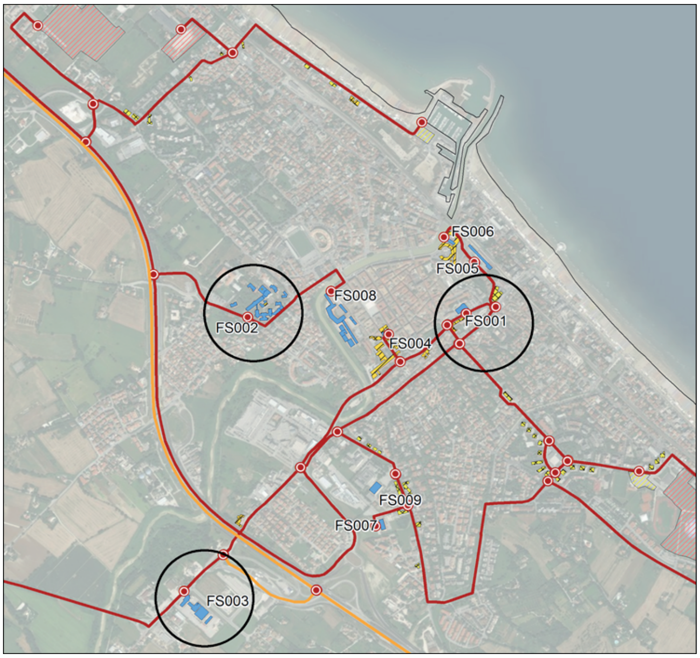

Fig. 6 - Relationship between infrastructural links and strategic nodes by population size class.

## 4. LCE and simplified LCE

The notable variability among LCE analyses, in terms of numerousness of strategic nodes and road network connections, brings about that their mutual comparison is not straight. As a consequence, a criterion was required in order to make their comparative analysis more reliable and application of I.OPà.CLE more consistent. In fact, it turned out from the previous analysis, that most of the CLE analyses are far from being minimal, as they are supposed to be coherent with the LCE concept. Thus, a simplification has been made through the reduction of the number of FSs, while preserving the number of EAs, as they strongly depends on the topography of the municipality. Three basic FSs were preserved in each minimal system: emergency coordination, sanitary relief, and operational intervention.

Fig. 7 shows an example of a simplified LCE: the emergency system in its original configuration, consists of 11 FSs and 8 AEs, with a total of 19 strategic nodes and 190 resulting mutual infrastructural links. The simplified configuration preserves only the buildings serving the three mentioned functions: municipal emergency coordination (FS001), hospital (FS002) and fire brigade headquarters (FS003). In Fig. 7, they are pointed out with a black circle. The resulting system has 11 strategic nodes and 66 relevant connections.

Because of the exponential ratio between strategic nodes and infrastructural links, the reduction of the former implied a considerable reduction of the latter. For 10 municipalities of the sample, the decrease of FSs reached 50% (in two cases FSs reduce from 13 to 3 in total) with a consequent 75% decrease of the number of connections, while around one third of the municipalities (11 out of 30) remained unchanged, being already sufficiently simplified.




| LCE ANALYSIS | |
|---|---|
| n. Strategic Nodes | 19 |
| n. Strategic Functions | 11 |
| n. Emergency Areas and Sheltering | 8 |
| n. Access Nodes | 2 |
| n. Connections | 190 |
| **SIMPLIFIED LCE ANALYSIS** | |
| n. Strategic Nodes | 11 |
| n. Strategic Functions | 3 |
| n. Emergency Areas and Sheltering | 8 |
| n. Access Nodes | 2 |
| n. Connections | 66 |
| **ROAD NETWORK (LCE)** | |
| n. Routes (max) | 950 |
| n. Routes (min) | 190 |
| n. alternative Routes | 722 |
| **ROAD NETWORK (SIMPLIFIED LCE)** | |
| n. Routes (max) | 330 |
| n. Routes (min) | 66 |
| n. alternative Routes | 226 |

Fig. 7 - LCE example layout with three minimal FSs highlighted.

Fig. 8 compares the number of original strategic nodes with those in the simplified systems. For the 1st dimensional class the average reduction of strategic nodes is 23%, for the 2nd class is 20%, and for the 3rd class is 19%, consistently with the above considerations on the functional redundancy.

The histogram of Fig. 9 illustrates the number of connections in the original LCEs and the simplified ones. It is evident how the reduction of FSs, and consequently of strategic nodes, implies a significant reduction of the resulting connections.

## 5. Operational efficiency indices

Operational efficiency indices, providing the probabilities of preserving the functionality of the whole emergency system, of subsystems and of physical elements, were calculated through I.OPà.CLE for the two return periods ($T$=98 and $T$=475 years), as well as in absence of earthquake ($T$=0). The calculation was processed for both original and simplified LCE analyses.

