Seismic resilience of hospitals

Dissertation

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by

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*) Either the German or the Italian form of the title may be used.

“Dietro ogni problema si trova un’opportunità”
“Behind every problem lies an opportunity”
G. Galilei

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Abstract

The evaluation of the seismic resilience involves many different fields and therefore requires a multidisciplinary approach. As matter of fact, the technical literature needed to develop this research topic comes from many different fields and only few scholars have faced the complexity arising from the simultaneous adoption of varied backgrounds and competences. Nowadays most research in this field regards hospital buildings: this is due to the fact that hospitals play a strategic role in the management of the post-earthquake scenario.

This research is aimed at developing a comprehensive holistic methodology for the seismic resilience evaluation of healthcare facilities, taking into account all the aspects that are usually considered one by one. More specifically, this work proposes a parallel evaluation of two distinct kinds of information, say the physical and the organizational aspects involved in the healthcare facility. In order to achieve a comprehensive evaluation of the seismic resilience, for measuring both physical and organizational elements the same parameter has been used, i.e. the patients' waiting time, which is an objective and significant quantity, compatible with all the investigated aspects, and associated with the functionality of the system.

The works suggests a new methodology, which is based on fragility analyses, and adopts several tools. In particular, the use of fragility curves allows to compare non-homogeneous information concerning structural and non-structural components; the waiting time, chosen as the functionality measure of the system, is measured by simulating the effects of different organizational model settings (thanks to a Discrete Event Simulation – DES – model).

This new methodology is applied to a real case-study, i.e. the emergency rooms of the emergency department in a hospital situated in Tuscany, which is an integral part of the Tuscan healthcare system framework. The evaluation of the seismic resilience for the emergency department is developed with reference to a particular patient category (called yellow codes).

The technique allows to simulate the organizational operations of the hospital, as a direct result of the physical features of its (structural and non-structural) elements. A flow chart with different scenarios is drawn which takes into account the possible conditions, and therefore the functionality, of structural and non-structural components; besides, the technique assesses the waiting time under seismic events of different intensities. As a consequence of an earthquake, two different cases of room closure are supposed, i.e. the permanent closure and the temporary closure. The proposed methodology extends the resilience quantification to a more complex dimension including both the physical and the organizational aspects, by translating the physical system resilience into operational consequences. Three analytical models (meta-models) are built and implemented to represent all possible cases that arise by applying the methodology, in order to capture the waiting time for the patients in critical conditions.

The work not only relies on the adoption of already available tools, but also on the creation of new ones. More precisely, new fragility curves have been found for the hospital structure under investigation and for some of its non-structural components. A great deal of effort has been put on the correlation of all the required information, such as the statistical evaluation of organizational aspects associated with the case-study under different scenarios, the effects of

physical results on the organizational setup, the correlated functionality curve variation, and the final multiple cases of resilience assessment.

The analysis points out the structural inadequacy of the case study, together with the lack of some important knowledge about the seismic behaviour and performance of non-structural components.

Finally, the work proposes possible future applications of the methodology, like the setting of optimum emergency plans or the need to enhance specific components of the healthcare facility system Accordingly some conclusions are sketched regarding the possible implementation of the quality of the service under emergency conditions as well as the testing of the existing emergency procedures.

The main contribution of this study is the research framework, which combines the main aspects to be considered in a unique multidisciplinary methodology able to account for all the parameters involved in evaluating the seismic resilience of healthcare facilities. The proposed framework is an open platform; indeed it can be further improved by including factors and parameters which have not been considered yet. This methodology can effectively help hospital managers in taking decisions before and during a shock, allowing the optimal use of healthcare resources which are subject to various constraints. Given the lack of comprehensive knowledge concerning this applicative field, another merit of this work is that of contributing to increase the scientific interest in this area, to highlight its potentiality and to prompt further studies.

Zusammenfassung

Die Evaluation der seismischen Resilienz umfasst diverse Forschungsfelder und erfordert dementsprechend einen multidisziplinären Arbeitsansatz. Dies spiegelt sich auch in der Literatur wider, welche aus verschiedensten Bereichen stammt. Nur wenige Forscher haben sich mit der Komplexität beschäftigt, die sich aus den verschiedenen Hintergründen und erforderlichen Kompetenzen ergibt. Das Hauptaugenmerk der Forschung liegt aktuell auf Krankenhäusern, da diese eine strategische Rolle im Management des Post-Erdbeben Szenarios einnehmen.

Diese Arbeit hat das Ziel, eine umfassende, holistische Methodik für die Evaluation der Erdbebenresilienz von Einrichtungen des Gesundheitswesens zu entwickeln. Im Speziellen wird die parallele Evaluation zweier verschiedener Informationsarten entworfen, welche zum einen die baulichen, zum anderen die organisatorischen Aspekte der betrachteten Einrichtung berücksichtigen.

Um eine umfassende Evaluation der Erdbebenresilienz zu erhalten wurden diese Aspekte anhand eines Parameters, der Patientenwartezeit, gemessen. Die Patientenwartezeit ist ein Parameter, der zum einen als Zielvorgabe dient, zum anderen ein Maß für die Funktionalität des Systems darstellt.

Basierend auf der Fragilitätsanalyse wird eine neue Methodik präsentiert, wobei einige der bereits vorhandenen Methoden übernommen wurden. Fragilitätskurven erlauben den Vergleich zwischen nicht-homogener Information über die tragenden und nicht-tragenden baulichen Komponenten. Die Auswirkungen verschiedener Organisationsmodelle auf die Patientenwartezeit wurde durch eine Discrete Events Simulation (DES) simuliert.

Die entwickelte Methodik wurde in einer Fallstudie angewendet: Untersucht wurden die Räume der Notfallaufnahme eines Krankenhauses in der Toskana, welches ein integraler Bestandteil der toskanischen Gesundheitssystems ist. Dabei wurde die Erdbebenresilienz der Notaufnahme für eine Patientenkategorie, die so genannten „yellow codes“, evaluiert.

Die vorgestellte Methode erlaubt die Simulation der Organisation des Krankenhauses, abhängig von den physikalischen Eigenschaften sowohl der tragenden als auch der nicht-tragenden Elemente. Ein Fließdiagramm verschiedener Szenarien wurde erstellt, welches sowohl den Zustand, und damit die Funktionalität, der strukturellen und nicht-strukturellen Elemente als auch die Patientenwartezeit bei seismischer Aktivität verschiedener Intensitäten, darstellt. Als direkte Folge des Erdbebens werden zwei verschiedene Arten von Raumschließungen postuliert: permanente und temporäre Schließung. Die vorgestellte Methodik erweitert die Quantifizierung der Resilienz, indem sie sowohl die physischen als auch die organisatorischen Aspekte einschließt: Die Resilienz des physikalischen Systems wird auf betriebliche Konsequenzen übertragen.

Drei Analysemodelle wurden erstellt und implementiert um die Wartezeit von Patienten in kritischem Zustand für alle denkbaren Fälle zu erfassen.

Für die Arbeit wurden sowohl vorhandene Methoden verwendet als auch neue entwickelt. Speziell wurden neuen Fragilitätskurven für das Krankenhausbauwerk und die nicht-tragenden Elemente erstellt. Die Zusammenhänge zwischen den verschiedenen Aspekten wurde intensiv untersucht; so wurde die Information über organisatorischen Aspekte der Fallstudie in

Verschiedenen Szenarien statistisch ausgewertet, die Auswirkungen baulicher Veränderung auf den organisatorischen Ablauf und die damit in Beziehung stehende Variaton der Funktionalitätskurve wurden ermittelt und schlussendlich mehrere Einschätzungen der Resilienz durchgeführt.

Die Auswertung der Fallstudie zeigt bauliche Defizite bezüglich der Resilienz auf. Weiterhin konnte gezeigt werden, dass es an Information über das seismische Verhalten von nicht-tragenden Komponenten mangelt.

Abschließend werden mögliche Anwendungen für die Methodik präsentiert, wie beispielsweise das Festlegen optimaler Notfallpläne oder das Erkennen von notwendigen Anpassungen der Baustubstanz. Folgen für die Qualität des Services unter Notfallbedingungen werden diskutiert und existente Notfallmaßnahmen geprüft.

Das grundlegende Ergebnis dieser Arbeit ist ein Konzept, welches alle Hauptaspekte in einer einzelnen multidisziplinären Methodik vereint, die alle Parameter innerhalb der Evaluation der seismischen Resilienz der Gesundheitseinrichtungen einschließt. Das entwickelte Konzept ist dabei erweiterbar: zusätzliche Parameter und Faktoren, die bisher keine Berücksichtigung gefunden haben, können hinzugefügt werden.

Effektiv kann dieses Konzept Krankenhausmanagern helfen Entscheidungen bezüglich der Erdbebenresilienz der Einrichtung zu treffen. So können die Ressourcen des Gesundheitswesens effizient eingesetzt werden.

Ein weiterer Beitrag der vorliegenden Studie ist das Aufzeigen grundlegender Wissensmängel in diesem wichtigen Anwendungsgebiet: In dieser Hinsicht ist eines der Ziele dieser Arbeit, das Interesse in diesem Feld zu erhöhen und weitere Entwicklungen und Forschung anzuregen.

