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(Article begins on next page)

Effects of Business Recovery Strategies on Seismic Risk and Cost-Effectiveness of Structural Retrofitting for Business Enterprises

Marco Donà,^{a)} M.EERI, Luca Bizzaro,^{b)} Federico Carturan,^{b)} and Francesca da Porto^{c)}

Recent earthquakes in Italy have significantly affected productive activities, particularly in business interruption (BI) and, consequently, heavy losses for companies, highlighting the need for appropriate seismic risk assessment and management. To estimate seismic risk accurately, both direct (repair/replacement) and indirect (BI) losses must be quantified. Companies' balance sheets can be used to estimate BI losses, which, however, are very sensitive to business recovery strategies (BRSs) devised by corporate managers after the seismic event. The aim of this study is to evaluate the effects of BRSs on seismic risk estimates and consequently on structural retrofitting cost-effectiveness. A loss model (including direct and indirect costs and BRS effects) was defined, based on a real-life case study (a biomedical packaging company that was damaged by the 2012 Italian earthquake but recovered soon after) and was used in parametric risk analyses assessing several types of company vulnerabilities and seismic hazards. In areas with low-to-moderate seismicity, seismic retrofitting of existing reinforced concrete factories may be justified or otherwise, depending on whether BRSs are considered or not. [DOI: 10.1193/041918EQS098M]

INTRODUCTION

Although seismic risk assessment of productive activities is not a new topic, in Italy, interest in it has become widespread only recently, particularly after the earthquakes in Emilia-Romagna in 2012. One of the main aspects that makes seismic risk assessment an essential research topic for businesses is their extremely high exposure, i.e., serious economic consequences of damage. Businesses are affected by a variety of mechanisms (Zhang et al. 2009, Brown et al. 2015), including physical damage to property and assets, downtime, and disruptions to labor supply, customers, and suppliers. In particular, losses caused by such disruptions are comparable in scale to repair or reconstruction costs (Zareian et al. 2012, Carturan 2013, Rose and Huyck 2016, Hofer et al. 2018). Another sensitive point is that

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prolonged downtime of an entire industrial area may have disastrous consequences on the local economy and community (Brown et al. 2015).

Appropriate risk assessment methods accounting for both direct and indirect losses are essential. Over the years, the Pacific Earthquake Engineering Research Center (PEER) has developed a probabilistic performance-based earthquake engineering framework (Porter 2003) to evaluate the probability of some parameters suitable for describing losses, according to the total probability theorem, to combine all uncertainties in defining seismic hazard, vulnerability, and exposure.

In general, the term “direct loss” is used to refer to repair or replacement costs caused by structural damage or collapse; damage of building contents and nonstructural elements are also significant sources of direct loss. Costs that are due to other sources, e.g., downtime, can be defined as “indirect” (as in Calvi et al. 2014).

Both direct and indirect losses are closely related to the concept of resilience to seismic events (Bruneau et al. 2003, Brown et al. 2015), the assessment of which is necessary to accurately predict such losses. Resilience is generally associated with two categories of actions: those implemented before any adverse event, designed to attenuate the frequency and magnitude of disasters (Bruneau et al. 2003), and actions taken after such an event, aimed at resuming business to minimize losses in the flow of goods and services, i.e., costs that are due to business interruption (BI; Tierney 2007).

In the case of productive activities, both types of actions are important, and appropriate risk assessment must take into account possible economic resilience actions in addition to structural aspects, both of which require a certain level of interdisciplinary knowledge. These resilience actions include firm-level business recovery strategies (BRSs) implemented by corporate managers after earthquake-induced downtime.

Even though the financial stability of small-to-medium enterprises (SMEs) is seriously threatened by downtime and reduced production capacity (Zhang et al. 2009), only a few authors have carried out probabilistic risk analyses assessing indirect losses for businesses (e.g., Hofer et al. 2018, which, however, focused on the production process and did not evaluate the possible building damage scenarios).

In addition, although several authors have discussed the great potential of BRSs (Kajitani and Tatano 2009, Brown et al. 2015), and the primary firm-level BRSs have been identified in an established framework (Rose 2017, Dormady et al. 2018), measuring their effectiveness is still an open issue. In this regard, some researchers have recently proposed various methods to account for the business resilience in economic disruption models, based on theoretical justifications (Rose et al. 2007, Rose 2004) or empirical approaches (Brown et al. 2019, Dormady et al. 2017). However, no study has been carried out on the effects of BRSs in terms of risk reduction, which would be more effective for insurance estimates.

In light of this, this study aims to integrate the most important structural and financial aspects of SMEs in probabilistic risk assessment and to evaluate the role of economic resilience strategies in mitigating seismic risk. In particular, this study provides a general operational method for assessing the cost-effectiveness of BRSs and seismic retrofitting in the same probabilistic framework so that interactions can be evaluated. This method is presented

in the *General Operational Method: Key Aspects and Main Steps* section, followed by a detailed application of a real-life case study: a biomedical packaging company damaged by the Italian earthquake of 2012.

First, a production model was calibrated on the case study and, together with the calibration of other economic parameters, was used to define the company's exposure model. The study was then generalized by means of a parametric risk assessment involving several combinations of recovery strategies, structural and machinery vulnerabilities, and seismic hazards, to quantify the effects of the BRSs in various situations. Lastly, risk estimates were used to evaluate the effectiveness of seismic retrofitting for existing factories of various degrees of vulnerability. Similar studies, generally conducted to evaluate the best retrofitting strategy, have been defined as "cost-benefit analysis" (as in [Calvi 2013](#), which focused on retrofitting of ordinary buildings) or "profitability analysis" (as in [Hofer et al. 2018](#), which examined retrofitting of machinery in production processes). However, "cost-benefit analysis" also refers to a long-established method in welfare economics that considers all benefits and costs from the perspective of society as a whole ([Boardman et al. 2010](#)); this study refers instead only to the interests of the company and therefore, for the sake of clarity, it is defined here as "cost-effectiveness analysis."

Examining the seismic risk both for the building and the production process in the same cost-effectiveness analysis, and the effects of BRSs, represents a novelty. In addition, such an analysis is of great interest to companies in areas of moderate and high seismicity, partly because insurance systems focus more on covering direct rather than indirect losses arising from BI because of the difficulty of estimating the latter.

GENERAL OPERATIONAL METHOD: KEY ASPECTS AND MAIN STEPS

In general, seismic risk is estimated according to the PEER approach, i.e., by means of the convolution of three probability functions: hazard, vulnerability, and exposure.

Exposure is the most interesting aspect of this study to which most attention is paid. As already noted, a precise estimate of company exposure should include both direct and indirect losses. In view of the difficulty of collecting much detailed economic information of indirect losses (e.g., costs and methods of implementing BRSs, loss of market share, etc.), a simple but robust deterministic loss model was derived and calibrated for the company of the case study as a function of only damage state (DS) and BRS (as described in the following).

Another key aspect of the company's risk evaluation is the need to assess multiple vulnerabilities, i.e., for buildings, machinery, contents, and, when appropriate, supplies of commodities. In addition, possible interactions should be evaluated case by case, as they are sometimes significant (as in this case study).

These vulnerabilities are defined here according to the HAZUS-MH MR4 technical manual ([Federal Emergency Management Agency \(FEMA\) 2003](#)), which provides average information for aggregate and large-scale analyses and is therefore also suitable for this study. Indeed, the aim of this study is to provide general information on seismic risk, including the effects of BRSs, for companies with exposure similar to that of the case study but evaluate various situations of hazard and vulnerability. Obviously, if the aim is the specific seismic

risk of a certain company, assessment of its specific seismic hazard and vulnerability is essential.

HAZUS was also used to define the reference DSs of structures and machinery and to set some variables for the application of the BRSs; the latter information, when missing, was integrated with that of the case study.

Lastly, cost-effectiveness analyses on the retrofitting of existing factories were carried out based on the previous risk estimates comparing the seismic risk reduction caused by retrofitting (i.e., the economic benefit for the company) with the retrofitting cost.

The main procedural steps to define the company's loss model and evaluate the cost-effectiveness of retrofitting are briefly reported as follows.

PROCEDURE FOR DETERMINING COMPANY'S LOSS MODEL

Step 1: Definition and calibration of an appropriate model to simulate the production process (i.e., raw material supply, production lines and functions, raw materials, and finished product storage, etc.). The model used is based on machine processing time and queue capacity; the latter affects the former when maximum capacity is reached. Although beyond the aims of this study, such a model allows us to monitor the quantity of raw materials and processed products in queues and thus to simulate the supply chain when appropriate (Fukushima et al. 2010). In addition, two parameters to be defined at this stage, which are necessary to estimate the downtime-induced losses, are the product processing value (i.e., revenue per unit of raw material) and compound annual growth rate (CAGR).