Fig. 10, left, relevant to a return period of $T$=98 years, shows to what extent the operational indices of the systems, in their original configuration, are influenced by indices of relevant subsystems. Regression lines associated with each subsystem help for a better understanding of the system features. The closer a line is to the red diagonal, the more the subsystem to which it refers affects the whole performance. It turns out that the subsystem that mostly affects operational efficiency is infrastructural connectivity, which is often characterized by very low indices, next to 0, and hence determines the order of magnitude of operational indices of the systems they belong to. In fact, the high number of infrastructural connections is the major responsible of the low probability of this specific subsystem. The graph on the right is relevant to the simplified LCE sample. No substantial difference with the graph on the left is detected. Also in the

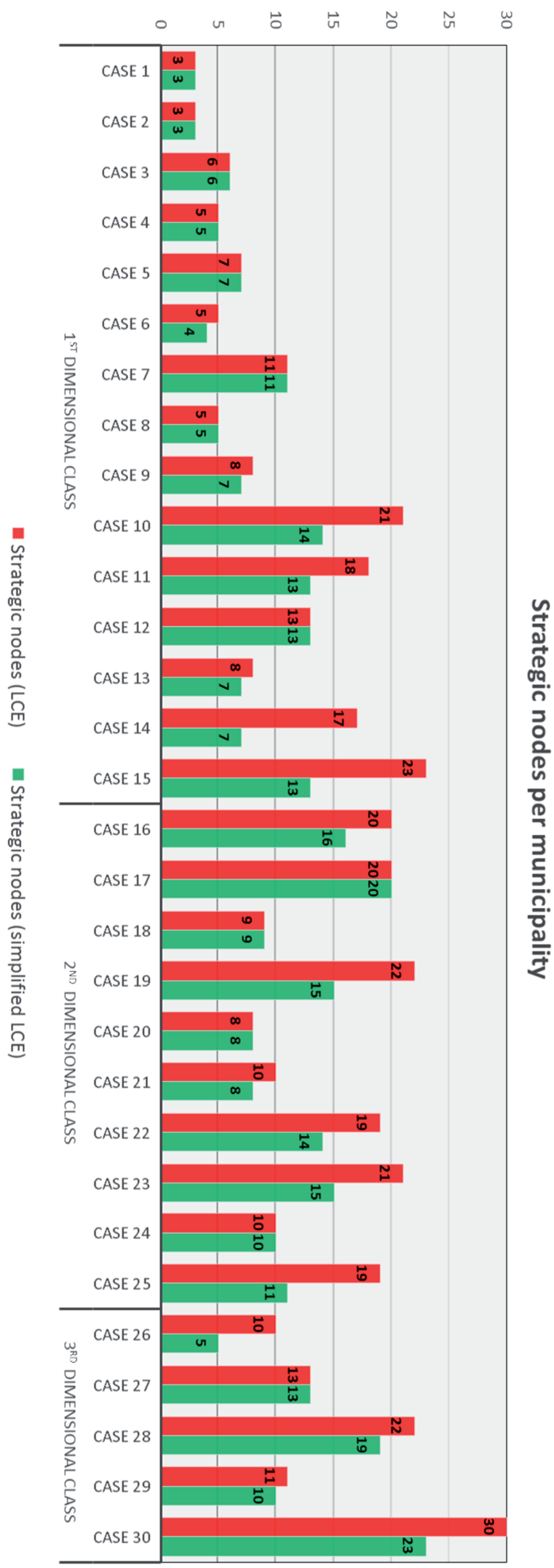



Fig. 8 - Strategic nodes per LCE and simplified LCE.

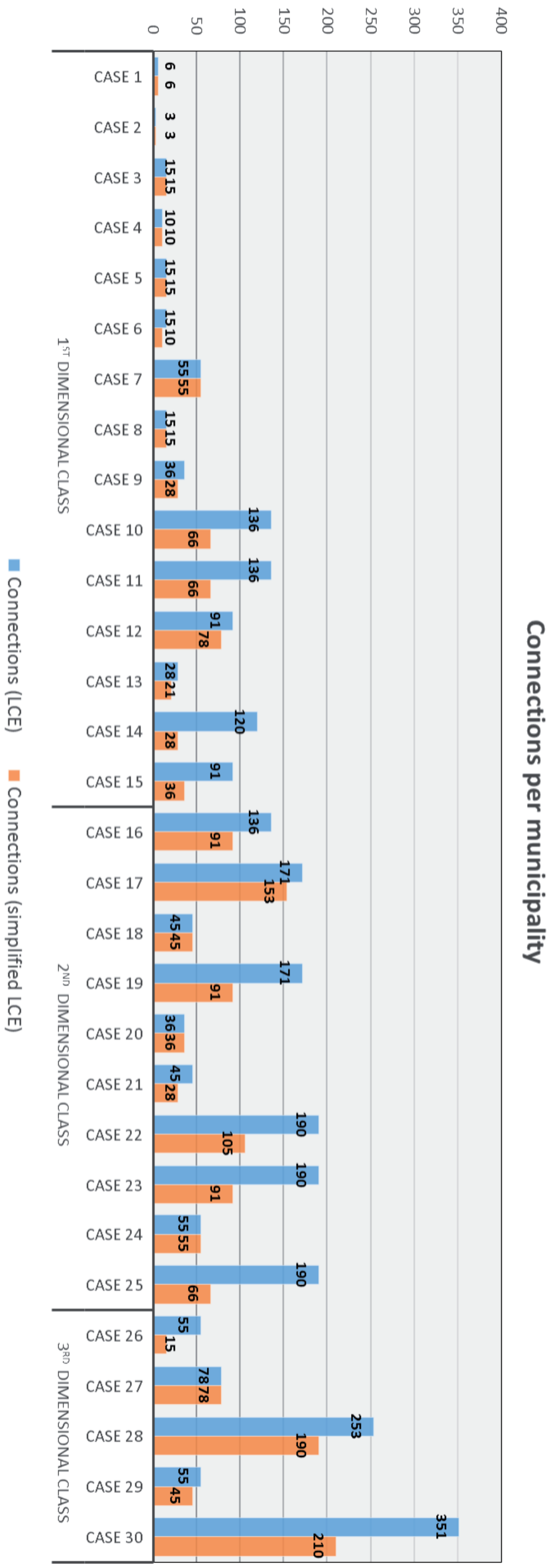



Fig. 9 - Connections per LCE and simplified LCE.