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Glossary

ɣ	=	redundancy factor
a	=	parameter of the first fitting for the meta-model construction
a_0	=	sub-parameter of the second fitting for the meta-model construction
a_1	=	sub-parameter of the second fitting for the meta-model construction
a_2	=	sub-parameter of the second fitting for the meta-model construction
ACM	=	clinic for minor codes
b	=	parameter of the first fitting for the meta-model construction
b_0	=	sub-parameter of the second fitting for the meta-model construction
b_1	=	sub-parameter of the second fitting for the meta-model construction
b_2	=	sub-parameter of the second fitting for the meta-model construction
BC	=	blue code
c	=	parameter of the first fitting for the meta-model construction
C	=	capacity
c_0	=	sub-parameter of the second fitting for the meta-model construction
c_1	=	sub-parameter of the second fitting for the meta-model construction
c_2	=	sub-parameter of the second fitting for the meta-model construction
cm	=	centimeter
CT	=	cross tee
CT-con		Connections in Cross Tee
C_u	=	class of use
D	=	demand
DES	=	discrete event simulation
DISCH	=	discharge
DTs	=	downtimes
E	=	efficiency
ECP	=	engineering capacity parameters
ED	=	emergency department
EDP	=	engineering demand parameters
EDt	=	Department Disposition time
ER	=	Emergency Room
FC	=	fragility curve
FIFO	=	First-In First-out
GC	=	Green Code
IDA	=	incremental dynamic analysis
IM	=	magnitude index
IUSS		Istituto Universitario per gli Studi Superiori
m	=	meter
MESP	=	Maintained for the entire simulation period
MLE	=	maximum likelihood estimation
MMI	=	Modified Mercalli Intensity
MPLT	=	multi-dimensional performance limit state threshold

MSA	=	multiple stripe analysis
MT	=	main tee
MT-Sp		splices in Main tees
n	=	number of beds
n	=	number of room
NSC	=	non-structural component
NSC_{room}	=	Non-structural components within a room
NTC	=	Norme Tecniche per le Costruzioni
Θ	=	median
OBI	=	Short Intensive Observation Rooms
ORs	=	Operating Rooms
OSS	=	help operator
PEMAF	=	Emergency Procedures for massive inflow of patients
PFA	=	peak floor acceleration
PFs	=	penalty factors
PGA	=	Peak Ground Acceleration
p_j	=	probability of collapse
p_j		True probability of collapse
PLS	=	performance limit state
$Pr_{F/D}$	=	probability of failure/damage
Pr_{STR}	=	probability of exceeding the structural limit state
PT	=	pre-hospital time
PVR	=	Probability of Exceeding
Q(t)	=	Quality of of infrastructure
$Q_f(t)$	=	function-based metric
$Q_{QS1}(t)$		Qualitative functionality
$Q_{QS2}(t)$		Quantitative functionality
QS	=	quality of service
R	=	ratio n/m
R	=	Resilience
R^{-1}		ratio m/n
RC	=	Red Code
Rc	=	Reinforced concrete
R_i	=	redistribution of function *i*
$r_i\ lim$	=	dependent response threshold parameter (deformation, force, velocity, etc.)
RT	=	recovery time
RTPC	=	recovery time probability curve
SC	=	structural component
SDCU		same day care unit
Sf	=	scale factor
SLC	=	Collapse Limit State
SLD	=	Damage Limit State
SLO	=	Serviceability Limit State
SLV	=	Life Safety Limit State
TOSE	=	technical, organizational, social, economic aspects
T_R	=	return period
VN	=	nominal life
V_R	=	Reference Period
WC	=	White Code
w_i	=	weighting term
WR	=	Waiting Room
WT	=	Waiting Time
WT_{crit}		critical waiting time
WT_{max}	=	maximum waiting time
YC	=	Yellow Code
α	=	seismic arrival rate factor
β	=	standard deviation
λ	=	Arrival rate of patient at the hospital (Cimellaro et al.)
λ_u	=	Critical arrival rate of patient , when the hospital reaches its satured conditions (Cimellaro et al.)

Motivation

Recent seismic events, like L'Aquila (2009) and Emilia (2012), have shown how structural buildings are vulnerable to natural disasters, due to human errors and system failures. Strategic structures, particularly those which are considerably significant for a community in case of calamity, must guarantee a full operability, especially in the first hours after the disaster (or the emergency). These "strategic buildings", i.e. hospitals, have a complex organization and their functionality crucially depends on the functionality of each component. As matter of fact, the cascading effects due to a calamitous event, like an earthquake, can make the system – or the whole healthcare framework – completely dysfunctional, also preventing rapid responses and urgent recoveries. To assess the functionality of health care facilities recent research contributions have introduced a new parameter, i.e. the "resilience", as a comprehensive variable for describing the whole system in terms of both structural and functional responses.

Aim and objectives

The main purpose of this work is to develop an exhaustive holistic methodology for the seismic resilience evaluation of health care capabilities, taking into account all the aspects that are usually analysed one by one.

This comprehensive approach is aimed at proposing proper measures to be used for understanding and manage all the issues constituting the "resilience" of healthcare systems, addressing the contribution and benefits of various research activities into a unique framework.

Accordingly the main aim of this thesis is to describe a method to define the "resilience". To this purpose, a preliminary assumption about the resilience measure must be made. The choice of such a measure cannot be independent of the way to measure and quantify the safety of the structural building and the efficiency of the provided services.

In order to reduce the structural and functional losses in the investigated systems, preventive analyses and strengthening interventions are suitable and precious. An effective preliminary investigation, indeed, allows to effectively predict and simulate the effects of earthquakes; consequently, it is possible to optimize the available resources and to largely increase the functional performance of the system.

This system administration's enhancement permits a better coordination and a more conscious management of hospitals: for instance if appropriate decisions are taken before and during a shock, the optimal response of the healthcare system can be achieved, despite the possible presence of various constraints.

Given the wide lack of knowledge regarding the different disciplines involved, this work remarkably increases the interest in this area, also encouraging further developments in this field.

Overview

The work is structured in seven chapters.
Chapter 1 introduces the research topic, and focuses on the hospitals' reliability also providing an overall overview of different legislations for seismic hospital safety in different countries; the most vulnerable systems of hospital buildings, on the base of past eartquakes, have been pointed out, and the main aspects involved in the functionality evaluation have been introduced.
Chapter 2 is focused on the technical definition of "resilience"; special attention has been paid to the resilience as an evaluation approach to hospital systems. A careful presentation of the state of the art is proposed both concerning the general concept of resilience and its application to hospital buildings.
Chapter 3 describes the proposed methodology for assessing the seismic resilience of hospital buildings by taking into account physical and organizational responses. As a guideline, a flowchart is provided, where the combination of many possible structural, non-structural and organizational aspects is sketched.
Chapter 4 and Chapter 5 deal with a case study: the hospital of Sansepolcro. In particular, Chapter 4 illustrates the analysis of the hospital, taking into account all the relevant aspects, that is: structural (e.g. fragility curves associated with the *peak floor acceleration* (P*F*A)), non-structural (e.g. fragility curves of the suspended ceiling system used in the emergency department; fragility curve derivation of the cabinet), and organizational components (e.g. organizational model associated with the possible emergency scenarios).
Chapter 5 reports the results obtained for the organizational part, following the proposed method. Since different situations – regarding the structure, the non-structural component and the organizational aspects – can occur, different scenarios can arise representing the effectiveness of the hospital system as a consequence of a seismic event. All the possible "scenarios", called "cases", have been described and analysed. A different meta-model, describing the whole behaviour of the entire hospital system, has been developed for each case, representing a specific possible disruption of the medical service. At the end of the chapter, the simplified methodology to assess the resilience is presented, together with the necessary steps to build the graphical resilience function.

A discussion of the results of the proposed methodology is presented in Chapter 6, where the method presented in Chapter 3 is followed and applied to the case-study, providing an estimation of the seismic resilience. Furthermore some applications – already possible or expected in a close future – are discussed. Namely, the effect of the introduction of redundant elements into the system in case of an emergency scenario has been simulated and a study regarding the optimisation of the resources is illustrated. Chapter 7 resumes the research outcomes, drawing some conclusions. A possible guideline to apply to the proposed method is proposed, and possible future developments are presented.

Finally, the Appendices report all the results discussed in the work.

Chapter 1

The seismic reliability of Hospital Buildings in the post-earthquake scenario

Seismic countries have often faced the difficult experience of the post-earthquake scenario. The destructive impact of an earthquake is usually measured in terms of life losses and constructions collapse. There is, however, another variable that largely affect the impact of the earthquake on the community. This quantity is the time needed by the community to recover and revert to its main functionalities. In the last years a lot of technical literature[1] has been dedicated to this complex aspect. Although a comprehensive dissertation on this issue is beyond the aim of this thesis, it can be said that an effective emergency plan, together with the functionality of the health system, are at the base of the potentiality of a community to recover after a strong earthquake.

This work deals with the analysis of the post-earthquake functionality of hospital systems. As matter of fact Hospital buildings are the focus of the entire healthcare system (Viti et al. 2006). They play a vital role for the health and life quality of the population even in “standard” times, since people rely on them for their health and well-being. But in case of emergency they become

[1] The technical literature rapidly developed with the last earthquake events: from all the world the needing to a deeper comprehension of the hospital system involved several fields at the same time. National agencies started to improve codes and prescribe provisions (FEMA, WHO, PEER 2002-2005), while researchers focused their attention on specific studies regarding the hospital building. Italian researchers from different University studied the vulnerability of hospital (a Masi et al. 2012), while others started the investigations on non-structural performance (Cosenza et al. 2014), or the functionality maintenance of hospital in post-earthquake scenario (C. Nuti 1998). In Japan, many researches are in more detailed area, such as the seismic risk assessment of lifeline by Kuwata et al. 2008, or the Taiwanese study on the identification of earthquake damaged operational and functional components in hospital building by Yao & Tu 2011. All these researches are not focused on a unique comprehensive variable for assessing the hospital functionality, actually the most part of researchers are focusing on specific subjects. Only few are the studies which take into account all these aspects. Examples are the American MCEER group (Cimellaro, Fumo, Reinhorn, Bruneau, 2009) which conducted a research on the quantification disaster resilience of health-care facilities; the New Zealand group with C. Jacques, J. McIntosh, S. Giovinazzi, T. Kirsch, T. Wilson, J. Mitrani-Reiser (the research developed after the 2011 Christchurch earthquake, which caused a big interruption on the whole healthcare framework of the Canterbury region). To the latters are dedicated more description into chapter 2.

even more crucial. Their extraordinary importance during an emergency is due to many factors like:

- the social function;
- the strategic role in case of calamity;
- the high value of content;
- the complexity of internal sub-systems and functions;
- the high rate of occupancy and the continuous cycle of activities.

Hospitals are the final point of the rescue chain and, therefore, they represent the focus of the disaster response. In case of calamity, especially immediately after earthquakes, they must guarantee immediate medical services to the injured population, and protect the patients who are not self-sufficient or depend on life support devices. Due to all these reasons the safety of hospital buildings is a strategic goal for each community. The efficiency of an hospital building, even after a seismic event, is related to its own organization and coordination, which are based on appropriate emergency plans. Any action plan, however, needs a proper, suitable and integer building to work. Accordingly the “engineering” safety of the buildings used as hospital facilities plays an important role in the post-earthquake strategy chosen by each community. In order to guarantee the required efficiency to the hospital building, the role of the hospital in the emergency scenario must be known and understood: it is this key-information which ensures each function to be performed according to the plan.

To provide the essential safety requirements – even those related to the post-earthquake scenario - the complexity of the hospital must be analysed and taken into account. Section 1.1 deals with the complexity of hospital buildings, which involves both spatial organization and logistic planning, underlining and investigating the connections among the main factors. The necessity of having a measurable variable for the seismic reliability is explained, and the concept of resilience as operative approach to the problem is introduced. Section 1.2 is dedicated to the legislation frame that supports the hospital buildings checks: special attention is paid to the results achieved by the California State, where the most advanced technical code has been produced, and to the Italian technical state of art.