Step 2: Evaluation of direct losses related to building, machinery, and contents depending on DSs. To this end, reference was made to the repair cost ratio (RCR; i.e., ratio between repair cost and total replacement cost), which is defined by HAZUS for each DS, and to the total replacement costs of factory, machinery, and contents calibrated in the case study. In particular, the replacement cost of a factory can be estimated with the average unit costs of demolition and reconstruction identified in the specific area of the company; with reference to machinery and contents, this information depends greatly on the type of company and may be evaluated through specific expertise documents (e.g., appraisal reports).

Step 3: Evaluation of indirect losses, depending both on DSs and possible BRSs. For this, parametric simulations of the production process are required to estimate the turnover losses (i.e., losses of production volume multiplied by the product processing value) for all the damage scenarios and BRSs examined; for such simulations, BI times must be defined according to DS and BRS. Therefore, the loss of profit (LOP), which is the main indirect cost, can be calculated by multiplying turnover loss by gross profit ratio (GPR), defined for LOP insurance policies (in Italy) as follows:

$$GPR = GP/T \quad (1)$$

$$GP = T - VC = T - (Rm + 0.7 \cdot Se + 0.11 \cdot Pe + 0.12 \cdot Daw + \Delta Mat + Pr + Op) \quad (2)$$

where GP is gross profit, T is turnover, and VC represents variable costs, which are Rm , raw materials; Se , services; Pe , personnel; Daw , depreciation, amortization, and write-offs;

ΔMat , changes in raw materials and semifinished and finished products; Pr , provision for risks; and Op , other operating expenses. The values of these items can be found in the company's financial statement. In reality, variable costs do not scale linearly with turnover after production disruptions, so the GPR is not generally constant. However, this hypothesis seems reasonable for preliminary parametric risk estimates and has the benefit of minimizing assumptions about the specific circumstances of the event, which are a priori unknown.

Other important sources of indirect loss are BRS implementation costs, which are mainly due to rent and installation of temporary structures, transfer of machinery, and outsourced production. Loss of market share may also be a significant indirect loss for companies (as in this case study). These costs depend on the specific company and its assessed BRS and must therefore be defined case by case; specific expertise documents are useful for this purpose.

Step 4: Evaluation of total loss, direct plus indirect, for each DS and BRS examined. Building and machinery losses must be analyzed separately in risk calculation, as they refer to different probabilities of occurrence (different vulnerabilities). In this study, all indirect losses were associated with building vulnerability.

PROCEDURE FOR COST-EFFECTIVENESS ANALYSIS OF STRUCTURAL SEISMIC RETROFITTING

Step 1: Calculation of total benefit caused by retrofitting, B_{TOT} , as the reduction of seismic risk or total expected loss (EL) between cases "as-built" (without retrofit) and "retrofitted" for the hazard associated with several planning horizons, T , i.e., for T values ranging from 1 year up to the nominal (or reference) life of the building, V_R , in 1-year steps.

Step 2: Calculation of annual benefit, B_y , as the difference between B_{TOT} values related to subsequent values of T (see Equation 3):

$$B_y(i) = B_{TOT}(T_i) - B_{TOT}(T_{i-1}) = \left[\underset{As-built}{EL(T_i)} - \underset{Retrofitted}{EL(T_i)} \right] - \left[\underset{As-built}{EL(T_{i-1})} - \underset{Retrofitted}{EL(T_{i-1})} \right] \quad (3)$$

Step 3: Calculation of expected net present value (NPV) of retrofit investment, chosen as a measure of the cost-effectiveness of the work, for all T values examined. In general, NPV is the difference between the present (discounted) values of incoming and outgoing cash flows (i.e., benefits and costs) over reference period T : an investment with positive NPV is profitable (i.e., it adds value to the company) and vice versa. Based on the evaluation of NPV as a function of T , break-even time or discounted payback period T_0 can be estimated and is the period needed to recover the investment (i.e., $NPV(T < T_0) < 0$ and $NPV(T \geq T_0) \geq 0$). In this study, NPV was estimated as follows:

$$NPV \approx \sum_{i=1}^T \frac{(1+f)^i}{(1+r_n)^i} B_y(i) - I_0 \approx \sum_{i=1}^T \frac{1}{(1+r_r)^i} B_y(i) - I_0 \quad (4)$$

where $B_y(i)$ is the expected annual benefit in year i , I_0 is the initial retrofitting cost, f is the inflation rate, r_n and r_r are nominal and real discount rates, respectively, and T is the planning horizon (which, according to FEMA 227 1992, should reflect the effective life of the rehabilitated building). Two equivalent ways are generally used to account for inflation: the

“nominal method” (Equation 4, left), which converts real cash flows into nominal cash flows and discounts them at the nominal rate, and the “real method” (Equation 4, right), which discounts real cash flows at the real rate. The relationship between these rates is as follows:

$$r_n = (1 + r_r)(1 + f) - 1 \approx r_r + f \quad (5)$$

Therefore, retrofitting cost and discount rate are two important information for this analysis. The former mainly depends on building type, reduction of vulnerability sought with respect to the initial state, and the location of the building. As regards the discount rate, for this type of study, it can reasonably be assumed to be equal to the yield offered by risk-free financial assets in the medium-to-long term, although more precise financial assessments may require higher and variable rates to include risk, opportunity cost, and other factors.

A frequently used parameter for measuring and comparing the effectiveness of retrofitting strategies is expected annual loss (EAL; Calvi 2013, Hofer et al. 2018). EAL is calculated on the basis of the annual exceedance probability of the earthquake, which is a function of the reference life (V_R) of the building, rather than on the basis of the total probability associated with planning horizon T (as for total EL). In particular, EAL simplifies discounting operations, as it is a constant annual parameter; in fact, the variation of EAL between the as-built and retrofitted cases provides mean annual benefit, B_y , which is also constant. However, its use is based on the hypothesis of using the building for its entire reference life V_R , as V_R influences the annual exceedance probability. As the main result of this analysis is payback period T_0 , this hypothesis may be too restrictive for the company from a “capital budgeting” perspective; therefore, for evaluating T_0 without any assumption regarding V_R , annual benefits, B_y , were calculated from the total benefits B_{TOT} (which depend only on T) rather than from EAL (which depends on V_R).

Another limitation, when using EAL, is related to the age of the building and the fact that the as-built case is an actual alternative when retrofitting is not cost-effective; in this case, in fact, the reliability of the results is based on the assumption that the building (as-built) will remain operational for a further period, V_R , without benefitting from any structural intervention (the costs of which, if taken into consideration, would increase the cost-effectiveness of retrofitting).

CASE STUDY AND MODEL OF PRODUCTION PROCESS

The Emilia-Romagna region is one of the most highly industrialized regions in Europe. Approximately 85% of its industrial buildings (about 80,000) are built of reinforced concrete, of which two-thirds are prefabricated (Braga et al. 2014). These are mostly single-story buildings constructed before 2003, when the territory of Emilia-Romagna was first classified as a seismic zone (Ordinanza del Presidente del Consiglio dei Ministri (OPCM) 2003); they were therefore mainly designed for vertical loads, with roofs and floors without in-plane stiffness or arrangements for diaphragm behavior (required to distribute seismic forces uniformly between vertical elements); secondary beams were simply laid over the main ones, and the latter were connected to the tops of pillars with hinge constraints (i.e., according to iso-static schemes, which do not allow redistribution of stresses within the structural element when its resistance is overcome, consequently resulting in sudden collapse). Their overall structural behavior can thus be reduced to that of a series of simple “inverted pendulum”

systems represented by single pillars, which do not interact with the rest of the structure, revealing the enormous seismic vulnerability of such buildings.

The first tremor on 20 May 2012 was followed by several high-intensity aftershocks, the highest being that of May 29; the most badly damaged buildings were those used for productive activities, such as warehouses and manufacturing facilities. The Emilia earthquake was thus clearly one of the most expensive Italian quakes and was also the worst natural disaster with the greatest economic damage in Europe in 2012, estimated at about 12.6 billion euros by the [Swiss Reinsurance Company \(2013\)](#).

During a survey of companies damaged by the earthquake, particularly in the biomedical district (one of the largest in this region), a good representative case study was found in Mirandola, one of the leading Italian firms in the packaging sector for pharmaceutical and medical products. Its production process is shown in Figure 1 and mainly consists of processing three materials: medical paper, Tyvek, and plastic film. The main steps are paper-Tyvek bonding, printing and cutting, plastic film lamination, and subsequent welding to paper-Tyvek products. The final products are mainly of two types: finished products, i.e., those requiring all stages of processing, and printed products, i.e., those not including plastic film.