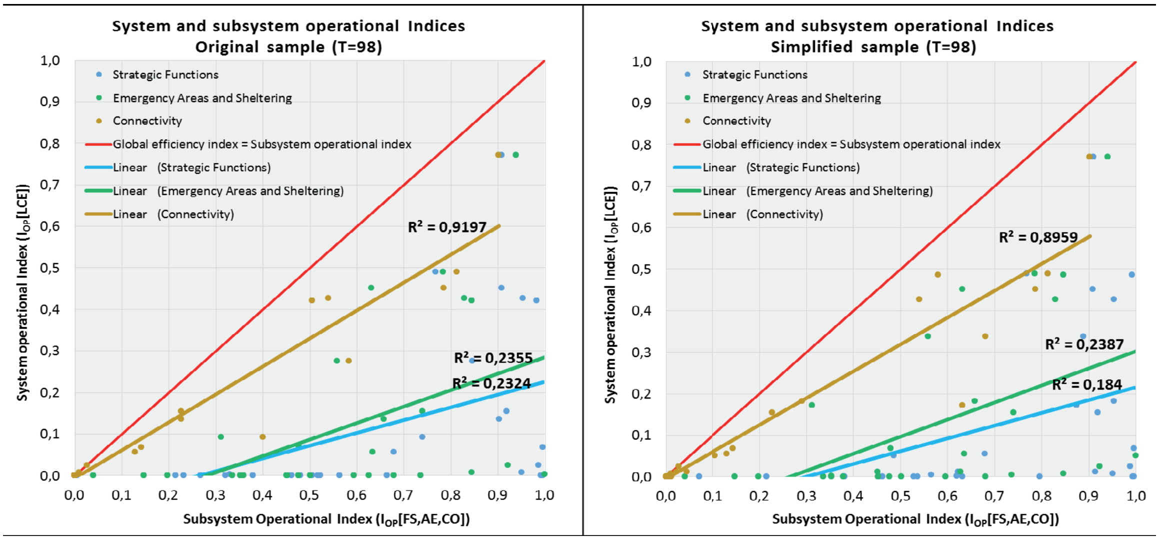



Fig. 10 - Relationship among subsystem operational indices and indices of the systems for the original LCE sample (left) and simplified one (right).

simplified analyses the infrastructural connectivity remains the most influential subsystem.

This aspect is further investigated in the graphs of Fig. 11, relevant to the original sample and to the simplified one (left and right respectively). The graphs show the distribution of system operational indices, for the three return periods, as a function of the number of strategic nodes of the network they refer to. Y-axis is in logarithmic scale due to the large variability of the indices.

In accordance with the formulation of the model, by increasing the number of strategic nodes, the operational indices of the system tend to decrease. Similarly, by increasing the severity of the event, the operational indices are progressively lower. Regression lines associated with the indices relevant to the three return periods are, in fact, progressively staggered toward lower probabilities. It is worth noticing that in both graphs, for $T$=0, thus in absence of earthquake, the operational probability is significantly lower than 1, due to intrinsic criticalities of relevant physical components belonging to one or more subsystems. The trend of the regression line in the absence of earthquake is, in fact, not far from that of $T$=98 years. However, it can also be noticed that the lowest correlation factor associated with the regression line at $T$=475 (0.098) is attributed to the larger dispersion of macroseismic intensities found for this return period, as outlined in Fig. 3 (right).

When looking at the simplified systems (Fig. 11 right), the regression lines, despite preserving a similar dependency on the number of nodes of the network, show a substantial increase of the operational probability compared with the original systems. This is basically due to the fact that by reducing the number of strategic nodes and associated infrastructural links, the operational indices of subsystems (FSs and CO) tend to increase and likewise the indices of the whole systems.

The histogram of Fig. 12 illustrates, for each LCE analysed, the ratio between the operational indices relevant to the original and the simplified LCE respectively.

One can note that 11 case studies (36% of total) show ratios equal to 1, since these systems were already minimal or almost so. Indices of the remaining cases even for $T$=0, are lower than 1 and progressively decreasing down to values very close to 0. Just in few cases the reduction rates are small (around 30% with respect to $T$=98 years), while residual case studies show very high reduction rates (up to 90%).