1.1 The reliability of hospital buildings

Any hospital is a complex organism, where different functions, goals and competences interplay to achieve the expected global efficiency. To achieve the required reliability a hospital building must be faced and understood as a complex system consisting of spaces, technical devices and people.

The system can be divided into hospital sub-systems, which in turn can consist of individual elements or groups of elements. The management of the functionality of all the elements composing a sub-system, and consequently the system as a whole (intended as a hospital), is the main need for assuring an acceptable health service both in a global sense and in the punctual performance of single elements. Each component has its own role in the cascade-loss of functionality of the global system. Precise requirements must be defined for all components, connections and interconnections so that a satisfactory control of the whole system can be achieved. As matter of fact, it is not sufficient to assure the stability of the structure or of a single element: their behaviour is converted into cause-effect phenomenon that should be easily comparable: complex responses from different elements must be compared and harmonized with each other in order to guarantee the global response of the hospital. Furthermore the identification of each proficiency ensures the efficacy of a management able to pinpoint the problem and find the best solution. The following paragraph presents a specific overview on hospitals subjected to an earthquake: the main aim is to describe the cause-effect phenomenon and the complex interrelation between the several elements the global system consists of.

When an earthquake strikes, as a result of sudden movements along a fault, it creates a motion that travels as waves towards the site of a structure. These waves are transferred to the foundation of the structure, passing through the overlying soils at the site. The response of the building depends on several properties, which in many cases are very difficult to predict, for instance: the material of the structure, the geometry of the structure, the frequency and the amplitude of the ground motion. The structural performance is not sufficient to describe the response of the single functions and elements dislocated within the building. As Figure 1.1 shows, the behaviour of the building is composed of several “responses”, starting from the structural one, passing through the non-structural components performance and depending on the organization of the functions allocated inside each space. As matter of fact the image represents the need of a multi-disciplinary knowledge, especially regarding the non-structural components that have a key role since the level disposition in a structure determines significantly different acceleration and displacement demands at spatially different locations. It is not only worth to underline the importance of all these components and networks, but also other aspects which are hard to catch, like the personnel’s behaviour and the panic of injured people, beside the falling of roads and communication connections. The literature and past experiences reveal that healthcare discontinuity is common after an earthquake, while it is not very clear which are the causes of discontinuity, even under low intensity earthquakes. The overall hospital serviceability depends on the performance of multiple elements and interacting systems rather than just on the structure remaining standing. Even if the structural components of a building achieve an immediate occupancy performance level after a seismic event, failure of architectural, mechanical, or electrical components of the building can lower the performance level of the entire building system. Moreover, non-structural components and equipment are usually much more vulnerable to seismic events, since they are assumed to not have a structural role. It has been documented how the damage of both architectural and mechanical non-structural building components can have a strong effect on the safety of occupants, functionality of facilities, and loss of property.

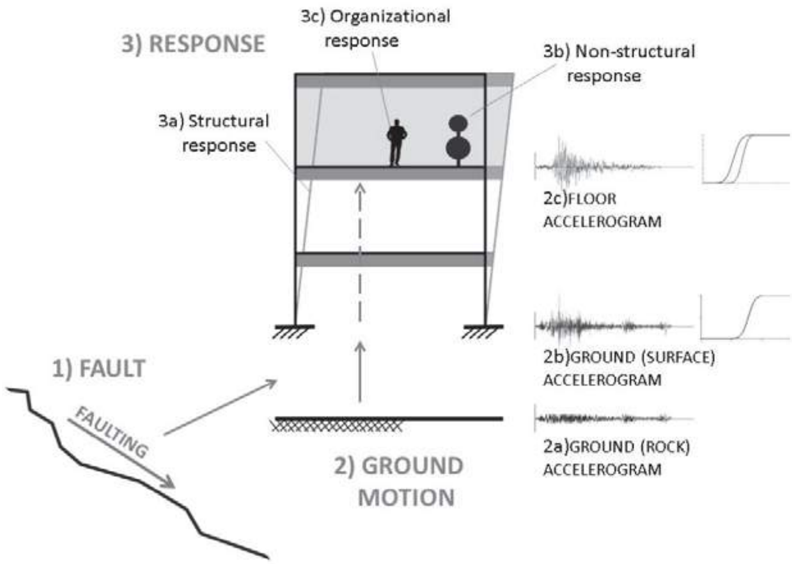

Figure 1.1 Overview of the system behaviour including all the aspects having a significant role into the hospital.

The described overview shows the complexity in assessing and managing the global response of a hospital. The cause-effect phenomenon induced by a single element within the hospital clearly demonstrates the need of a depth-knowledge of the behaviour of non-structural elements and the harmonization of non-structural and structural components. The hospital has not to be conceived as a container, but also the contents with all their peculiarities are to be taken into account for determining the overall response of the “hospital-system”. In this sense, not only material elements are included, but also the organizational aspects that represent an important part of the global response. On these aspects depends the continued and fully operation of healthcare facilities after an earthquake, and the consequent prevention of the hospital inoperability. Accordingly the key element to be studied and investigated in order to prevent a crisis after an earthquake is the functionality, defined as operability, of the hospital.

Previous studies on hospital systems (A. Masi et al. 2012; Nuti & Vanzi 1998; Kuwata et al. 2008; MCEER, 2009), including all their components and elements, remark the complexity of the problem. This intricacy is not only due to the various and different elements inside the building, but also to the presence of several supervisors at the same time. In fact numerous figures are simultaneously in charge: structural engineers for a building project are traditionally focussed on the design of the building structure, while architects generally specify non-structural elements such as ceiling systems, cladding systems, partitions and architectural finishes. The building service and fire engineers specify mechanical services, electrical systems, piping and fire protection systems. Finally the design and installation of the seismic bracing system for the non-structural proprietary elements is typically a responsibility of the contractor and subcontractors. Therefore it is essential to provide a performance measure of the global response that will eventually be used by policy makers; consequently, the management during the shock will only improve – leading to a prevision of the time needed to restore the hospital – in case failures are localised, and their effects are determined and solved. This concept, defined as seismic resilience, has been introduced a few years ago and resumes the main objective of this work.

The knowledge of the response of hospital systems in normal conditions and previsions during emergency phases, including all the aspects briefly introduced, is the main goal of this work, which intends to hypothesize resilient functions. To this purpose, the functionality of the hospital must be properly investigated and “quantified”.

The functionality of a hospital is hard to quantify: it cannot be defined according to simple engineering units, as it is the case of power grids or water distribution networks, where simple and conventional units, such as kilowatts or litres, can be used. As matter of fact such a functionality can be defined in different ways, depending on different occurring emergencies, and the type and range of mitigation actions that are expected. Moreover, this functionality must be related to the amount and the efficiency of the available facilities, which are a function of the seismic event itself since the earthquake can largely damage the effective medical facilities.

In addition to the problems identified for different countries in developing and following a unique method for functionality assessment, even within the same country the existence of “similar” hospitals does not guarantee the same functionality and consequently the same probability to predict the performance during an emergency. The ability of a hospital to keep its functionality can substantially depend on its layout. This may differ very much from case to case even for hospitals having similar dimensions, i.e. having the same number of beds, having been built in the same period, and is due to many factors, the most frequent one being the later creation of new buildings to face the varying and often increasing functional needs.

This brief introduction to the problem underlines the difficulties to find a unique way to represent the overall hospital serviceability, and to resume it into a single methodology. The only possibility to include and represent several field and aspects is that of relying on a single parameter that can be eventually used by policy makers, such a parameter is seismic resilience.

1.2 Knowledge and legislation development on seismic reliability of hospital buildings

All seismic regions of the world have experienced the inconvenience of healthcare interruption due to seismic events. Many of these countries, therefore, have tried to provide proper guidelines to prevent further losses. Technical developments flew into seismic codes that produced guidelines for structural and non-structural elements in order to ensure the continuity of hospitals service care. Researchers, engineers and decision makers have been pushed to investigate the causes of different failures; their studies are mostly based on the observation of previous experiences: what went wrong in the seismic response of a hospital and why the hospital building could not be properly used after the seismic event.

As a consequence, many countries have set a seismic technical code which includes specific and proper provisions concerning the design of hospital buildings. Nevertheless, even now most codes focus exclusively on structural components and when non-structural elements are considered, they are limited to architectural, mechanical and electrical components (FEMA 2007); although these constitute the most important elements for a hospital design, they are not sufficient by themselves to ensure a fully efficiency. The economic losses due to non-structural components have been two or three times greater than the cost of replacing collapse buildings or structures (Taghavi & Miranda 2003). Even recently, despite more requirement are needed and new steps into the international codes have been done, the damage to non-structural elements has determined the majority of the losses also leading to the hospital closure: this happened in Italy – l'Aquila (2009) and Reggio Emilia (2012) – and in New Zealand (2010).

After an earthquake the importance of non-structural components is, in effect, far away from being of minor importance, both in economic and serviceability terms. For most buildings non-structural elements and building contents make up around 50%-70% of the total building cost according to Taghavi & Miranda (2003), as shown in Figure 1.2.

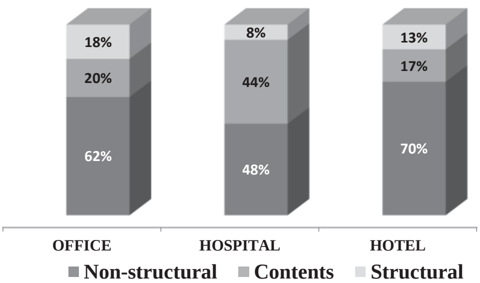

Figure 1.2 Building type–cost breakdown

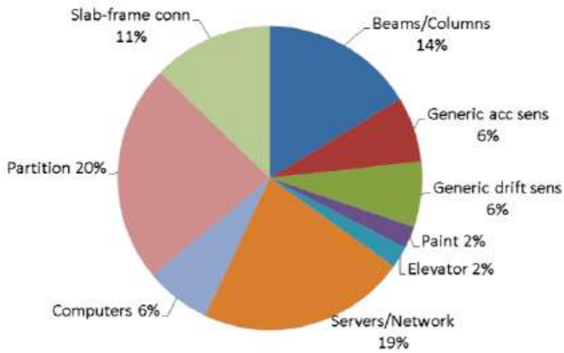

Figure 1.3 De-aggregation of expected loss, by component, for a 10 storey reinforced concrete office building

The economic consequences can be primarily attributed to: (i) the direct economic losses associated with the repairing damage within a structure; (ii) the direct losses associated with the loss of income due to business interruption; and (iii) the indirect losses associated with the loss of income due to business interruption.