From the total cost of raw materials reported in the 2011 financial statement (the year before the earthquake), a processed volume of about 1,500 tons was estimated, assuming an average cost of €4/kg (information provided by the manager). Then from the revenues of the same year for finished and printed products, representing about two-thirds and one-third of both total production and use of raw materials, their processing value was also estimated as the ratio between revenues and raw material volumes, which were €7.0 or 5.9 per kilogram of raw material, respectively. Lastly, CAGR of 5.3% was calculated from the financial statements of the three years preceding the earthquake (2009–2011); this value was assumed to be constant in the following years to estimate a reasonable annual production increment in the reference case without the earthquake. All this information (product volumes in 2011; product processing values; CAGR) was used as in the *Company's Exposure Model, Including Recovery Strategies* section for parametric loss estimates.

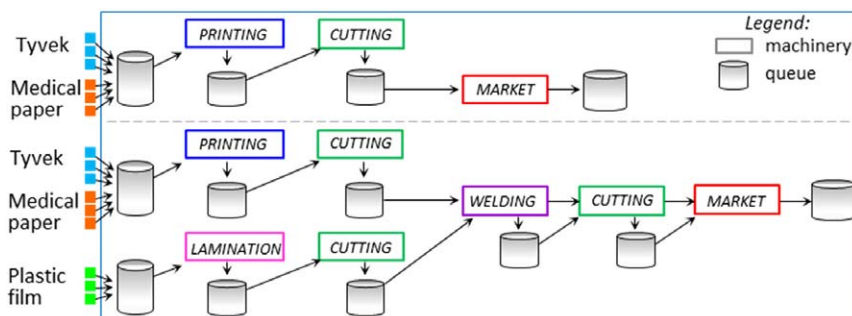


Figure 1. Simplified representation of production process of the company assumed as in the case study.

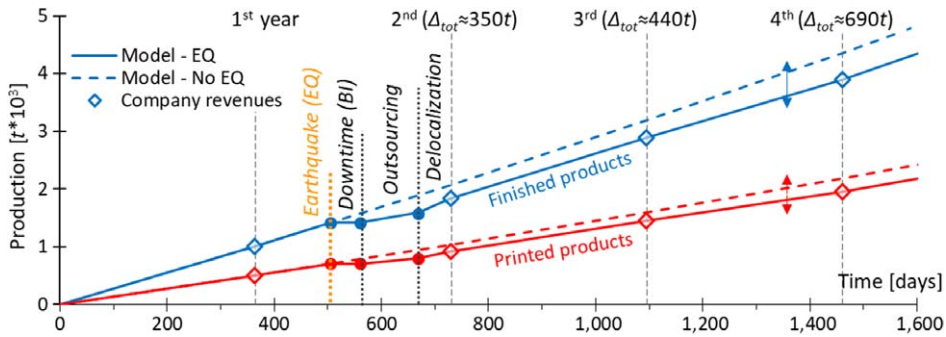


Figure 2. Calibration of production model and estimated production loss Δ_{tot} caused by the 2012 Emilia earthquake (EQ).

Calibration of the production model, based on both company revenues and personnel information about applied recovery strategies, is shown in Figure 2 and compared with the expected production in the case without an earthquake for a period of 4 years, starting from 2011. As can be seen, the loss suffered by the company continued to increase slightly for more than 2 years after the event, partly because of loss of market shares (see *Parametric Seismic Risk Assessment* section).

COMPANY'S EXPOSURE MODEL, INCLUDING RECOVERY STRATEGIES

This section presents the parametric analysis to estimate the total (direct and indirect) losses of the company and based on the various DSs proposed in HAZUS-MH MR4 (FEMA 2003) and the resilience tactics listed in Table 1. The DSs, associated with a specific damage ratio or RCR (i.e., ratio between repair costs and total replacement costs) are None

Table 1. Description of business recovery tactics

Reconstruction	
Definition	Company stops production, awaiting reconstruction
Main costs	Reconstruction or repairs
Main risk	Loss of customers and reputation because of BI time
Relocation	
Definition	Company temporarily continues production in alternative structures to reduce BI time, awaiting reconstruction
Main costs	Transfer of equipment and setting-up of operations, rent and installation of temporary structures
Main risk	Possible loss of customers in case of great DS because of high BI time
Outsourcing (not implemented in HAZUS-MH MR4, FEMA 2003)	
Definition	Company asks external companies to produce in its place to minimize BI time, awaiting relocation and reconstruction
Main costs	Higher production costs
Main risk	Possible loss of know-how and therefore greater competition

(RCR = 0%), Slight (2%), Moderate (10%), Extensive (50%), and Complete (100%). These losses, representing a deterministic model of the company's exposure, are used for the risk assessment in the *Parametric Seismic Risk Assessment* section.

The applied recovery strategies (BRS) combine the tactics of reconstruction, relocation, and outsourcing; in particular, when the last two are chosen, product volume may be lower than expected in ordinary circumstances. In the case of relocation, this is due to the non-optimal configuration of work (insufficient space or production subdivided into several separate areas); as regards outsourcing, this is caused by the reduced availability of time and resources of external companies. Therefore, various production ratios, referring to production in ordinary circumstances, were assumed for the whole period of the tactic, producing the six case studies shown in Figure 3. According to information from other Emilian companies in the area struck by the earthquake, the strategies examined are the main ones and the most representative for these types of companies. However, for more information on economic resilience strategies, see specific studies, such as [Rose \(2017\)](#) and [Dormady et al. \(2018\)](#).

The main analytical steps performed for all combinations between DSs and BRSs were the following:

- Simulation of the production process for 2 years, starting from 1 January 2012 and placing the seismic event on 20 May 2012 (as in the case study), to calculate the loss of production and therefore of turnover for a certain DS and recovery strategy;
- Calculation of all losses, direct and indirect, including costs to implement the strategy.

Analysis was carried out by evaluating the factory both rented (as in the case study) and owned. These different conditions seem to influence companies' impact and recovery from the disaster in favor of those who rent, as concluded in a recent study based on evidence from the 2010/2011 Canterbury earthquakes ([Brown et al. 2015](#)).

BI times must be defined for the first step of analysis (Table 2). For reconstruction and relocation tactics, HAZUS-MH MR4 ([FEMA 2003](#)) was again assumed as a reference. In the absence of other information, BI time for outsourcing was set at that of the case study,

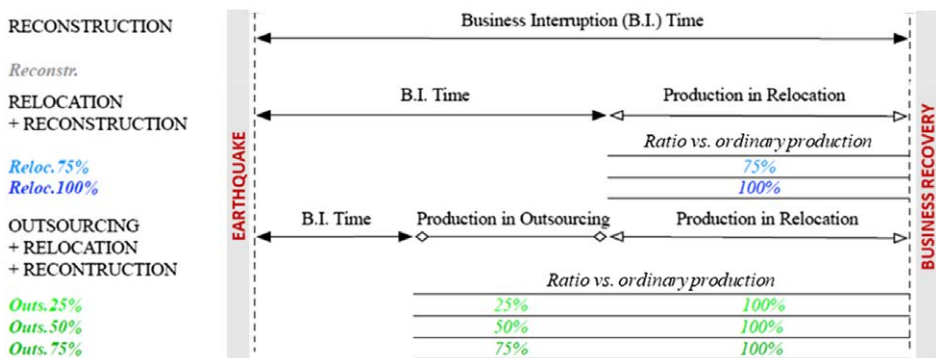


Figure 3. BRSs implemented in parametric analysis.

Table 2. BI time, in days, for each DS and recovery tactic

Recovery tactic	DS				
	None	Slight	Moderate	Extensive	Complete
<i>Reconstr.</i>	0	20	135	360	540
<i>Reloc.</i>	0	4	27	108	216
<i>Outs.</i>	0	2	14	54	54

Sources: HAZUS-MH MR4, FEMA 2003 (“High Technology Industry”) for *Reconstr.* and *Reloc.*; case study for *Outs.*

which suffered DS Complete and only resumed production in outsourcing after 54 days; this value was kept constant for DS Extensive because of the negligible variability between the highest DSs. Instead, for the lower DSs, BI times were reasonably assumed to be half those for relocation. With the previously calibrated model, together with this information, a production trend was predicted for each combination of DS and BRS; in addition, the production model was used to simulate the case without an earthquake, which was the reference case to calculate production losses. Examples of production trends are shown in Figure 4 for the DSs Extensive and Complete; as can be seen, the variation in production volumes among the various strategies is substantial. Lastly, loss of turnover was calculated by multiplying the loss of production volume for both types of products by the related processing value (see *Case Study and Model of Production Process* section).