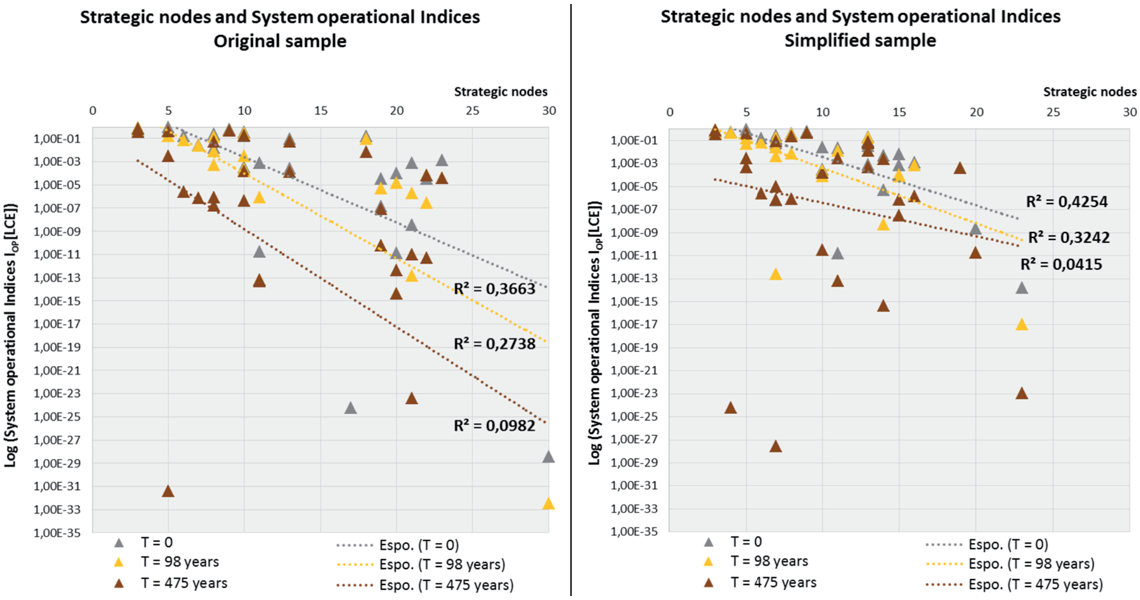



Fig. 11 - System operational indices and strategic nodes for original LCE sample (left) and simplified (right).

## 6. Operational classes

Statistical elaborations previously carried out by the authors (Dolce *et al.*, 2017, 2018) suggested the definition of a set of operational classes, that summarise the characteristics and potential criticalities of the system as a whole, as well as of its subsystems, in order to easily check the potential criticalities of each system. The operational classes are defined by considering three parameters: the probabilistic index of the system or subsystem, the mean values ($\mu$) and the standard deviation ($\sigma$) of the indices of the elements belonging to the considered system or subsystems [e.g. all the strategic functions included in the subsystem FSs: Dolce *et al.*, (2018)].

The probabilistic index is arranged in five subclasses, ranging from A (very high probability) to E (very low probability). Mean value and standard deviation are arranged in three subclasses each, ranging from 1 (operational efficiency averagely high) to 3 (operational efficiency averagely low), and from “a” (high uniformity) to “c” (low uniformity), respectively for mean value and standard deviation. The combination of the above subclasses brings about the 45 classes shown in Table 1.

On the basis of the results of the I.OPà.CLE analyses, all the LCE of the sample have been assigned a class. The graphs of Figs. 13, 14, 15, and 16 illustrate the distribution of subclasses, for the systems and their subsystems respectively. Results are delivered for the 3 return periods and for the original and simplified configurations of LCE.

As shown in Fig. 13, yet in the absence of earthquake (*T*=0), 50% of the LCE analyses is characterised by probabilistic indices falling in the last subclass E (probabilistic operational efficiency very low, <1% probability), outlining the presence of considerable critical elements intrinsic to the system (either complexity or lack of redundancy of the infrastructural system or low quality indices of the elements). The rest of the LCE analyses in the original configuration mostly fall in classes D and C, that means low (1-25%) and fair (26-50%) probability. The simplification of the systems improves the operational efficiency and the subclass assignment consequently. In