The documented experiences prompted politicians and authorities to develop and implement new techniques in order to improve the existing codes and to apply a more careful legislation regarding the complex system integrated into a hospital facility.

1.2.1 The USA as a leading country in the seismic legislation for hospital subjected to earthquakes: the Northridge experience and further efforts by other countries

The evolution of design philosophy and design provisions in building codes started with the need by government officials, design professionals and healthcare providers in California for a general recognition of time codes. After the 1971 San Fernando earthquake, the first "hospital Seismic Safety Act" was developed, with a focus on structural and non-structural resistance; in fact since March 7, 1973, the design, maintenance and construction of California's hospitals have been governed by special statutes, regulations and design standards aimed at ensuring the hospital functionality after major earthquakes. The main goal was to ensure safety to vulnerable patients in an earthquake, to maintain the functionality of the facilities after such a disaster and therefore to protect the inpatient population and to provide the necessary service for injured person in the community.

After 1973 all Californian hospitals, have been built, remodelled or re-designed according to these stringent requirements.

In the 1994 Northridge earthquake, several facilities built prior to the HSSA[2] experienced structural and non-structural damages had to be evacuated. Actually, non-structural damages affected both old and new hospitals (with the latter built in accordance with the stringent HSSA law/requirement). This event clearly showed that in many cases the non-structural components and systems did not conform to the "functionality" standards which had to ensure a good performance during major earthquakes.
Requiring seismic evaluation the Act was amended by Senate Bill 1953, after the Northridge earthquake; in case hospitals were found to have structural or non-structural vulnerabilities, retrofits or replacements were required. Accordingly, the legislation in California has been developed on the base of lessons learned from previous experience and reflect the complexity of hospital systems.

Figure 1.4 Example of suspended ceiling damages during the 1994 Northridge earthquake (FEMA).

The California legislation SB[3] 1953 is very important even for the new approach to the seismic design: codes and instructions are the result of previous experience as well as of the awareness of the complexity of hospital systems and clearly demonstrate the authorities' strictness in ensuring the continuity of medical care in case of calamity.

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[2] Hazardous Substance Account Act (HSAA) creates a number of subaccounts in the General Fund that are administered by the director of DTSC. The stated purposes of HSAA are threefold: (i) to provide for response authority for releases of hazardous substances that pose a threat to the public health or environment, (ii) to provide compensation for out-of-pocket medical expenses and lost wages or business income resulting from injuries caused by exposure to hazardous substances, and (iii) to make available adequate funding to meet federal requirements that California pay 10 percent of the cleanup costs. HSAA.

[3] Senate Bill 1953 (SB 1953) was introduced on February 25, 1994. It was signed into law on September 21, 1994 and filed by the Secretary of State on September 22, 1994. The bill was an amendment to and furtherance of the Alfred E. Alquist Hospital Seismic Safety Act of 1983 (Alquist Act). SB 1953 (Chapter 740, 1994), is now chaptered into statute in Sections 130000 through 130070 of the Alfred E. Alquist Hospital Facilities Seismic Safety Act, and part of the California Health and Safety Code. The regulations developed as a result of this statute are deemed to be emergency regulations and became effective upon approval by the California Building Standards Commission and filing with the Secretary of State on March 18, 1998.

Other countries, such as Turkey, understood the importance of this need and started conducting comprehensive retrofitting activities to reduce the vulnerability and enhance/improve the performance of their infrastructures including hospitals, schools and bridges (IPDED 2010). As a consequence to previous risk and events, new techniques were developed and implemented, like the implementation of base isolation to protect structural and non-structural components from failures. Despite significant improvements in techniques and practices, during the 2008 Sichuan earthquake (China) many newly built schools and hospitals collapsed, mainly due to poor design and poor structure quality.

Also in Italy inadequate detailing and design irregularities were the main cause of the "new" L'Aquila hospital to suffer severe damage after the 2009 earthquake (EEFIT 2009).

Figure 1.5 Damage to the ceiling during the l'Aquila Earthquake.

The lesson learnt from past experience clearly indicates that preventive care has largely paid off in subsequent emergencies and it needs to be planned and implemented through a continuous process. Code implementation can be done by enforcing designers and architects to follow the law, but it can also be achieved by spreading awareness. For example, Taiwanese authorities make use of awareness and legislation to push architects and contractors to design and construct resilient buildings; one of the interviewees stated that currently architects and contractors are more willing to comply with seismic detail and willing to pay more attention to what structural engineers suggest.

Accordingly seismic resistance codes for hospitals are needed which could provide guidelines for the structural and architectural elements (for new and existing buildings), the continuity of utility supplies and the stability of equipment. The efficiency of these codes depends on the method they are developed on and the effectiveness of their implementations. Codes should be based on scientific evidence (i.e. field investigation, theory and best practice) and should take into account the local culture of construction method as well as experiences on past earthquakes and, most importantly, they must be provided with implementation and enforcement strategies. The existence of a reference model has certainly encouraged the renewal process of other countries; however, the particular features of the construction techniques, the properties of the soil, the building maintenance and management policy of each country as well as different economies, resulted in an inability to slavishly follow the USA model, despite the increasing awareness to face calamities with methods and codes *ad hoc*. As a matter of fact there is a worldwide amount of public buildings, originally designed without seismic criteria, that are currently located in places classified as seismic zones. For example, in Italy, the National Department of Civil Protection (DPC) estimates that there are about 75’000 public buildings designed without seismic criteria, and nearly 35’000 of them are placed in areas having either medium or high seismic hazard (Dolce et al. 2006); crucially, many of these buildings are hospitals.

Although the incredible achievements of the Californian community, current guidelines are still insufficient to assess a satisfactory level of security for hospital subjected to earthquakes. Despite the harmonization between structural and non-structural components is developing, it is still far away from being a daily practice: indeed no attempt to practically relate the structural damage with the organizational aspects has been proposed so far. Accordingly an integration between legislation and tools able to include all the aspects involved into medical disruption (both for the physical part and the organizational planning) is urgently needed. In this framework seismic resilience represents the unique all-embracing measure. This new idea suggests a new approach that must be studied in-depth and could allow the inclusion of new methodologies into hospital codes based on the concept of hospital functionality and grouping all the above described aspects.

1.2.2 Italian code development on hospital safety

In Europe, and specifically in Italy, the current state of affairs regarding the prevention of hospital safety is not so advanced as in California. In Italy public buildings, including hospitals, showed poor performance during past earthquakes. For example, during the Mw 6.4 1976 Friuli and the Mw 6.9 1980 Campania-Basilicata earthquakes, the healthcare system suffered severe and extensive damages. Specifically, the 1980 earthquake caused the complete collapse of the Sant’Angelo dei Lombardi Hospital (RC structure, 7-storeys) and serious damage to the Curteri Hospital at Mercato San Severino.

Until 1986 the Italian design for hospital was not supported by any specific code about seismic events, when the design of seismic action was amplified of 40% compared to ordinary buildings, through the introduction of the coefficient of importance, related to the building function. In the following years only few and punctual research projects were financed for the protection of new and existing hospitals. This effort interested some specific regions, without a comprehensive and extensive project for realizing a new specific code for the protection of hospital buildings.

It must be noted that in Italy the safety conditions of hospital buildings is particularly difficult. Many hospitals are located into existing buildings, often historical constructions, with all the problems related to them. Although there are some exceptions – big healthcare located into appositely made new buildings – their date project results to precede the newest code due to the duration of the construction practice. For instance, it was necessary to wait until 2002 for the publication by the Ministry of Health and Infrastructures of the “guidelines for improving earthquake safety and functionality of hospitals”, which was followed by a second edition. These guidelines define levels of protection for both the limit state of damage (with the purpose of immediate usability) and the limit state of protection of human life and protection from collapse. These levels are much higher than those of common building constructions: for the latter only the protection against the collapse (with a modest request in verifying the damage of functionality levels) is defined.

In 2003, after the publication of the order of civil protection number 3274, hospitals were defined structures essential for the civil protection, even not taking into account their functional aspects. Despite these new requirements, during the 2009 L'Aquila earthquake the complete evacuation of the most part of local hospital complex was needed; in addition, in the last 2012 Emilia earthquake the hospitals lost their care capacity due to the loss of equipment and failure of non-structural components.

Recently the new seismic codes have provided more adequate methods and techniques to achieve the seismic risk mitigation of both new and existing strategic buildings, where considerations concerning the structural performance against collapse risk prevail. Moreover, the new seismic code aims at limiting damage to non-structural components through the limitation of inter-storey drift values, whereas no specific provisions about content restraining (e.g. medical equipment) are provided.

Chapter 2

Seismic resilience: definition, peculiarities and metrics

A unique and univocal definition of resilience is not easy to find since this concept is commonly used in many different fields, ranging from the environmental research to materials science and engineering, also including psychology, sociology and economics. Moreover, in recent years the definition of resilience has been strongly developed and reinforced even in the medical field. Consulting a dictionary it is possible to find a definition which concerns both strength and flexibility; more specifically, resilience can be is defined as “the capacity to cope with unanticipated dangers after they have become manifest, learning to bounce back” (Wildavsky 1991), or “the ability of a system to withstand stresses of ‘environmental loading’ […] a fundamental quality found in individual groups, organizations, and systems as a whole” (Horne & Orr 1998).

A proper and more suitable definition of resilience, however, requires to know the scientific field we are dealing with and the limits within which the term resilience applies. As matter of fact, “resilience” can be investigated at any scale of a system, ranging from the smallest elements constituting a specific sub-system up to the most general system that has to be limited as well. For instance, the concept can be applied to a specific material to a finite element (e.g. a column or a beam in the engineering field), to coupled elements (e.g. a structural concrete frame) or even to an entire community. Accordingly defining the scope of resilience and its purpose, focusing on the specific system involved, are the main priorities of the discipline.

According to the engineering approach the definition of resilience presumes the existence of a system to be investigated and the occurrence of an event that disturbs the normal state of this system. In this framework even resources and skills employed to face new situations and operating conditions are included.