As regards the second step of analysis, for simplicity of presentation, we refer first to the taxonomy of Table 3 and then to the information as follows on adopted reference costs.

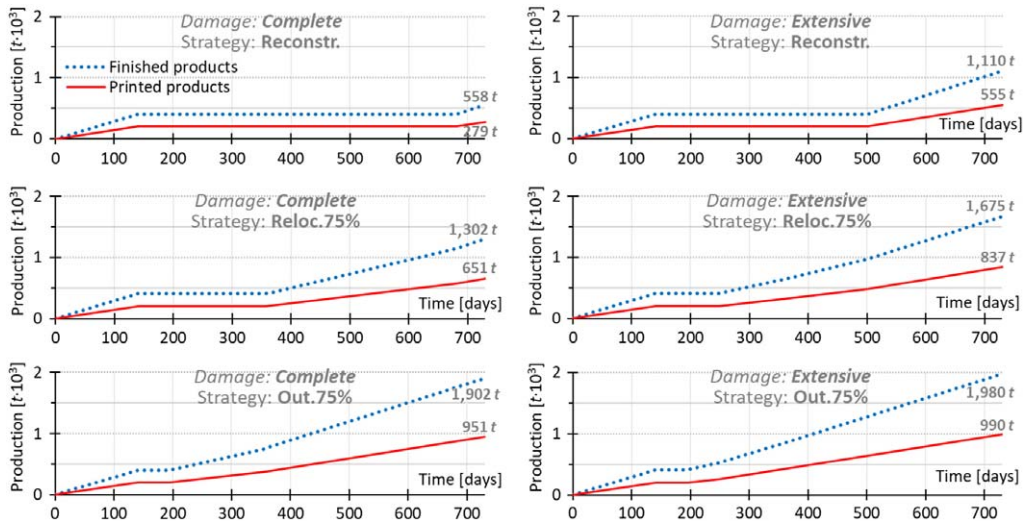


Figure 4. Examples of simulated production trend for two damage levels and three types of strategy. Reference production volumes for the case without an earthquake are 2175 ton (finished) and 1088 ton (printed).

Table 3. Trend proportional to direct and indirect losses examined

Direct losses	Data source	Proportional to trend
Building losses (from reconstr./demolition costs)	Ordinance of the President of the Emilia Romagna region, No. 57 (2012) Emilia Region (Italy), Annex 2, “Sfinge”	Damage ratio
Plant and machinery losses	Appraisal report of case study	Damage ratio
Indirect losses	Data source	Proportional to trend
LOP	Production process simulations with model calibrated on case study	Loss of turnover times GPR
Rent and installation of temporary structures	Appraisal report of case study	Damage ratio and days of use
Transfer of equipment	Appraisal report of case study	Damage ratio
Production cost in outsourcing	Appraisal report of case study	Production in outsourcing
Saving of factory rent (in case of rented factory)	Revenue Agency database (Italy) – OMI (real-estate market observatory)	Number of days for reconstruction
Loss of market share	General management of case study	Production downtime

DIRECT LOSSES

- According to Annex 2 of [Ordinance of the President of the Emilia Romagna region, No. 57 \(2012\)](#) of the Emilia-Romagna region, reconstruction costs are 500, 450, and 410 €/m² for extensions of damaged areas of less than 2,000 m², up to 5,000 m², and exceeding 5,000 m², respectively.
- Demolition costs, from the same data source, are 40 €/m².
- As regard losses of plants and machinery, the expertise documents of the case study were examined, associating a cost of €1,771,876 with DS Complete (damage to the company) and calculating the losses for the other DSs through simple proportions with damage ratios. The loss of shelving was not calculated apart from that of machinery, as the former is much lower. In addition, interruption in supplies of commodities was not taken into consideration, as such companies are not very sensitive to this type of disruption and the case study did not suffer this damage; however, this lack does not reduce the validity of this study.

INDIRECT LOSSES

- The LOP was calculated (see *General Operational Method: Key Aspects and Main Steps* section) by multiplying the turnover loss (estimated in the first step of analysis) by the GPR, defined as in Equations 1 and 2. The GPR was calculated for the years 2009, 2010, and 2011 from the company’s financial statements, and an average value of 0.29 was used.
- When the relocation tactic is applied, the costs to rent and install temporary structures must also be considered as well as the costs of transferring equipment;

for both, information from the case study was used. In particular, for use of temporary structures, an equivalent unit cost of €1.106 per day and per square meter was derived; the cost of transferring equipment, associated with a DS Complete, was €523,680. Extrapolation of these costs for the various cases examined was straightforward; as regards temporary structures, the unit cost was multiplied by the relocation period and the extent of damage (function of DSs); transfer costs were obtained by simple proportion with damage ratios.

- In outsourcing, the damaged company must also pay production costs to external companies; according to our information, these were reasonably assumed to be 80% of the total profit obtained with outsourced production. Although this strategy may not seem very effective besides allowing a non-negligible reduction of indirect losses caused by LOP, it significantly reduces the risk of loss of customers caused by production downtime.
- In addition, in the case of a rented factory, rent is no longer due for the damaged (unusable) part of the factory; this represents a kind of saving for the company. According to information in the Revenue Agency database – OMI (real-estate market observatory; [Revenue Agency 2017](#)), €0.12 per day and per square meter were taken as the average unit cost to rent an ordinary factory.
- As anticipated, loss of market share was also examined; according to the manager's information, this was assumed to be half the LOP per year for the 2 years following the event. The reason for this period is that companies producing packaging for biomedical instruments are subjected to rigorous checks to obtain the necessary certifications required by their particular clientele, with waiting times that sometimes exceed 6 months.

The results, obtained for all DSs and BRSs, are shown in Figures 5–8 for DS Complete. Figures 5 and 6 also include, for comparison purposes, the actual losses suffered by the case study company (with rented factory).

For each strategy examined, Figure 5 shows both its implementation cost and the related LOP, excluding the probable loss of market share, the sum of which is the total indirect cost.

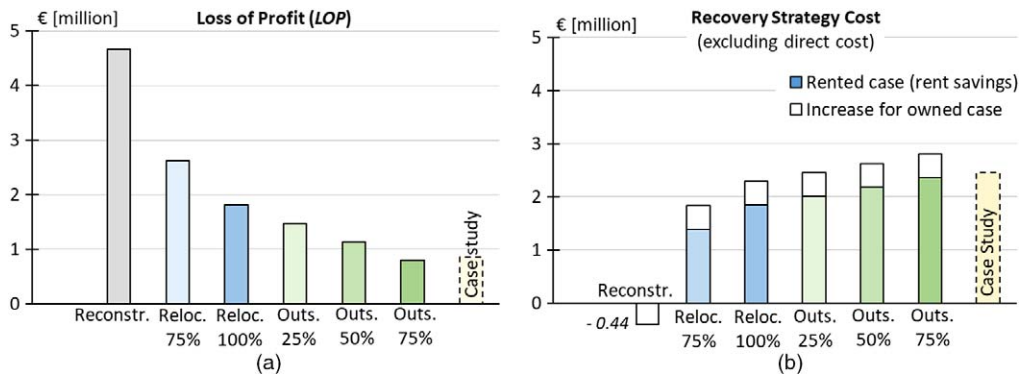


Figure 5. (a) LOP without loss of market share and (b) strategy implementation cost for each BRS with DS Complete.

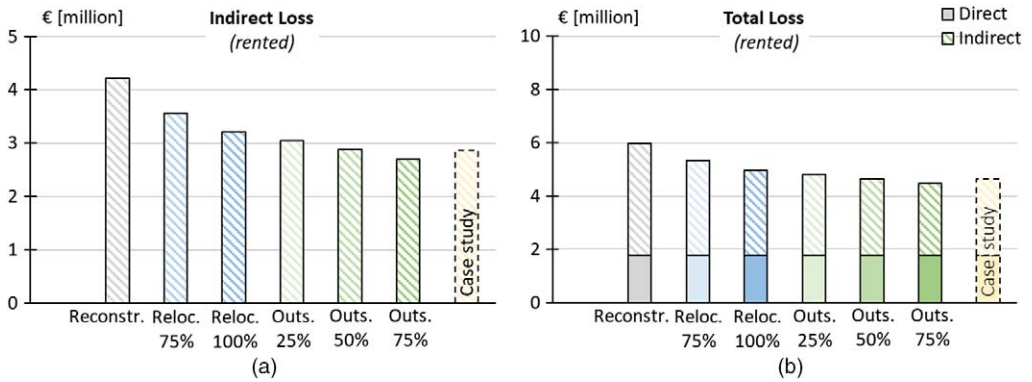


Figure 6. Case of rented factory with DS Complete: (a) indirect loss (i.e., LOP and strategy cost) and (b) total loss for each BRS without loss of market share.