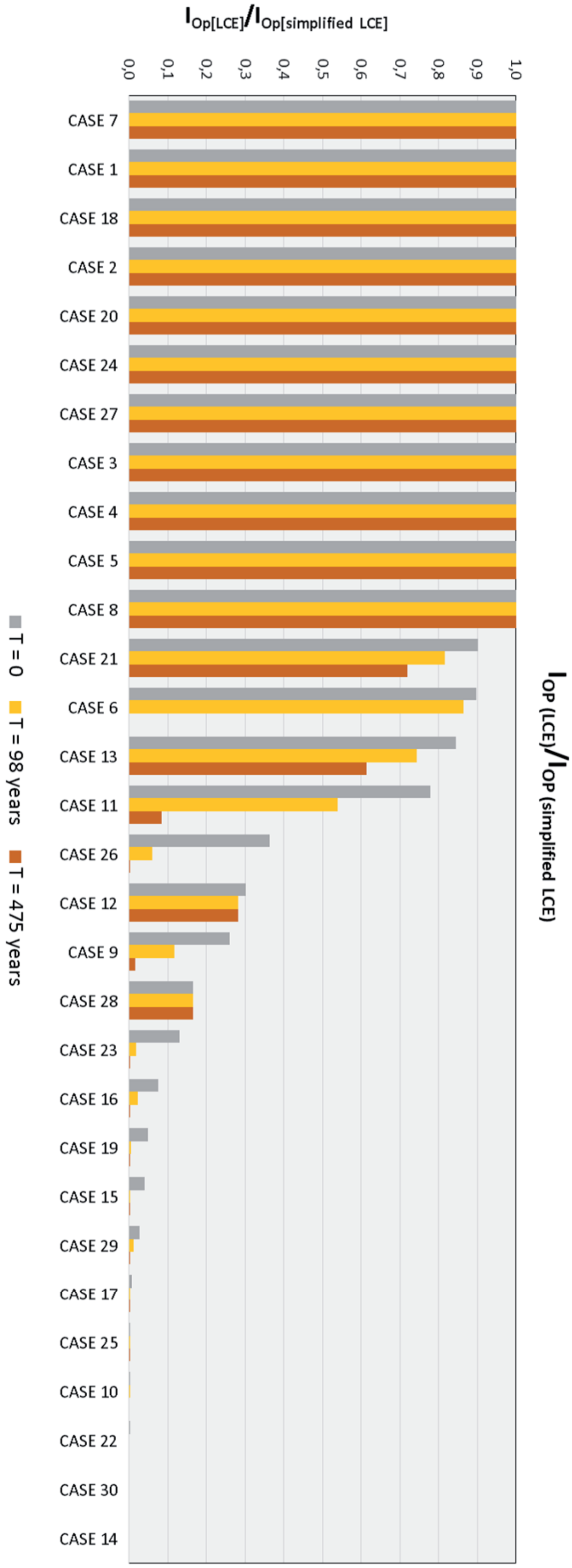



Fig. 12 - Ratios between $I_{OP\ (LCE)}$ and $I_{OP\ (simplified\ LCE)}$

Table 1 - List of 45 operational classes, defined as combination of subclasses

| | | | | |
|---|---|---|---|---|
| **A1a** | **B1a** | **C1a** | **D1a** | **E1a** |
| **A1b** | **B1b** | **C1b** | **D1b** | **E1b** |
| **A2a** | **B2a** | **C2a** | **D2a** | **E2a** |
| **A1c** | **B1c** | **C1c** | **D1c** | **E1c** |
| **A2b** | **B2b** | **C2b** | **D2b** | **E2b** |
| **A3a** | **B3a** | **C3a** | **D3a** | **E3a** |
| **A2c** | **B2c** | **C2c** | **D2c** | **E2c** |
| **A3b** | **B3b** | **C3b** | **D3b** | **E3b** |
| **A3c** | **B3c** | **C3c** | **D3c** | **E3c** |

fact, in the simplified layout, the worst class (E) lessens to 40% (12 systems out of 30), and brings about a slight increase of more operational class such as D. The same trend can be also observed in case of earthquake with $T$=98 and $T$=475.

By examining the other parameters (mean value and standard deviation), the high and fair mean values observed (subclasses 1 and 2), associated with a low-medium standard deviation (subclasses "a" and "b" corresponding to high and fair uniformity), emphasise that in several cases low probabilities resulting from analyses can be attributed to the complexity of the systems (in terms of number of components), rather than to specific improper functioning of few components. In fact, at $T$=0,90% of CLE's (27 out of 30 falling in classes a and b) are characterized by high to fair uniformity. The remaining 10% is characterized by low uniformity, implying that criticalities can be due to singular though not fully operational elements (such as alluvial ground of AEs or vulnerable or damaged strategic buildings). By increasing the earthquake severity ($T$=98 and $T$=475), the probabilistic index worsens with consequent increase of subclass E.

Similar remarks can be made for subsystems, by examining the distribution of the relevant operational subclasses. Fig. 14 considers FSs. Although a good percentage of the FS structures (hospitals, schools, fire brigade stations, and so on) is associated with very high and high operational probability, a notable percentage shows initial indices ($T$=0) lower than 50%, falling in subclasses C and D. This means that the selection of strategic elements in emergency plans does not always occur in the appropriate way from a functional point of view.

The subsystem of AREs (Fig. 15) is also affected, to a greater extent, by intrinsically critical elements, such as the absence of utilities (water or electricity or sewerage) or the presence of

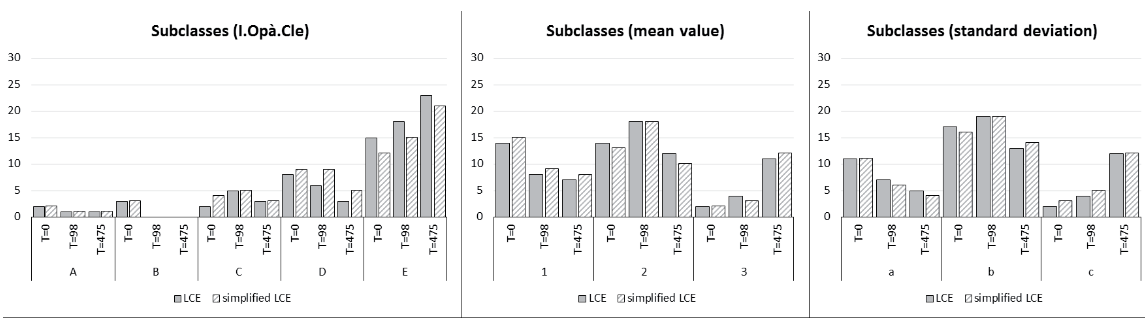



Fig. 13 - Operational subclasses of systems (LCE and simplified LCE).

criticalities due to either geology or hydrogeology of the location, while it is less affected by indirect damage resulting from the risk of collapse of structural units placed on area borders. The distribution of the sample, in fact, remains virtually unchanged for the three reference events, with a slight worsening for events with a return period of 475 years. As previously outlined, the subsystem of AREs does not suffer any reduction in the passage to simplified LCE layouts and, therefore, operational classes remain unchanged.