2.1General measure of resilience and definitions

2.1.1 Resilience in a system

There are two main approaches to define and evaluate resilience. The first approach is related to the definition provided by Bruneau *et al.* (2003), i.e. the *ability of the system to reduce the chances of a shock, to absorb a shock if it occurs* (like the abrupt reduction of a performance) *and to recover quickly after a shock* (to re-establish its normal performance). This definition relies on the assumption that a unique measure, which is time-variable, is representative of the quality of the system. The performance can change in a range and the restoration of the system is expected to occur over time. The representative measure of the system functionality must depend on all the factors affecting the system. Therefore if the object under investigation is a system, the first step to take is the definition of its parts, the comprehension of the relevance of each part in the whole system and the unit-element to be considered as the smallest one to assess. If the parts of the system do not have the same measurable quantity, a common property to be measure must be found. The more complex the system is, the more difficult it becomes to find a conjoint measure to evaluate since such a measure must be representative of the behaviour of the whole. A revised definition can be provided for the seismic resilience of those systems where the performance is characterised by multidimensional measures, which are interconnected and depend on the level of performance desired. In effect in a measurable (complex or simple) system, the performance can be measured in terms of different quantities and can change, gradually or drastically, depending on the event and its nature. A reduction in performance can concern all or some of the quantities assumed as a reference. The evaluation of performance reduction/loss is obviously affected by such a choice. External events can create abrupt changes in performance and can be followed by different restorations to achieve fully satisfactory (or acceptable) levels, depending on the employed elements. The cascading loss of the system can be approached in different ways.

The second approach to the problem relies on the assumption that the system is to be perceived as a series of interconnected sub-systems. Accordingly a fault-tree analysis can be used to measure the reliability and the safety level of complex engineered systems: their functionality can be related to the state of each sub-system and component they depend on.

The analysis of the performance of a system implies the analysis of each sub-system and their correlation, otherwise it needs a unique value which is sensitive to all the involved components and which can represent the functionality of the whole system.

In this work, the object under investigation is the *hospital*, the quantity to be measured is its *functionality* and the event that disturbs the object is an *earthquake*. In order to establish a common frame of reference, scholars have analysed the fundamental concepts of resilience in order to unify the adopted terminology and to restrict its application to healthcare facilities.

Definition 1: *Resilience is defined as a normalized function indicating capability to sustain a level of functionality or performance for a given building, bridge, lifeline, networks or community* *over a period of time T_{LC} (life cycle, life span etc.) including the recovery period after damage in an extreme event.*

Definition 2: *The recovery time T_{RE} is the time necessary to restore the functionality of a community or a critical infrastructure system (water supply, electric power, hospitals, etc.) to a desired level below, same or better than the original, allowing proper operation of the system.*

Definition 3: *Disaster resilient community is a community that can withstand an extreme event, natural or man-made event, with a tolerable level of losses and can take mitigation action consistent with achieving that level of protection (Mileti 1999, p.5).*

Definition 4: *Coupled Resilience is defined as the normalized function indicating capability to sustain a level of functionality or performance for a given building, bridge, lifeline, networks or community over a control period of time T_{LC} (life cycle, life span etc.).*

In this frame it is possible to recognize the community seismic resilience (Bruneau et al. 2003) as the ability of social units to mitigate hazards, to contain effects of disasters when they occur, and to carry out recovery activities in a way that minimizes social disruption and mitigates the effects of future earthquakes.

In case of earthquakes, the effect of resilience should be that of reducing loss of life, injuries and other economic losses; more generally speaking, it means that resilience has to guarantee the minimization of a reduction in the quality of life due to an earthquake. Seismic resilience comprehends all those strategies and instruments which are exploited during and after an earthquake in order to restore as soon as possible the levels of pre-disaster functioning (or other acceptable levels).

Inside the community, various institutions, organizations and elements within the environment contribute to resilience: among them some are essential to the community due to their functions in the aftermath of earthquake disasters. These critical facilities include water and power lifelines, acute-care hospitals and organizations being responsible for the emergency management at the local community level (Bruneau et al. 2003).

Due to the lack of detailed loss-of-function assessments it is very difficult to draw a realistic picture of what can be expected during an emergency. Therefore to give support to hospital administrators, planners and emergency personnel to manage the emergency phase is a true challenge.

These functions are essential for the overall community resilience since they enable communities to respond, provide for the well-being of their residents and put into action recovery activities in case an earthquake strikes. For this reason hospitals are crucial for the community resilience: the recovery activities start immediately after an earthquake and hospitals provide emergency care for injured victims. The recovering activity, together with power and water lifelines, constitute the backbone of a resilient community. The necessity of a continuous operation and rapid restoration of these service is an essential condition for the community to quickly recover.

2.1.2 The hospital system

If the hospital – given its complexity – is considered as a system it is worth to indicate the sub-systems evaluated and, within them, the "unit-element" to assess. Moreover, the connection among the different parts cannot be neglected: the intricate nature of hospitals necessarily leads to cascading problems and interrelations which are difficult to estimate. Therefore it is essential to have an adequate awareness of the problem.

As introduced in Chapter 1, "hospital-systems" can be divided into two big branches: the physical system and the organizational one. As Figure 2.1 shows, within the first branch it is possible to distinguish two main groups: the structural part (constituted by the structural elements) and the non-structural part (constituted by all the non-structural elements).

Figure 2.1 The main parts (or aspects) of hospital systems.

All the branches are indispensable for a good performance of the "hospital-system" since the lack of one of them compromises the global performance of the hospital.

In addition, each branch is composed of single elements or groups of elements which the performance of the main part depend on. The hospital performance, indeed, does not only depends on structural resilience, but also on non-structural components, like medical technology and organizational aspects (e.g. emergency planning and technical maintenance). As matter of fact the quantification of physical resilience is not enough to assess critical facilities like hospitals; therefore the need to include organizational resilience as part of the whole has pushed researchers to find closer ties between these two aspects (i.e. structural ones and non-structural ones).

This brief description introduces the high complexity of the problem which also induced different scientific approaches. Over time many different approaches have been developed and many aspects have been neglected: for instance, researches carried out by medical scholars miss relevant engineering or architectural aspects, and vice versa (see Chapter 1 for a more detailed account regarding the authorities involved).

2.2 Approaches hospital assessments

In addition to the current different methodologies which have been developed for the assessment of the seismic risk in hospitals, many others have been dedicated to the definition and assessment of the resilience of the structure, considering all the aspects playing a critical role in the functionality of the system.

The most common deficiency, according to these methodologies, is the lack of knowledge about one of the three parts (structural, non-structural or organizational) constituting the "hospital-system". Actually these approaches tend to evaluate separated aspects of the hospital performance, while resilience involves all of them, as shown in Figure 2.2.

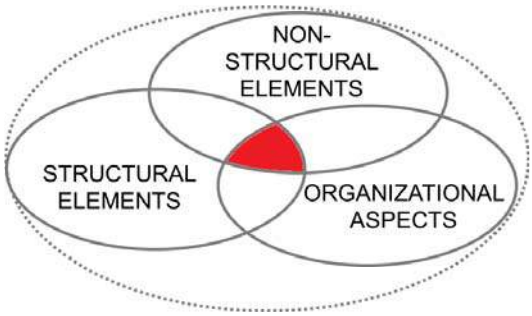


Figure 2.2 - Resilience as the ideal intersection of different fields.

Despite the numerous approaches that can be found in the literature (Maxwell 1984; McCabe et al. 2010; Thompson et al. 1996), a more comprehensive view taking into account both the physical structure (including structural and non-structural elements) and the service provided to patients and personnel does not exist (given the difficulties in comparing and linking different scientific fields). As a consequence a satisfactory representation to assess the seismic resilience of healthcare facilities is hard to achieve since some methods are good at representing the organization of the system, but reveal to be inadequate with real data, while others are more effective with real data, but inadequate to properly describe the complexity of the hospital system.

Technical aspects and organizational aspects remain divided since they do not share a common value to measure their effects during an emergency phase. Even the recent earthquakes (Christchurch, 2011; l'Aquila 2009) have revealed the key-importance of considering all three aspects, without neglecting any of them, since the impairment of one single aspect can cause a whole loss of functionality. Imagine, for instance, the consequences of a low earthquake: the hospital structure is completely safe and undamaged and the personnel is ready to care patients, however with contents overturned, damaged of fault down the global performance of the system would be totally unsatisfactory despite the positive response of the majority of the sub-systems. Similarly if both structural and non-structural components show a good behaviour, but emergency procedures for the hospital staff are missing, or previsions for the organizational response in case of emergency are lacking, the hospital response would be unsatisfactory as well.

2.2.1 First steps in hospital assessment

In the past years, the scholars dealing with the seismic impact on the physical structure of healthcare facilities mostly focused on two of these three aspects, that is: structural and non-structural elements. The structural vulnerability has been identify by the WHO (2006) and the Federal Emergency Management Agency (FEMA 2007) as depending on three factors: the level to which the seismic hazard forces have been addressed in the structural system, the quality of the construction and the materials employed, and the architectural and structural shape of the building.

Moreover, much research on structural and non-structural systems in hospitals regards specific physical components, specific seismic events, or specific regions. Questionnaires completed by the coordinators of disaster hospitals, security staff, facilities managers and the heads of major hospital departments, were used by Myrtle et al. (2005) to identify the non-structural systems considered critical to the functionality of the hospital in different stages of an emergency. In a case study in Florence, Miniati & Iasio (2012) developed a system for the rapid evaluation of hospitals affected by the earthquake, including both structural and non-structural elements. Masi et al. (2012) carried out an analysis of the seismic risk level for hospitals in the Basilicata region (Italy) taking into account the building stock of the region's hospitals and the expected structural and non-structural performance under different levels of peak ground acceleration. Uma & Beattie (2010) identified the critical non-structural elements for hospital performance observing the performance of these elements in recent events and specifically in relation to the New Zealand code. Davenport's work (2004) focused on the New Zealand's building code, with regard to its specifications regarding the structural and non-structural design for seismic hazards over time.

As evident all these works deal with physical aspects also including non-structural components to evaluate the performance of the system by gathering information from past events of post-earthquake assessing. Excluding the above mentioned physical impacts – which are "objective" and "measurable" – the "human" aspect and the impact of disasters on patients and hospital personnel, despite their relevance for guaranteeing healthcare facilities, have been almost completely neglected or not included in a global assessment.

Actually organizational aspects, in terms of preparedness of the staff and the impact that a disaster has on the hospital personnel and patients, have been the subject of many studies. The Institute of Medicine and the office of Assistant Secretary for Preparedness and Response were particularly concerned with the state of the Emergency Department during the emergency operations and the changes it undergoes during the critical phases. In particular, the Institute of Medicine (IoM 2006) identified some of the vulnerability-keys to individuals, which include: a lack of surge capacity, variable levels of emergency training and lack of adequate protection for hospitals and their staff from hazards (i.e. chemical and infectious agents that may be part of the disaster). Similarly, the office of the Assistant Secretary for Preparedness and Response (ASPR 2013) underlined the crucial capacity that must be considered in the creation of an emergency plan. It includes: healthcare system preparedness, healthcare system recovery, emergency operation coordination, fatality management, information sharing, medical surge, responder's safety and health and volunteer's management. A social network analysis which models the coordination between the Emergency Departments of different hospitals was used by Hossain & Kit (2012) to examine the effect of group interaction on patients' treatment. A model of patient care including the transportation of patients to healthcare facilities and the response of these facilities after the patients' arrival was presented by Fawcett & Oliveira (2000). All these examples, however, assume that the hospital facilities are not affected by damages, resulting in partial or total loss of critical functions.