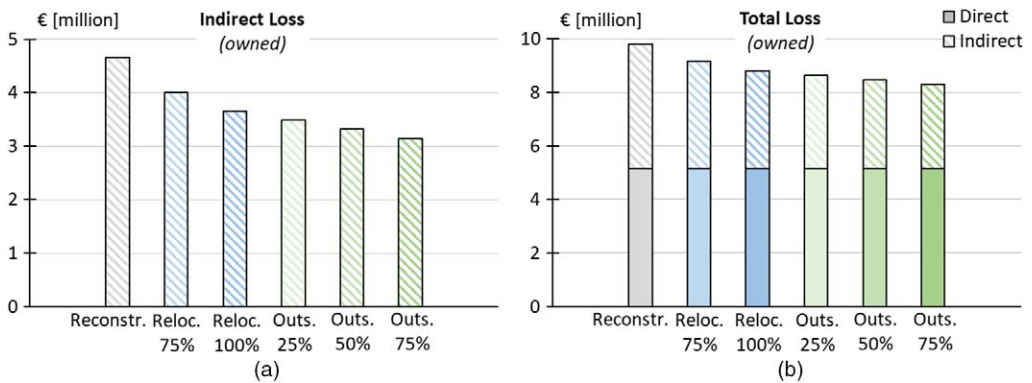


Figure 7. Case of owned factory with DS Complete: (a) indirect loss (i.e., LOP and strategy cost) and (b) total loss for each BRS without loss of market share.

Depending on whether the factory is owned or rented, the LOP remains unchanged, whereas the strategy costs vary slightly, because of savings on rent for the days necessary to repair or rebuild. As expected, although the LOP is significant, it can also be considerably reduced by recovery strategies, which, however, have substantial implementation costs.

The effectiveness of strategies, again excluding market losses, can be seen in Figures 6 and 7, which show indirect and total losses for the case of rented or owned factory, respectively. Clearly, the faster the company returns to production, the better, although higher strategy costs must be borne. Another interesting outcome is the ratio between indirect and direct costs; in the case of a rented factory, this ratio may vary from 1 (*Outs.75%*) to 2 (*Reconstr.*); in the case of an owned factory, the range may be 0.5 (*Outs.75%*) to 1 (*Reconstr.*). In addition, in the latter case, the total loss is 1.5–2 times higher because of the higher direct loss. Figure 6 also shows the benefit that is due to the outsourcing strategy actually applied by the

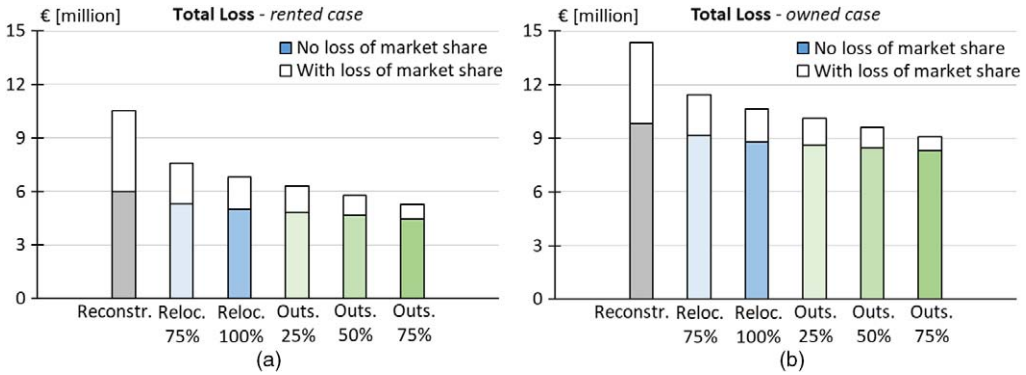


Figure 8. Total loss with loss of market share for DS Complete and all BRSs: (a) rented and (b) owned factory.

company; since it was similar to the ideal strategy, *Outs.50%*, this comparison proves the goodness of the calibrations made for defining the loss model.

The strategy effectiveness shown in Figures 6 and 7 is a lower limit for such companies, which are sensitive to market losses, especially for long BI times; as shown in Figure 8, this effectiveness increases when market losses are examined, since they are quite high.

In general, building and machinery have different vulnerabilities, i.e., different fragility curves (or probabilities) for the same DS (see *Parametric Seismic Risk Assessment* section); therefore, the sum of their losses, for the same DS, is not conceptually correct. For this reason, Figure 9 shows the company’s total losses without machinery costs for all recovery

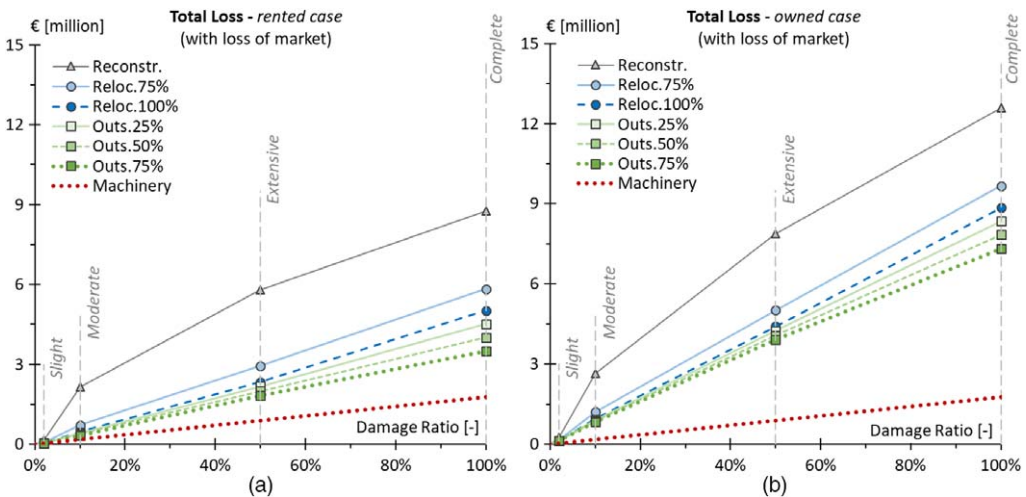


Figure 9. Total loss with loss of market share for all DSs and BRSs: (a) rented and (b) owned factory.

strategies separately from the machinery costs. Figure 9a shows the case of a rented factory and Figure 9b shows that of an owned factory; both include the loss of market share. These figures show that effectiveness of strategies increases when damage ratio increases, *Reconstr.* is the strategy that differs most from the others, and *Outs.75%* is the strategy that performs best. Examining the total losses at DS Complete, including machinery costs, *Outs.75%* reduces losses by about 50% compared with *Reconstr.* and 20% compared with *Reloc.100%* in the case of a rented factory; these reductions become about 40% and 15%, respectively, in the case of an owned factory.

PARAMETRIC SEISMIC RISK ASSESSMENT

The loss model defined was used to quantify the seismic risk of companies with the same exposure as in the case study in various situations of hazard and vulnerability.

As regards vulnerability, the fragility curves for buildings and machinery of category PC1 (i.e., “precast concrete tilt-up walls”) from HAZUS-MH MR4 (FEMA 2003) were used (Figure 10). These curves, which associate the probability of a certain DS with the related peak ground acceleration (PGA), are provided for four types of seismic code (High, Moderate, Low, and Pre-Code) and, for each of these, for all the DSs. In this study, building and machinery were associated with the same type of code. The national contextualization of the HAZUS codes is necessary to apply this vulnerability information properly; the first code requiring a seismic design in Emilia-Romagna was OPCM 3274 (2003); therefore, buildings constructed in this area before 2003 may appropriately be associated with a Pre-Code. The factory of the case study, constructed in the 1970s, suffered damage of Extensive type, caused by the main shock on 20 May 2012 (PGA of 0.26 g), and Complete, with the aftershock on May 29 (PGA of 0.29 g); this is appropriately represented by the damage probabilities from HAZUS when a Pre-Code is used, being 8% Slight (*S*), 20% Moderate (*M*), 31% Extensive (*E*), and 31% Complete (*C*) for the main shock, and 6% *S*, 18% *M*, 31% *E*, and 38% *C* for the aftershock.