The distribution of the subclasses related to the subsystem of infrastructural CO, shown in Fig. 16, follows the trend observed in Fig. 13 for operational indices of systems, in line with previous observations. This subsystem, even for *T*=0, is affected by very low probabilistic indices, implying that 50% of the sample falls in subclass E. This amount increases up to 70% for events for *T*=475. The complexity of the network is one of the main causes determining the large amount of class E, depending on the numerousness of the samples analyzed. However, still in this case, the functionality of subsystems is also hindered by specific critical road segments with some specific vulnerabilities or road impediments.

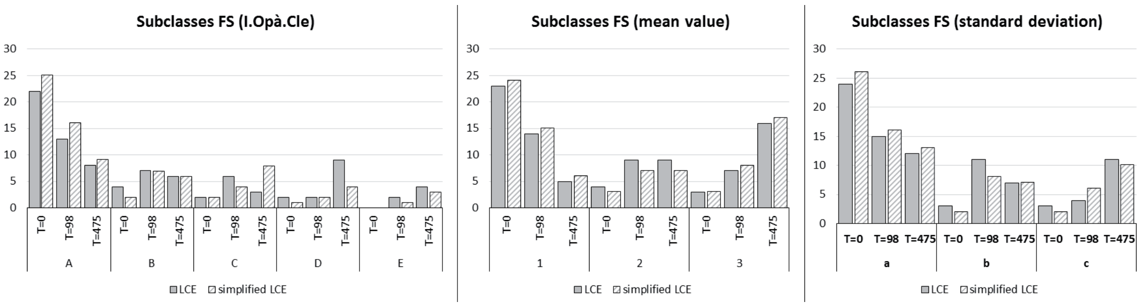



Fig. 14 - Operational subclasses of subsystem FS (LCE and simplified LCE).

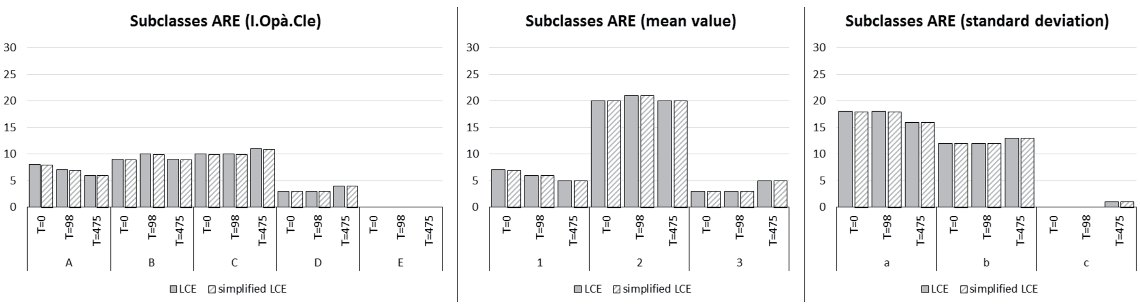



Fig. 15 - Operational subclasses of subsystem ARE (LCE and simplified LCE).

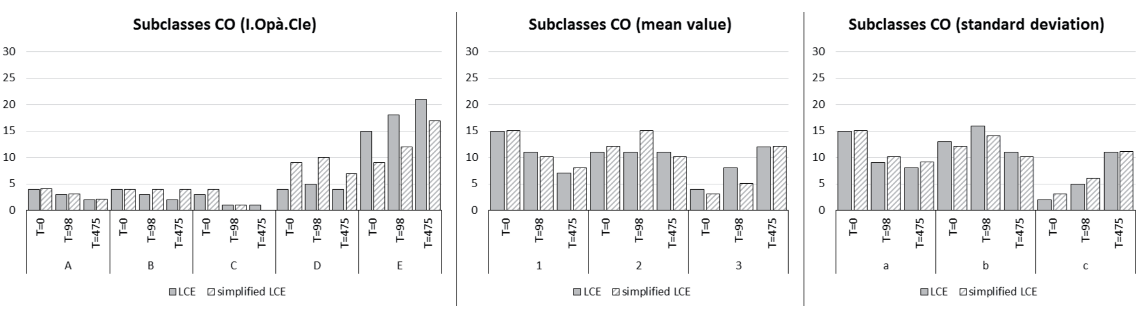



Fig. 16 - Operational subclasses of subsystem CO (LCE and simplified LCE).

## 7. Case study

In order to make the method and its capabilities clearer, an application of I.OPà.CLE to a specific municipality is illustrated. Coherently with the objectives of this work, the application is carried out for both the original and the simplified layout of the LCE analysis. The example is chosen among those of the experimental sample (case 25), whose map is shown in Fig. 7. The municipality belongs to the 2nd dimensional class above introduced. The intensities associated with the two considered return periods (*T*=98 and *T*=475 years) are VII and VIII MCS respectively.