Recently many researchers have applied fault-tree analyses to characterise the risk of an individual facility losing functionality due to earthquake damage (Porter & Ramer 2012), or to predict the overall system's response to a hurricane (Unanwa et al. 2000). Jacques et al. (2014) created a framework for assessing the loss of function of facilities conditioned on disaster impacts to different branches.

These methodologies include models taken from the complex system theory such a reliability analysis (Setola 2007; Kuwata & Takada 2007; Yao 2000; Lupoi et al. 2008), from the input-output analysis Leontief model (Haimes & Jiang 2001; Haimes, Horovitz, Lambert, Santos, Lian, et al. 2005; Haimes, Horovitz, Lambert, Santos, Crowther, et al. 2005), from the network flow modelling (Lee et al. 2003), and the dynamic simulation (Arboleda et al. 2007). Furthermore, together with numerical seismic analyses on buildings, the World Health Organization (WHO) has recently developed many guidelines concerning the rapid assessment of the seismic impact for hospitals in developing and developed countries.

As shown by Ardagh et al. (2012) in their description of the 22 February 2011 earthquake in New Zealand that affected the Christchurch Hospital, in case of calamity there are many difficulties to face, included the interruption of utility systems (e.g. power and communication), damaged facilities (e.g. collapse of ambulance bay), fluctuating staff, and the fear of patients that the building would collapse. Accordingly to choose a method of analysis the main hurdle is the ability to combination all the features as well as the definition of a measurable parameter.

2.2.2 Integrating approaches in assessing hospital resilience

To portray a realistic and all-comprehensive behaviour of the system is a true challenge since there are only few methods able to assess the hospital vulnerability including the physical aspects, the structural and non-structural performance, the personnel systems and their impact on patient care. The main difference with respect to previous approaches is the definition of what has to be taken into account for hospitals: authors started to adopt a comprehensive outlook regarding the functionality of hospitals in terms of performance by abandoning the separate analysis of vulnerable parts (structural, non-structural and organizational) in favour of more comprehensive assessments.

An example is provided by the Hugo framework (WHO 2006, UN/ISDR 2005), which includes strategies and guidelines for mitigating the impact of disasters. The result of these guidelines is the Safe Hospital initiative, which offers a set of metrics for structural, non-structural and administrative vulnerability of hospitals. Another procedure to assess these vulnerabilities has been provided by the World Health Organization (WHO 2006) by using the health facility vulnerability evaluation (HVE) that relies on the rapid qualitative assessment of the structural, non-structural and personnel aspects by field-specific experts. Although it is a unique form, the interconnections between physical and organizational aspects are extremely limited due to the non-disciplinary consulting during the post-event assessment. Yavari et al. (2010) proposed a metric for assessing post-disaster functionality on the base of four major interacting systems of hospitals: structural, non-structural, lifelines and personnel. Their framework accounts for all the combinations of damage to these four systems to assess the overall hospital functionality, but due to the lack of available data the authors did not include the personnel system in their case study. A complex combination of systems analysis and empirical data from rapid seismic vulnerability assessment was associated by Miniati & Iasio (2012) to evaluate weaknesses in a hospital system. This analysis accounts for damage to structural and non-structural systems, as well as organizational factors (i.e. staffing levels, emergency plans, redundancies in equipment, etc.), but the model, based on experts opinions to establish interdependencies into the hospital system, is not validated dealing with historical events. McCabe et al. (2010) describe the "ready, willing and able" framework which approaches the damage through its effects on the ability and willingness of providers to respond to an emergency; however, it does not take into account physical damage.

Physical damages and loss of equipment certainly have a great impact on the functionality of the structure especially because they can cause the interruption of the normally provided service. However, the extent of the damage, as well as the service disruption, is difficult to predict and, consequently, to measure. It is necessary to formally link the two aspects (physical and organizational) in a model able to take into account this connection, comprehensive of systems and supplies damage, the impact on personnel and redundancies availability. The first integration of "organizational resources" was introduced at the Multidisciplinary Centre for Earthquake Engineering Research (MCEER, Bruneau et al. 2003), and can be also conceptualized in four interrelated dimensions.

Among the physical aspects, resourcefulness is defined as the capacity to identify problems, to establish priorities and to mobilize resources when there are conditions threatening to disrupt some elements, the system, or other units of analysis, applying material or human resources. Moreover, these aspects are underlined and better defined in two dimensions of the resilience: the organizational aspect and the social one. These two aspects can be combined to define some specifications and other interconnections with physical characteristics.

2.2.3 Properties and dimensions of resilience

Properties and dimensions of seismic resilience have an important role in the system definition and in the correct comprehension of the resilience.

As described in the literature, the four main properties which govern the problem are:

- robustness;
- redundancy;
- resourcefulness;
- rapidity.

These properties have different connotations depending on the reference system applied. It is easy to understand that different systems, having different natures, differ from each other as regards these properties; but even in systems of the same nature, i.e. healthcare facilities, these properties can play from case to case a very different role. For instance, a singular hospital differs very much from a hospital network.

The first property, robustness, is the strength, or the ability of systems, elements, and other units of analysis to withstand a given level of stress or demand without suffering degradation or loss of functionality. Redundancy can be defined as the property of elements, systems, or other units of analysis to be substitutable, i.e. capable of satisfying functional requirements in the event of disruption, degradation, or loss of functionality. Resourcefulness is the capacity to identify problems, applying material and/or human resources in order to face problem. This property can be conceptualized as the ability to apply material (i.e., monetary, physical, technological, and informational) and human resources to meet established priorities and to achieve goals. Finally, the last property, i.e. rapidity, is the capacity to meet priorities and to achieve goals in a timely manner containing losses and avoiding future disruption.

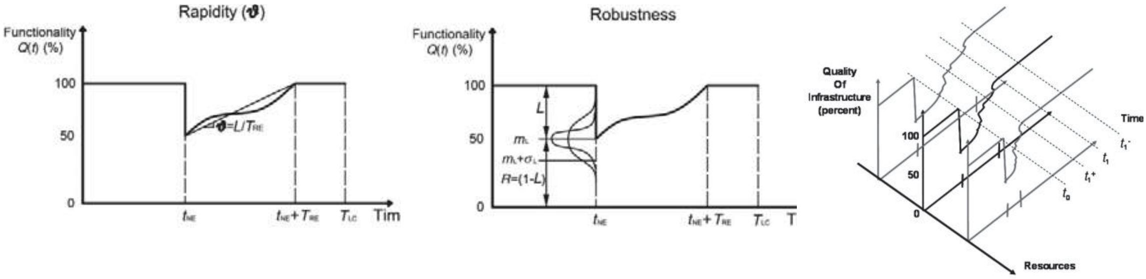


Figure 2.3 Properties of resilience: robustness, rapidity and resourcefulness.

Moreover, resilience has been conceptualised as encompassing four interrelated dimensions:

- technical;
- organizational;
- social;
- economical.

As Table 2.1 shows, these four dimensions (TOSE) refer to complete different single measures of performance. The first dimension, i.e. the technical one, refers to the ability of physical systems to display acceptable/desired levels of performance when subjected to seismic forces (due to an earthquake shock). The organizational dimension of resilience refers to the capacity of organizations to manage critical facilities. This dimension, in case of disaster, is strictly correlated to the others, because it leads to the achievement of a greater robustness, redundancy, resourcefulness and rapidity.

The social dimension of resilience acts to reduce the consequences due to the losses in critical services. This dimension involves communities and governmental jurisdictions. The economic dimension works in a similar way, with the main aim of reducing both direct and indirect losses resulting from earthquakes.

Table 2.1 Seismic resilience dimensions in a single hospital

Dimension/Property	Technical	Organizational	Social	Economic
Robustness	Building codes and construction procedures for new and retrofitted structures	Emergency Operation Planning	Social vulnerability and degree of community preparedness	Extent of regional economic diversification
Redundancy	Capacity for technical substitutions and "work-around"	Alternate sites for managing disaster operations	Availability of housing options for disaster victims	Ability to substitute and conserve needed inputs
Resourcefulness	Availability of equipment and materials for restoration and repair	Capacity to improvise, innovate and expand operations	Capacity to address human needs	Business and industry capacity to improvise
Rapidity	System downtime, restoration time	Time between impact and early recovery	Times to restore lifeline services	Time to regain capacity, last revenue

2.3 Seismic resilience in healthcare facilities: metrics

In 2007, Bruneau & Reinhorn, explored the operational and physical resilience of acute care facilities, without recognizing a simple engineering unit for their key-dimension, but basing their approach on the measure *Q(t)*. This measure is assumed to vary with time, and it is defined as representative of the quality of an essential system in the community. The performance can change in a range from 100 to 0 (in percentage), where 100% represents no degradation in service and 0% means no service available. If an earthquake strikes at the time t_0, the measure *Q(t)* can be affected by reduction; restoration of the system is expected to occur over time, until time t_1, when the measure *Q(t)* is achieved again.

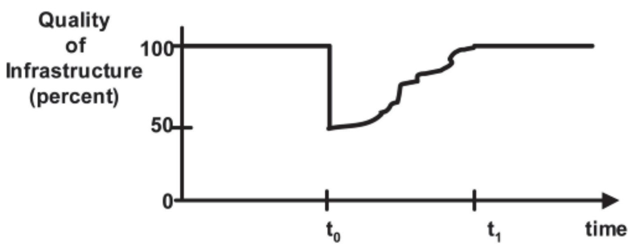


Figure 2.4 Measure of seismic resilience – conceptual definition

Analytically *Q(t)* is a non-stationary stochastic process and each part is a piecewise continuous function. Resilience can be measured by the size of the expected degradation in quality (probability of failure) over time (time to recovery). The return to 100% pre-event level may depend on several factors. These complexities must be taken into account depending on the specific system. According to the general definition by Bruneau et al. (2003), resilience can be expressed mathematically as shown in (Eq.2. **1**:

$$R = \int_{t0}^{t1} [100 - Q(t)]dt \tag{Eq.2. 1}$$

The measure of the quality of the service is expressed through a loss function expressed as a function of the earthquake intensity and the recovery time. Losses are divided in two groups: structural losses and non-structural losses. The recovery process is oversimplified by using recovery functions that can fit the more accurate results obtained with the model by Miles & Chang (2006). The result is a complicated Multidimensional Performance Limit Threshold (MPLT) that aims at providing a quantitative definition of resilience in a rational way on the base of an analytical function that may fit both technical and organization aspects. The latter are, however, considered as a function of the conceptual community recovery model without any link with the punctual physical losses, or with direct association with the studied facility. The MPLT is represented by the equation in (Eq.2. **2**, where $r_i lim$ is the dependent response threshold parameter (deformation, force, velocity, etc.) that is correlated with damage, while $r_i lim, 0$ is the independent capacity threshold parameter and N_i represent the interaction factors determining the shape of the *n*-dimensional surface:

$$L(r_{lim}) \sum_{i=1}^{n} \left(\frac{r_i lim}{r_i lim, 0} \right)^{N_i} - 1, \tag{Eq.2. 2}$$

This model can be used to determine the fragility curve of a single non-structural component, or to obtain the overall fragility curve for the entire building including its non-structural components. This function allows the inclusion of different mechanical response parameters (force, displacement, velocity, accelerations, etc.) and permit to combine them in a unique fragility curve. The organizational aspects are not directly included in the function: they are intrinsically considered by the recovery community model.