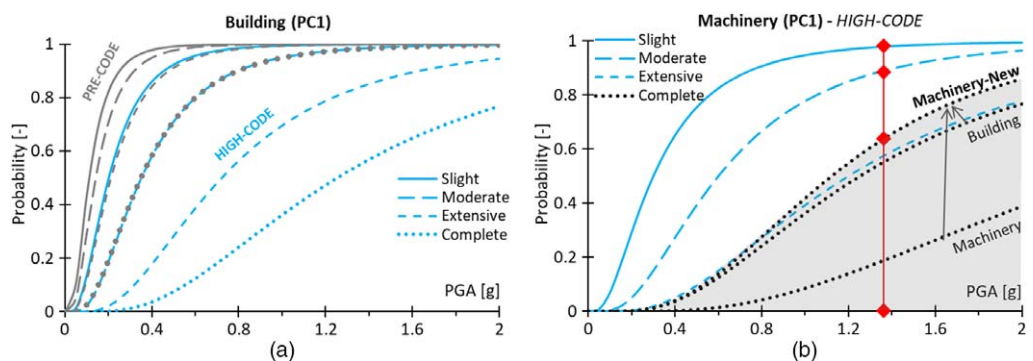


Figure 10. Examples of fragility curves for (a) building, from HAZUS (FEMA 2003), and (b) machinery, based on HAZUS and adjusted to include probability of damage caused by building collapse.

A simplified interaction between the vulnerabilities of structure and machinery, which assumes the total loss of machinery in the event of complete damage to the building, was reasonably assumed for the company of this case study for the following reasons:

- Presence of an “isostatic structural scheme” (see *Case Study and Model Production Process* section) so that a building DS Complete is likely to cause roof elements and beams to collapse onto machinery;
- Presence of “clean rooms” (the exposure of which was included in that of machinery); these rooms, for which the costs for repairs or transfer are substantial, are directly anchored to the building and thus may suffer damage together with structural damage, especially when the latter is high.

This assumption, which increases the probability of damage to machinery, to take into account the additional probability resulting from complete damage to the building, required the definition of a new fragility curve for DS Complete of machinery. The formula for the combined probability ($P_{\text{tot}} = P_A + P_B - P_A \cdot P_B$) of two independent events (A, B) was therefore used because these events are the complete-damage scenarios of building and machinery associated with independent HAZUS fragilities. Lastly, the HAZUS curves of machinery below this new curve (DS Complete) were discarded as impossible, as shown in Figure 10.

As regards seismic hazard, several cases were studied for the purpose of comparison (Figure 11). In addition to the low-moderate seismicity of Mirandola (case study, Central Northeastern Italy), the seismicity of Cosenza (Southern Italy), one of the highest in Italy, was also examined; for both sites, two definitions of seismicity were assumed, i.e., that of the current Italian code DM-2018 (Italian Ministry of Infrastructure and Transport 2018) and the more recent one from the SHARE Project (Woessner et al. 2015; data from OpenQuake, Global Earthquake Model (GEM) 2017). The parameters assumed to define the hazard, according to DM-2018, are nominal reference period V_R of 50 years (for ordinary buildings, as in the case study), soil type C (i.e., deposits of medium-dense sand, gravel, or stiff clay with thicknesses exceeding 30 m), and topographic category T_1 (i.e., flat surface). According to the design strategy of DM-2018, the limit states of interest are associated with the following exceedance probabilities, P_{V_R} , in V_R (or return periods T_R): 81% (30 years), 63% (50 years), 10% (475 years), and 5% (975 years). The PGAs for a T_R of 475 years (Life-Safe limit state) for Mirandola and Cosenza are 0.208 g and 0.354 g, respectively, according to DM-2018, and increase to 0.281 g and 0.456 g, respectively, according to SHARE.

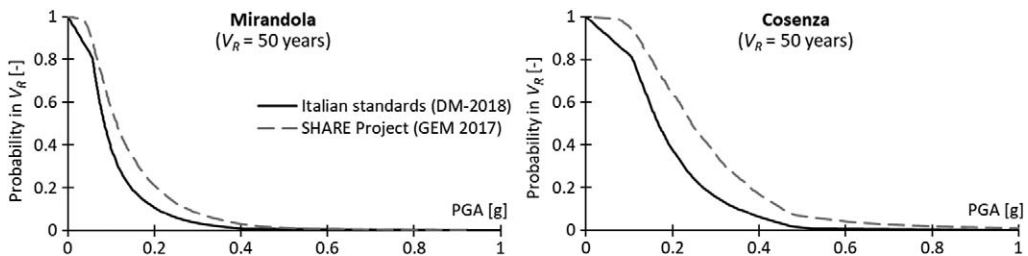


Figure 11. Seismic hazards examined (nominal reference period V_R of 50 years).

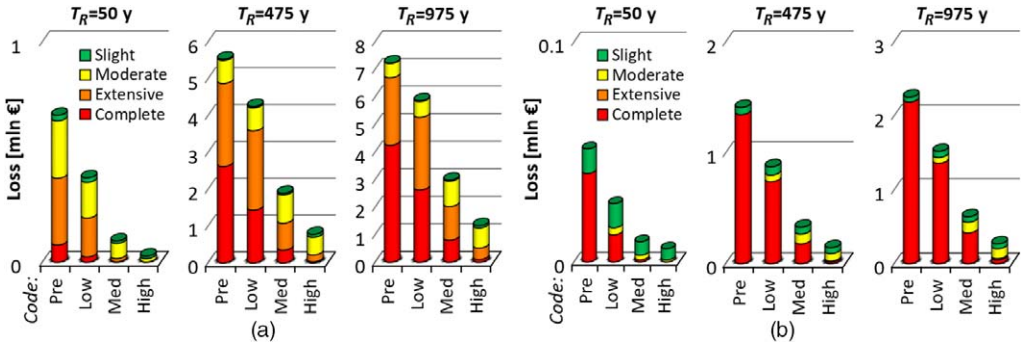


Figure 12. Loss, with owned factory and strategy *Reconstr.*, disaggregated by DS and for some main return periods (T_R): (a) building; (b) machinery; hazard of Mirandola (DM-2018).

The risk was calculated according to the PEER approach for buildings and machinery separately (as they are associated with a different set of fragility curves), and these two components were then added together. Indirect losses, including loss of market share, were considered within building risk.

For both buildings and machinery, and for all codes, Figure 12 shows some disaggregated losses, i.e., expected costs subdivided among the various DSs for some main return periods T_R of the seismicity of Mirandola (defined as in DM-2018). In general, the components of loss associated with the highest DSs increase with increasing T_R and decreasing code performance to the detriment of those related to minor DSs, which are more important for lower T_R and better codes. In addition, the machinery loss for the minor codes is mainly due to DS Complete, as the interaction with the building DS Complete led to excluding the intermediate fragilities of machinery and thus to a less gradual subdivision of the loss among DSs.

Calculating the expected total losses for the whole range of interest of T_R and associating these values with the exceedance probabilities (P_{VR}) related to the various T_R gives the risk profile of the company; examples are shown in Figure 13 for all recovery strategies and various situations of vulnerability and seismic hazard. These risk profiles effectively show not only the possibility of various seismic losses but also the beneficial effect of the BRSs in probabilistic terms, which is greater (like losses) for greater vulnerability and hazard.

Figure 14 shows the company risks, estimated by integrating the previous risk profiles in the probability range (from 0% to 100%), for all strategies and codes in the following cases: rented and owned factories, with a hazard of Mirandola from DM-2018, and an owned factory, with both hazards of Mirandola and Cosenza from SHARE. These risk estimates not only show the importance of the strategies (already seen in the loss estimates of Figure 9) but also highlight the difference between the *Reconstr.* strategy and the others. In particular, the risk difference between *Reloc.* and *Outs.*, which is important for Pre- and Low-Codes, is greatly reduced for the higher codes as the probability of greater damage is reduced; in this case, in order to estimate the risk, it would be sufficient to know whether any strategy other than *Reconstr.* can be applied. In addition, comparisons between the cases of rented and