The emergency system is sketched on the right hand table of Fig. 7, including the list of nodes, FSs, AEs and infrastructural connections in the double hypothesis of original and simplified layout. The layout is characterized by a central infrastructural network with lateral ramifications leading to strategic nodes (FSs or AEs). The infrastructural redundancy is not high, apart from the right hand side of the map, showing a close-circular path.

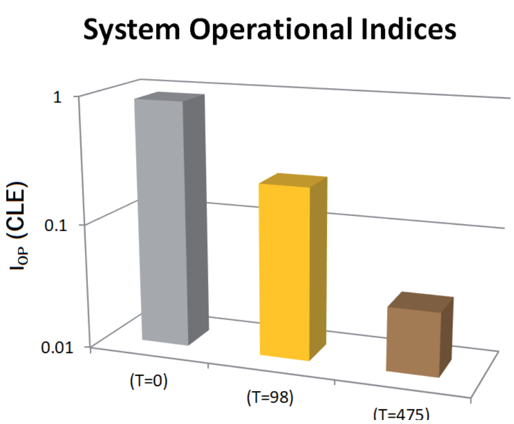
The reduction process of the emergency system is the one already described in chapter 4: FSs are reduced from 11 to 3, preserving just those strictly indispensable for the emergency management (FS1 - town council, FS2 - hospital and FS3 - fire brigade station). The eight AEs are unchanged.

Figs. 17 and 18 show the results achieved for the two configurations.

The whole system of the original LCE analysis is characterized by a very low probability of preserving operational efficiency (indices next to 0), even for *T*=0, with a resulting overall class E1b. It turns out that, even in absence of earthquakes, the system presents some intrinsic criticalities in one of its subsystems and related physical components. When looking at subsystems, on the right hand side of the figure, one can note that FSs are fairly working in absence of earthquake.

CASE 25 (Original Emergency System)

| | (T=0) | (T=98) | (T=475) |
|---|---|---|---|
| $I_{OP}$ (CLE) | 3.34E-05 | 4.92E-06 | 7.80E-08 |
| Mean value (μ) | 0.9553 | 0.9472 | 0.9317 |
| Standard deviation (σ) | 0.0760 | 0.0818 | 0.0997 |
| Operational class | E1b | E2b | E2b |




| | (T=0) | (T=98) | (T=475) |
|---|---|---|---|
| $I_{OP}$ (FS) | 0.9000 | 0.2329 | 0.0321 |
| Mean value (μ) | 0.9909 | 0.8858 | 0.7734 |
| Standard deviation (σ) | 0.0287 | 0.1269 | 0.2273 |
| Operational class | A1a | D2b | D3c |

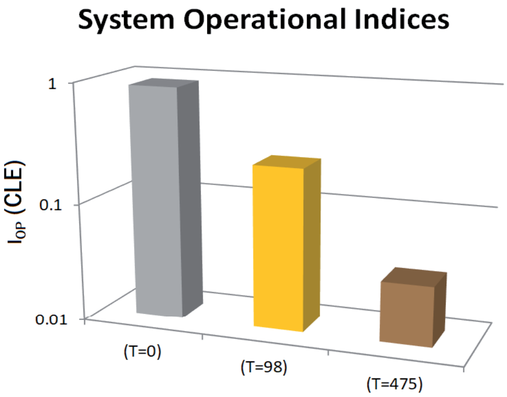
| | (T=0) | (T=98) | (T=475) |
|---|---|---|---|
| $I_{OP}$ (ARE) | 0.4533 | 0.4516 | 0.4366 |
| Mean value (μ) | 0.9075 | 0.9071 | 0.9034 |
| Standard deviation (σ) | 0.0547 | 0.0548 | 0.0563 |
| Operational class | C2b | C2b | C2b |

| | (T=0) | (T=98) | (T=475) |
|---|---|---|---|
| $I_{OP}$ (CO) | 8.2E-05 | 4.7E-05 | 5.6E-06 |
| Mean value (μ) | 0.9552 | 0.9524 | 0.9420 |
| Standard deviation (σ) | 0.0775 | 0.0774 | 0.0789 |
| Operational class | E1b | E1b | E2b |

Fig. 17 - I.Opà.CLE operational indices (original LCE).

CASE 25 (Simplified Emergency System)

| | (T=0) | (T=98) | (T=475) |
|---|---|---|---|
| $I_{OP}$ (CLE) | 0.0227 | 0.0125 | 0.0027 |
| Mean value (μ) | 0.9565 | 0.9497 | 0.9346 |
| Standard deviation (σ) | 0.0866 | 0.0914 | 0.1098 |
| Operational class | D1b | D2b | E2b |




| | (T=0) | (T=98) | (T=475) |
|---|---|---|---|
| $I_{OP}$ (FS) | 1.0000 | 0.6227 | 0.2732 |
| Mean value (μ) | 1.0000 | 0.8644 | 0.6976 |
| Standard deviation (σ) | 0.0000 | 0.1302 | 0.2347 |
| Operational class | A1a | B2b | C3c |

| | (T=0) | (T=98) | (T=475) |
|---|---|---|---|
| $I_{OP}$ (ARE) | 0.4533 | 0.4516 | 0.4366 |
| Mean value (μ) | 0.9075 | 0.9071 | 0.9034 |
| Standard deviation (σ) | 0.0547 | 0.0548 | 0.0563 |
| Operational class | C2b | C2b | C2b |

| | (T=0) | (T=98) | (T=475) |
|---|---|---|---|
| $I_{OP}$ (CO) | 0.0502 | 0.0445 | 0.0226 |
| Mean value (μ) | 0.9604 | 0.9587 | 0.9492 |
| Standard deviation (σ) | 0.0894 | 0.0894 | 0.0911 |
| Operational class | D1b | D1b | D2b |