Later, following the same approach, Bruneau & Reinhorn (2007) identified fragility curves distinguishing different possible cases. This further research better underlines the importance of non-structural components into a resilience framework; a flow chart of the procedure to achieve seismic resilience for a single hospital is defined, with respect to the physical dimension level, in Figure 2.5.

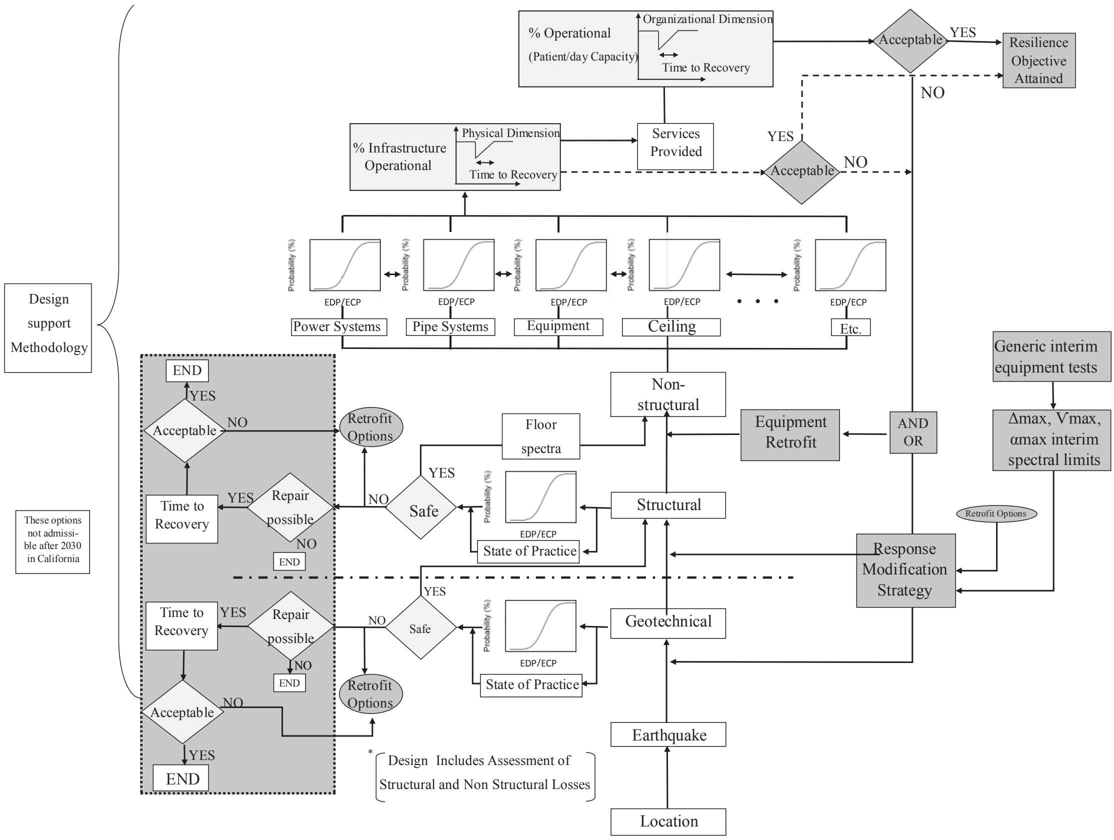


Figure 2.5 Flow chart regarding the procedure to achieve seismic resilience for a single hospital (Bruneau M. and Reinhorn A., 2007)

Until now a real link between physical and organizational aspects has been missing in the resilience metric, as well as the definition of the quality of the service provided by the system.

A first punctual definition of "functionality of the hospital" was proposed in 2009 by Cimellaro et al. who described it as the quality of service (QS) obtained by summing up the partial functionalities within the facility. The qualitative functionality takes into account a new parameter, that is, the waiting time of patients (see par. 3.1.1 for more details), and a quantitative functionality which corresponds to a function of the losses, defined as the total number of patients being not treated *vs*. the total number of care requiring patients. The work is based on the same flow chart displayed in Figure 2.5, using socio-economics information in order to generate the knowledge base for the organizational dimension and to translate the functionality of the system into operational consequences to mathematically obtain the recovery function.

This work is focused on the non-structural components, which are a possible cause of resilience reduction. The adopted approach assumes a unique factor (the monetary one) to be taken into account among all the quantities involved in the seismic performance.

A meta-model, i.e. an hybrid simulation combined with analytical modelling, is also introduced (Cimellaro et al. 2009) as being able to describe the dynamic nature of the hospital. In this kind of model, which uses a double exponential function (Paul et al. 2006), the relevant parameters are:

- n (number of beds);
- *OR* (number of Operating Rooms);
- and *E* (descriptive of the efficiency of the hospital).

This last parameter is given by the ratio between the number of surgeries per *OR* in a day. This parameter is not descriptive of the dynamic organizational system of the hospital when an event occurs. As matter of fact the work relies on the assumption that the organizational behaviour of the hospital is not affected by potential physical structural damages.

In 2010 a performed-based meta-model for healthcare facilities was developed (Cimellaro et al. 2010) the resilience metric is clearly divided between physical and organizational aspects, re-evoking the MCEER approach (as illustrated in Figure 2.6); the qualitative functionality of the structure is still divided from the quantitative one.

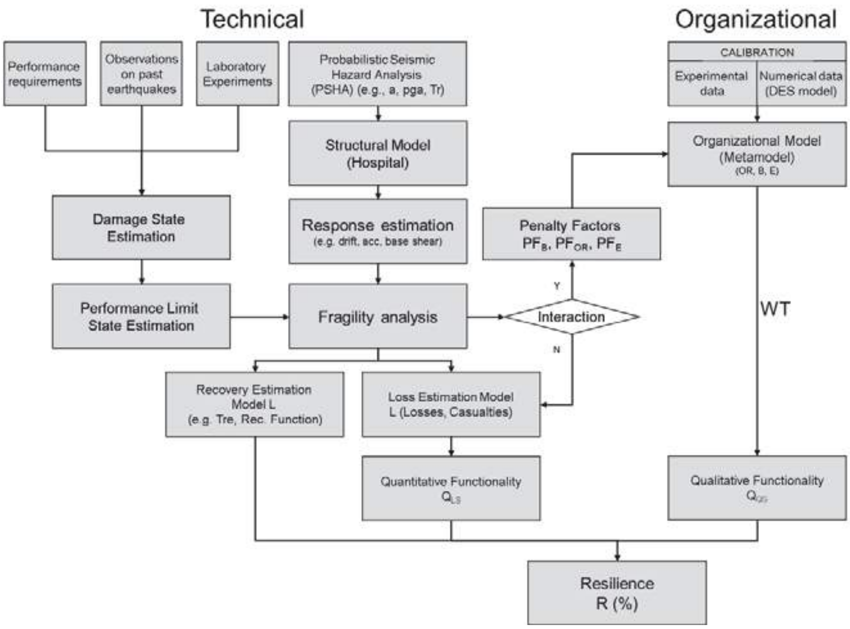


Figure 2.6 Resilience framework according to the MCEER approach

The link between these two "fields" is represented by "penalty factors" (PFs), that are given for each structural and non-structural component by the linear combination of the conditional probabilities to have certain levels of damage. The total penalty factor affecting all the organizational parameters of the hospital results from a linear combination of the individual PFs using weight factors obtained as the ratio between the cost of each component and the overall cost of the building.

Another approach to translate empirical data into loss functionality and to ultimately quantify the hospital resilience was suggested by Jacques et al. (2014). This metric uses a fault tree analysis based on three main contributing factors that represent the overall multidisciplinary system: *staff,* *structure* and *stuff*. This model introduces a new resilience metric based on the functionality of these facilities. The fault tree analysis of the hospital is composed of these sub-systems; each branch is associated with a sub-system, representing a part of the total loss. The branches associated with *staff* include the availability of medical staff, support staff, and backup plans for staffing during an emergency. The branches associated with *structure* account for damage to all physical spaces and support infrastructures associated with critical hospital services. Power, water, inpatients wards, means of egress, etc. below of this branch. To conclude the framework, the branches associated with *stuff* account for the loss of supplies and damage to equipment.

Accordingly the non-structural components are included both in the "architectural one components" of the *structure* and in the *staff* branches. Within the fault tree to assess the partial or complete loss of function, three different kinds of event are distinguished: top events, basic events, and intermediate events.

By definition these events have a different impact on the fault tree and they also include distinct elements.

Top events are associated with the complete loss of life-saving (or emergency) surgery inside the hospital, as well as with the failure or reduction of critical services, like emergency department, surgery, intensive care unit, in-patient ward, obstetric ward, laundry, kitchen, etc. IN case of top events the failure regards all three aspects, i.e. staff, structure, and stuff. Intermediate events are system-states that contribute to the top-level event, for instance: the failure of utility infrastructure, damage to surgical wards, loss of supplies. Basic events are the lowest level events, all matching the data collected using the field study surveys. They include structural and non-structural damages, geotechnical failure, damage to municipal water, wastewater, power and communications systems, as well as damage to their backup systems, damage to or loss of supplies and equipment, and failure to report by hospital staff (Jacques et al. 2014). For analysing basic events, scholars use field data, determining all fault trees as deterministic like the propagation of populated field data. In order to obtain the probability of losing functionality of hospital services, the probability of failure for basic events should be used, and the propagation to the tree branches should be considered.