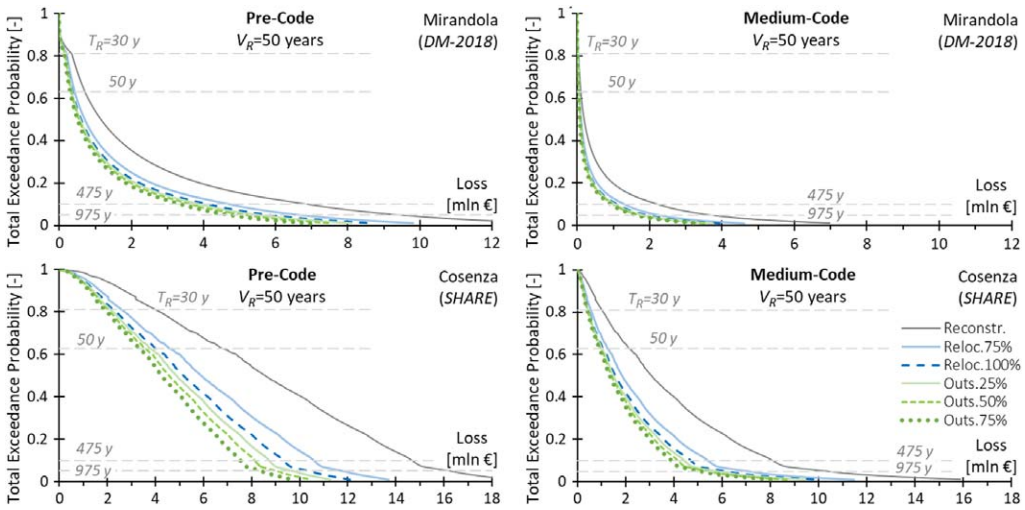


Figure 13. Company risk profiles with owned factory for all BRSs; cases: Pre- and Medium-Codes and hazard of Mirandola (DM-2018) and Cosenza (SHARE).

owned factories (Figure 14a versus Figure 14b) emphasize the greater influence of strategies when building losses are excluded. Comparison of Figure 14b and 14c clearly shows that the risk increases by 1.5–2.0 times (from Pre- to High-Code) when the hazard is defined according to SHARE; however, considerations regarding the role of the various strategies and codes do not change. The risk also increases by 2.5–3.5 times (from Pre- to High-Code) when the company is moved from Mirandola (low-moderate seismicity) to Cosenza (high seismicity), as Figure 14c and 14d show. Lastly, the risk reduction caused by raising one class of seismic code is lower than (for a Pre-Code) or at most similar to (for the other codes) that obtained when recovery strategies are applied. This means that strengthening interventions, which reduce the vulnerability of existing factories without reaching the highest safety levels, would be less effective than recovery strategies, as the latter do not require any initial investment because they are applied after the event. Instead, seismic retrofitting raising structural safety to the highest levels is more effective, although its economic justification should be evaluated through appropriate cost-effectiveness analyses (see below).

COST-EFFECTIVENESS ANALYSIS OF SEISMIC RETROFITTING

The previous risk estimates (with hazard defined according to the SHARE Project, GEM 2017) were finally used to evaluate the effectiveness of the seismic retrofit for existing reinforced concrete (RC) factories (not seismically damaged). Such retrofitting is intended to increase the structural safety up to a level equivalent to that required by the current code (Italian Ministry of Infrastructures 2018); this level was associated with a Medium-Code for Mirandola (low-to-moderate seismicity) and a High-Code for Cosenza (high seismicity) because of the differing structural vulnerabilities required by the code according to site seismicity.

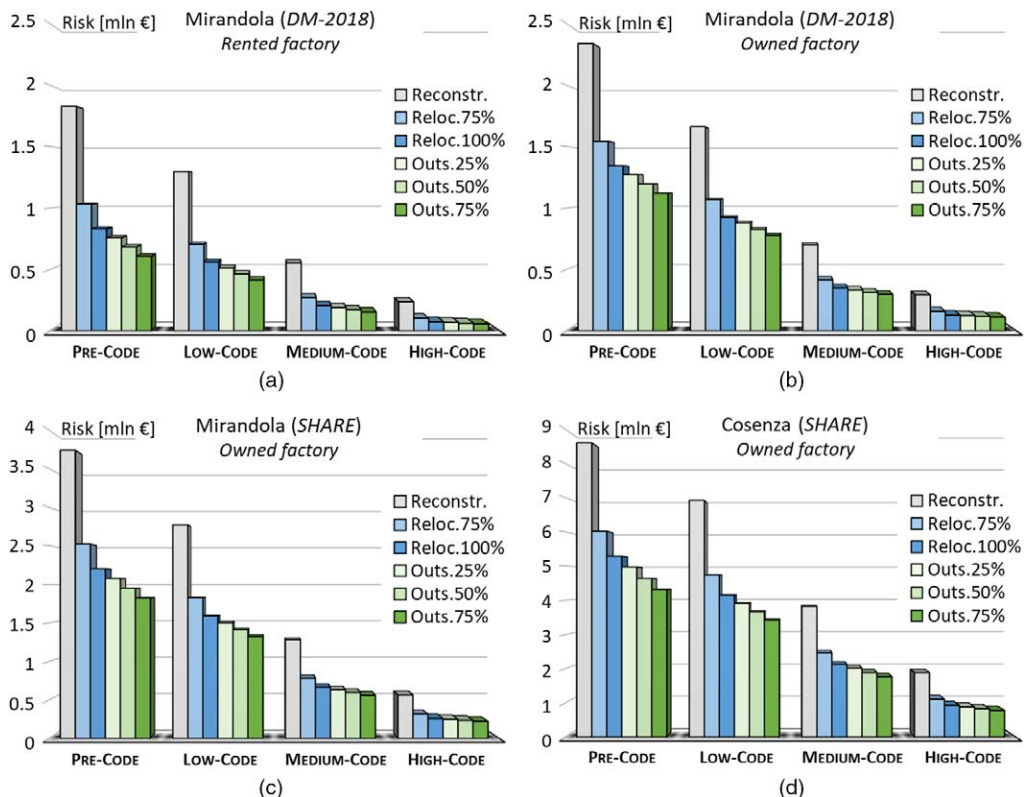


Figure 14. Seismic risk for rented and owned factories for all BRSs and seismic codes; hazard of Mirandola and Cosenza, from Italian standards DM-2018 and SHARE Project (GEM 2007).

The expected NPV, calculated as explained in the *General Operational Method: Key Aspects and Main Steps* section, was chosen as a cost-effectiveness measure of the investment (it is worthwhile when $NPV > 0$). Then to evaluate payback period T_0 , NPV was assessed for incremental values of planning horizon T up to 50 years, i.e., the reference period (V_R) for ordinary buildings in Italy. The key factors for calculating NPV are annual benefit, retrofit cost, and discount rate.

Annual benefit, B_y , was calculated as the difference in total benefits, B_{TOT} , for subsequent T values, where B_{TOT} is reduction of seismic risk or total EL in period T between the cases as-built and retrofitted (see Equation 3). Total EL corresponds to the area defined by the company risk profile (see Figure 13) or the loss-exceedance curve (i.e., curve with seismic losses associated with related total exceedance probabilities). As an example, Figure 15 shows these curves for both the as-built and retrofitted cases for two values of T and some recovery strategies. As can be seen, the difference between the areas subtended by the as-built and retrofitted curves associated with the same strategy, i.e., B_{TOT} of the strategy, increases with increasing T .

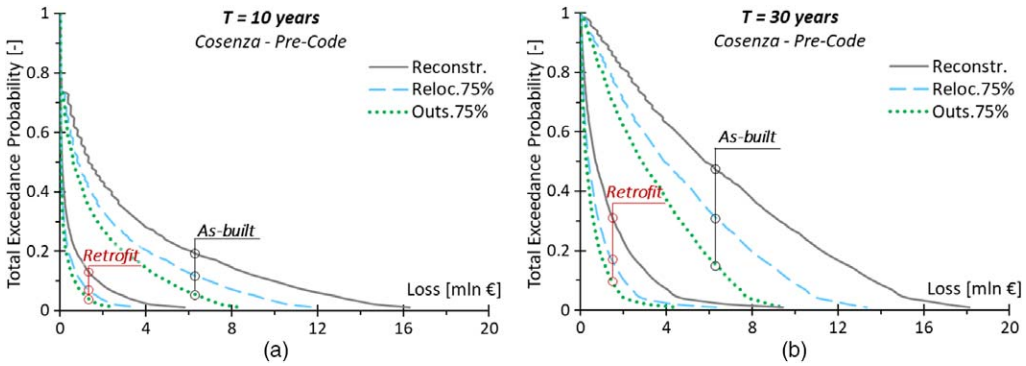


Figure 15. Loss-exceedance curves of cases as-built and retrofitted for planning horizons, T , of (a) 10 and (b) 30 years and some BRSs.