Fig. 18 - I.Opà.CLE operational indices (simplified LCE)

However operational indices quickly lessen with earthquake because of the high vulnerability of its critical buildings (passing from class A1a to D3c for $T$=475 years). ARE subsystem seem to be characterized by specific intrinsic criticalities (as natural background and lack of utility supply). However, when looking at the CO subsystem it becomes clear that this is the subsystem mostly governing the performance of the whole system. This is partially due to the high number of infrastructural links (190) but also to some criticalities of the road network, at $T$=0, as outlined by mean values (1-high) and standard deviations (b-fair uniformity) of the relevant class. So that operational classes pass from E1b ($T$=0) to E2b ($T$=475 years).

Considering the simplified model (Fig. 15), the system rises to operational classes such as D1b, D2b, E2b for the three return periods. When analyzing subsystem by subsystem, FSs show a steep decrease of classes from $T$=0 to $T$=98 years and to $T$=475 years (class passes from A1a to D2b and to D3c respectively). Detailed results show that this is due to one element in particular: the hospital, which is characterized by low operational indices in case of earthquake (0.6847 and 0.3674 for the three return periods h) that affect the performance of the whole subsystem. A good strategy would be to fix that element in order to recover the full effectiveness of the subsystem.

AREs are classified, as in the original layout, C2b, independently of the earthquake severity. Its modest operational index is due to criticalities prior to earthquake, above mentioned. Important deficiencies can be found out also in the CO, for $T$=0, as well as for $T$>0, due to indirect structural damage caused by building collapses. When looking at operational indices and associated classes, one can note that passing from the original to the simplified model, the probabilistic index sensibly increases: in fact, from almost 0 (E-05 to E-02 order of magnitude) it passes to 0.05, 0.04 and 0.022 for the three return periods, with a corresponding class upgrade (from E to D). Despite the reduction of infrastructural links, some road edges still remain critical (paving irregularities or other), with particular reference to infrastructural links with AE no. 5.

The above example outlines the capability of I.OPà.CLE to provide results that can help to identify criticalities and the way to solve them: from the global results the system provides further levels of indices, specific for subsystems and for individual components. This progressive process enables an effective identification of those critical components of the emergency system that require specific interventions or total replacement, so as to improve emergency response and resilience of the system.

## 8. Conclusions

The application of the I.OPà.CLE method on a sample of thirty real LCE analyses at municipality scale, allowed some early considerations to be made about consistency of these analyses with the definition of LCE, assumed as the minimal condition capable to guarantee the emergency management in case of earthquakes.

It turned out that most of the LCE analyses of the sample, relevant to different dimensional municipality sizes, are far from the concept of "*minimal system of emergency*". In fact, most of them include a large number of FSs, larger than those strictly required for the three basic functions, such as emergency coordination, sanitary relief, and operational intervention. In particular, the small and medium-sized municipalities are often more redundant in functional terms, while the largest ones are mostly redundant in the infrastructural network. Besides the original sample of LCE analyses, a second simplified and virtual sample was then generated, obtained by a reduction of the number of strategic elements included in each LCE system.

I.OPà.CLE was hence applied to both the experimental samples (original and simplified). When looking at the results, a first consideration is that the numerousness of strategic nodes of the network influences, with an exponential rate, the number of mutual infrastructural interconnections. So that for complex emergency systems, composed by a large number of strategic nodes, the preservation of their operational efficiency in case of earthquakes has probabilities next to 0. Conversely, the reduction of emergency systems to the strictly needed strategic elements enable higher probabilities for the system to survive and be operational in case of earthquake. A further and not negligible aspect, which came out from I.OPà.CLE application, concerns the presence of significant intrinsic criticalities of individual elements, which reduce the probabilistic operational efficiency of system and subsystems, even without earthquakes. Thus, it is possible to conclude that the identification of the strategic elements of an emergency system often relies upon the operational functionality of components that are not always suitable for that emergency purpose. These considerations could be helpful for future emergency planning, that is supposed to stake on just few good elements rather than on too many poor ones. On the other hand, it is reasonable to assume that in a real contingency system, redundancy of strategic elements (two hospitals rather than one, or subsidiary functions in general) guarantees a backup solution in case of failure of the main components. A probabilistic model taking into account the functional redundancy would then help for a more realistic outcome of operational efficiency.

Given the general framework, and the required coherency with LCE assumption, the results of experimentation of I.Opà.CLE confirm this method to be a simplified, though reliable, tool for evaluating operational efficiency of a contingency system at municipal level. The flexibility of analysis and the modularity of the results (system indices - subsystem - elements) allow the user to identify potential criticalities, so as to effectively support the decision-making process in defining its priority actions to improve the emergency system which the emergency planning rely upon.

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