Retrofit costs (which do not include repair costs) were defined per square meter according to information from the expert engineers who worked on these operations in the aftermath of the Emilia earthquake. In particular, costs are linked to two intervention phases: strengthening of connections for infills, pillars, and secondary and main beams to eliminate possible loss of support (Phase 1) and strengthening of vertical structures and foundations to increase the safety level (Phase 2). The cost range identified for a Pre-Code (or building constructed before 2003) is shown in Table 4 for each phase, and average values are used. The cost for a Low-Code was reasonably reduced by 25% because of the higher initial safety level. For Cosenza, in view of the higher performance requirements, retrofitting costs were increased by associating the total average cost of Table 4 (for a Pre-Code) to a Low-Code and varying it by +25% or -25% for a Pre- or Medium-Code, respectively.

Lastly, as regards discount rate, reference was made to the yield on Italian 10-year bonds in recent years; this fell from 5.7% in 2012 (with inflation $f \approx 3.0\%$) to 1.4% in 2016 ($f \approx -0.1\%$), returning to over 2% since 2017, with a current value of about 3% ($f \approx 1\%$; Italian Ministry of Economy and Finance 2018). These rates are nominal, as they include inflation; thus a reasonable estimate of the Italian real discount rate, r_r (see Equation 5), is 2%.

The obtained values of NPV are shown in Figure 16, normalized to the related intervention cost, for some significant cases. Figure 16a shows that, in a low-medium seismic area

Table 4. Seismic retrofitting costs for Mirandola and Pre-Code (buildings constructed before 2003)

Cost (€/m ²)	Min	Max	Average
Phase 1	50	65	57.5
Phase 2	80	95	87.5
Total	130	160	145

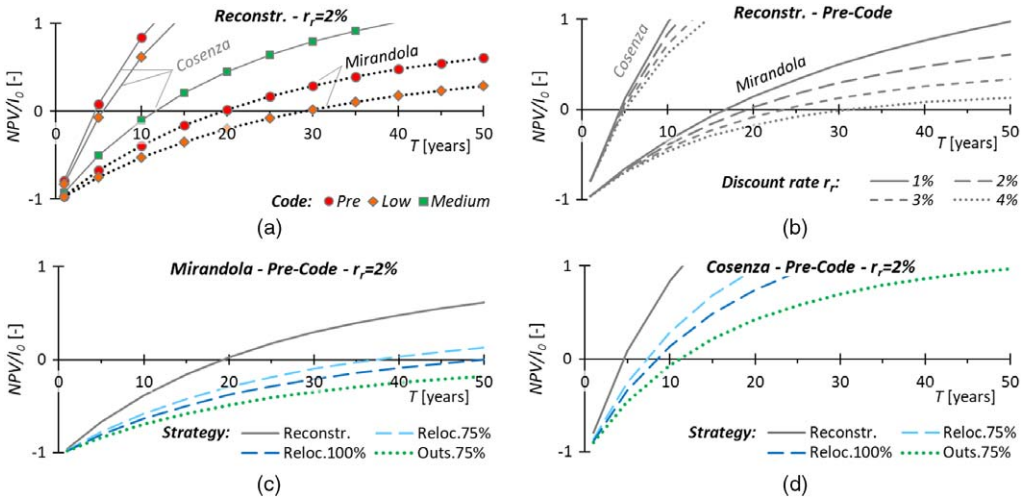


Figure 16. Ratio between NPV and intervention cost (I_0) versus planning horizon (T). Comparison between (a) codes, (b) discount rates, r_r , and (c,d) strategies for Mirandaola and Cosenza.

such as Mirandaola, the expected payback period (T_0) associated with the *Reconstr.* strategy and $r_r = 2\%$ is 20 or 30 years for a Pre- or Low-Code, respectively; therefore, the intervention seems justified only in the first case (Pre-Code), considering a typical planning horizon of 20–30 years (FEMA 227 1992). Moreover, for long payback periods, the effectiveness of retrofitting is significantly affected by the discount rate, as shown in Figure 16b; in fact, for the *Reconstr.* strategy and a Pre-Code, the retrofit in Mirandaola is cost-effective for $r_r \leq 2\%$ (current Italian values) but is no longer so for $r_r \geq 3\%$. Therefore, because of uncertainty concerning r_r and its possible variation over the years, sensitivity analysis is appropriate. Instead, in a highly seismic area such as Cosenza, T_0 is greatly reduced to about 5 years for Pre- and Low-Codes with the negligible influence of r_r , which makes retrofitting recommendable (a reasonable view considering the high ELs even for small damage levels caused by BI). The retrofit then still seems reasonable for a Medium-Code and more than a Pre-Code for Mirandaola.

Lastly, Figure 16c and 16d show the significant influence of recovery strategies (BRSSs) on the effectiveness of the seismic retrofit. In fact, in the case of a Pre-Code and $r_r = 2\%$, when the BRSSs are taken into account, the payback period (T_0) increases from about 20 to 40 years (and beyond) in Mirandaola (low-moderate seismicity), making the retrofit no longer worthwhile, whereas T_0 increases from about 5 to 10 years in Cosenza (high seismicity), greatly reducing the effectiveness of the retrofit, which however remains cost-effective. This is an interesting result because, when considering the “value case” for interventions, it is often assumed that a disrupted system otherwise operates in the same way or is not adaptive; in real-life situations, people generally find ways to adapt to disruption and reduce its costs, and it is therefore very reasonable (and desirable) to include these behaviors in risk assessments.

CONCLUSIONS

This work first presents a general operational method for assessing the cost-effectiveness of BRSs and seismic retrofitting in the same probabilistic framework so that interactions can be evaluated. Subsequently, this method is applied to a real-life case study: a biomedical packaging company affected by the 2012 Italian earthquake that resumed business after undergoing both direct and indirect losses.

In particular, a parametric study was carried out to define the company's exposure model, with the novelty that it takes into account the main BRSs in addition to direct and indirect costs for various DSs (as defined in HAZUS-MH MR4, FEMA 2003). To estimate correctly indirect losses caused by reduction in production volumes (i.e., profit losses), a production model calibrated on the basis of the case study was used for parametric simulations of the production process in various scenarios of damage and business recovery. Then a parametric seismic risk assessment was conducted with this exposure model, evaluating various building and machinery vulnerabilities (associated with the HAZUS seismic codes) and the seismic hazard of two Italian sites (defined according to Italian code DM-2018 and SHARE Project, GEM 2017). The main results obtained are listed as follows.

- The order of importance of the main factors involved in this risk assessment is (i-ii) structural vulnerability and site seismicity; (iii) whether application of recovery strategies takes place; (iv) hazard definition (DM-2018 or SHARE), and (v) type of recovery strategy; therefore, the dependence of risk estimates on the parameters defining recovery strategies (mostly financial parameters and recovery times) is lower than that of the other factors.
- The risk is significantly greater in a highly seismic area, such as Cosenza, compared with a low-to-medium one, such as Mirandola, e.g., 2.5–3.5 times higher (hazard from SHARE). Moreover, the risk increased considerably when the hazard was defined according to SHARE instead of DM-2018 (e.g., 1.5–2.0 times for Mirandola).
- Recovery strategies not requiring any initial investment are always worthwhile and are thus generally applied. They should therefore be considered for accurate estimates of risk, especially in cases of high vulnerability, as their influence is significant: they reduced the risk by 1.5–3 times according to the degree of vulnerability and whether the factory is owned or rented. This is also crucial from the perspective of insurance companies, which may consider such strategies to design rational and competitive policies for their customers.
- The risk reduction for an increase of one class of the HAZUS codes (i.e., reduction of a vulnerability class) is less than or at most similar to that obtainable by including BRSs in the risk assessment (more worthwhile, since they do not require any initial investment).

Lastly, a parametric study was conducted to evaluate the effectiveness, from the company's perspective, of the seismic retrofit of existing RC factories with respect to the vulnerabilities, hazards, and BRSs examined; in particular, the expected NPV was chosen as a cost-effectiveness measure of the investment and assessed as a function of the planning horizon to evaluate the payback period. The main results are given as follows.

- In low-to-medium seismic areas (such as Mirandola), seismic retrofitting may or may not be economically justified, depending on whether recovery strategies are considered; the discount rate also plays a fundamental role.
- In highly seismic areas (such as Cosenza), seismic retrofitting generally seems to be recommended, although its cost-effectiveness and payback period greatly depend on recovery strategies; the discount rate is less significant.

In conclusion, a sensitivity analysis of the various economical and financial parameters—not only those defining recovery strategies but also the GPR (depending on actual turnover and variable costs after the event) and repair/reconstruction costs—is strongly recommended for future studies if they aim to obtain general risk results, which are representative for many companies. These results may lead to the creation of a typological database useful for simplified estimates of companies' seismic risk on a regional or nationwide scale; the ultimate goal is risk management, which is essential even in low-to-medium seismic areas because of BI losses and the fact that their insurance coverage is currently considerably lower than that for building and machinery damage.

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