The loss of hospital functionality is captured as a weighted sum of the loss of critical hospital services, with the resilience metric described by the (Eq.2. 3, and defining $Q_f(t)$ as the function-based metric where n is the total number of functions considered, w_i is the weighting term representing the importance of function i, L_i is the loss of function i (ranging from 0-1, or "no loss" to "total loss"), and R_i is the redistribution of function i (ranging from 0-1, or "no redistribution of hospital functions" to "complete redistribution of hospital functions"):

$$Q_f(t) = \frac{\sum_n w_i(1 - (1 - R_i(t))L_i(t))}{\sum_n w_i} \quad \text{(Eq.2. 3)}$$

The term $Q_f(t)$ addresses the quality of care by examining the loss and redistribution of n critical clinical and support services in a hospital.

The fault tree analysis proposed Jacques et al. (2014) is compatible with the mathematical definition by Bruneau et al. (2003) proposing to measure the variation in hospital functionality over time. These studies demonstrate how the four elements of resilience can be updated by earthquake reconnaissance data collected with survey tools designed by the authors and available as an appendix in (Mitrani-Reiser et al. 2012a). It is worth to note the relevance that properties and dimensions have into the resilience metric, whichever methodology is applied. All the components of resilience must be included into the metric and each of them has an irreplaceable role. Therefore to measure resilience a multi-disciplinary approach is needed: this was stressed, indeed, by FEMA (2007) as a necessity in U.S. design guidelines for improving the safety of hospitals. No resilience metric is definitely able to capture the complex interaction of all the important systems constituting a functioning hospital. On the one hand, difficulties come from lack (or accuracy) of data from past earthquakes as well as from the impossibility to compare or complete the proposed metrics. On the other hand, the lack of direct links between the physical damages and the personnel aspects results in discrepancies between the methodologies applied.

The need to provide a unique resilience measure, i.e. a comprehensive methodology able to include all the aspects which are normally studied individually and suitable for quantifying the resilience of healthcare facilities/systems, cannot be neglected by researchers. Notwithstanding the significant progress made on seismic performance assessment of hospitals, more research is needed to fully understand relationships adaptable to predictive purposes in healthcare systems in various scenarios, and in the coupling between physical damages, non-structural performance, organizational response and their effect on loss of function.

Despite the numerous efforts to quantify seismic resilience with its parameters, there is not enough information regarding the modelling and the measure of the organizational aspects of resilience. Indeed, an organizational resilience model is needed, that can be able to determine the response of the community to hazardous events, and evaluate the real loss in terms of healthy population and quality of care provided. Direct links between the two aspects are necessary, and a particular attention should be paid to the non-structural components whose performance can compromise the global resilience of the hospital system as a whole.

Chapter 3

Methodology proposed in the study

This section proposes a methodology to estimate the resilience associated with the closure (temporary or permanent) of different rooms. This methodology highlights the significance of an holistic procedure taking into account the role of all the components of the hospital in its whole functionality, mainly using the comparison between structural and non-structural fragility curves to assess different cases. Moreover, a road map to identify the necessary steps to evaluate the resilience of healthcare facilities is presented as a guide-line. Connections between structural aspects and organizational aspects are identified in the closure of the emergency rooms, and estimated with a waiting time curve, representing the functionality parameter for the hospital. The changes displayed by the resilience curve in different segment are attributed to several characteristics of the non-structural failures and to the number of the elements involved, as well as their extension and redundancy.

This framework to quantify resilience can also help in the decision process for providing effective seismic mitigation, or the planning process to efficiently guide response and recovery. It also shows how the recognized components of resilience, such as fragility, performance limits, response and their interconnections, may substantially alter the response of the physical system. The latter is translated into a more suitable changing organizational response, which can effectively modify its capacity enhancements.

3.1 Tools used in the study

As mentioned in Chapter 2, there are currently no effective methods to adequately control complex systems like hospitals, also leading to the estimation of their resilience. Many different approaches can be followed, but none of them can be really applied, since they require instruments and tools which are not, or only partially, available. Some of them though permitting to take into account the complexity of the organization system are not sufficiently reliable once applied to real data; other procedures, which fit better the existent data, does not allow a proper and adequate description of the complexity of hospital systems.

In what follows all the tools needed for a method able to estimate resilience for the case study have been applied. Before determining the tools, however, some assumptions must be made about the target of the analysis. First of all, the vertical axis of the resilience curve of an hospital must be defined.

Following Bruneau et al. (2003), the methodology uses a quantifiable idea of functionality, expressed by a mathematical function. To analytically “measure” the functionality, a measurable quantity must be found which is suitable to represent the hospital functionality. The adequacy of the selected quantity must be checked at each step of the methodology.

It is worth to note that the choice of the quantity assumed as the efficiency measure of the system necessarily affects the results of the analysis: therefore such a preliminary choice must be related to the goal of the research.

In this work the estimation of the seismic resilience of the hospital aims at providing improvements and advantages for the people working into the hospital, for the hospital management and for the medical staff. Even if the intermediate stages of the methodology deal with engineering quantities, the final output must be as much as possible oriented towards the last operators.

Given the multidisciplinary nature of the problem multiple tools with different variables, often not comparable with each other, and numerous steps are needed. The final goal of this research is to take into account all the essential aspects (according to the technical literature) and to link them into a cause-effect chain, in order to measure the global hospital functionality by means of a unique measurable quantity that can comprehended and used even outside the engineering field.

Specifically, the selected tools used for the current work are *i)* the waiting time to measure the hospital functionality, *ii)* the fragility curves to measure the performance of structural and non-structural components, and *iii)* the recovery time probability curves to measure the effects of the physical system.

3.1.1 The waiting time

The key issue to determine the resilience of a system is to “perimeter” the problem to face and to find a parameter to measure it. Even for hospitals it is necessary to find a single parameter to use. The complexity of defining the functionality of a hospital, where multiple aspects are involved, requires the parameter – as an expression of the functionality of the hospital - to be unique and representative of the entire process of assessment. As for a healthcare system the parameter to be used necessarily concerns the final actors of the entire system, say, the patients.

Many studies define the functionality in terms of service quality. This choice is supported even by common sense since the hospital functionality is a function of the service quality. Therefore the quality of the service is the main parameter for describing the hospital functionality: if a measure of service quality is found, it can be assumed as reliable to measure the functionality of the healthcare facility. Till now much research has been dedicated to identify a measurable parameter for the quality of the service. The connection between quality of service and functionality has been largely investigated in the technical literature (McCarthy et al.,2000; Maxwell, 1984) where even the asset of the hospital buildings is driven by the goal to maximize the functionality.

According to Vieth & Rhodes (2006), the quality of care is affected by the level of crowding in the emergency department, which is directly related to the waiting time (WT).

The waiting time (henceforth, WT) is defined as the time patients spend into the emergency department before receiving the first medical treatment. The same parameter is chosen by McCarthy et al. (2000) as an indicator of the quality of the service. Furthermore, among the many factors guaranteeing hospital functionality, considering both technical and organizational aspects, the waiting time represents one of the most comprehensive factors since it also constitutes a good indicator for both normal and emergency conditions. In normal condition, indeed, this key-factor allows to measure the satisfaction of the patients (Thompson et al. 1995; 1996), including those housed in the hospital (Richards et al. 2006).

Di Bartolomeo et al. (2007) choose the pre-hospital time (PT) and the emergency department disposition time (EDt) as possible process indicators of trauma care, considering the time to receive medical care as an essential component of the survival chain.

Besides, WT also represents the main parameter to evaluate the response of the hospital during hazardous event operating conditions (Cimellaro et al. 2010), because in an emergency such a response is directly correlated to the number of (treated) outpatients.

Cimellaro, Reinhorn and Bruneau (Cimellaro et al. 2010) define the hospital functionality as the combination of the qualitative functionality related to the quality of the service (QS) and the quantitative functionality related to the losses in the health population.

More specifically, the QS is described through a linear combination of two functions, $Q_{QS,1}(t)$ and $Q_{QS,2}(t)$, shown in equations (Eq.3. **1** and (Eq.3. 2 in function of the waiting time of patients:

$$Q_{QS1}(t) = \frac{max\left(\left(WT_{crit} - WT_{(t)}\right), 0\right)}{WT_{crit}} \text{ , } if\ \lambda \leq \lambda u \qquad \text{(Eq.3. 1)}$$

$$Q_{QS2}(t) = \frac{WT_{crit}}{max(WT_{crit}, WT_{(t)})} \text{ , } if\ \lambda > \lambda u \qquad \text{(Eq.3. 2)}$$

In this procedure the authors divide the waiting time (WT) from the critical waiting time (WT_{crit}) at the hospital in saturated conditions, when λ (arrival rate of patients at the hospital) is equal to λ_u (the critical arrival rate of patients, when the hospital reaches its saturated conditions). Accordingly the quantitative functionality of the hospital is defined as a function of the patients being treated and not as a function of the waiting time.

Moreover, during an emergency phase, the waiting time is an essential factor for the survival organization and the consequent decisions to make: not only the organization of a single hospital, but also that of the entire survival chain in the hospital network, rely on the number of available beds for injured patients. Therefore, in order to provide an higher availability of treatments and a short waiting time all the emergency procedures inside the single healthcare structure must be activated in terms of addition resources and beds (involving the premature discharge of those patients having enough stable conditions). Besides, as the unique value of the quality of the system, the waiting time is influenced by various other factors that add to it additional intrinsic meanings. These factors are: hospital staffing characteristics, arrival time, gender, age, triage category etc.

In this work the notion of functionality is related to the quality of the service, that is directly connected to the waiting time of patients, both in normal and in emergency situations. This is a suitable choice to consider the hospital both in normal scenarios and in emergency phases. Even when the emergency is due to a seismic event and to the consequent arrival rate (see Chapter 4) WT represents an effective measure of the system functionality since a strict relationship between entries and waiting time can be found.

As mentioned above, WT is the parameter used for the evaluation of the quality of the healthcare system, which in turn is the characteristic used to express the functionality of a hospital. The discrete event simulation model allows to register the waiting time experienced by patients in different circumstances and scenarios (for more details see the following paragraphs).

In the wide literature on the subject, WT is defined as the time spent by patients in the emergency room (ER) before receiving care; more specifically, according to the Italian medical dispositions, WT is the time patients wait from the acceptance to the triage-desk until they receive first-aid treatments (this applies to all categories of patients, i.e. all colour codes, see Ch.4) . First-aid treatments can be provided by doctors and nurses: if a major code patient cannot wait until the doctor's arrival, the nurse can be required to stabilize his/her vital parameters.

During the simulation (for any case/scenario), WT starts from the patient's arrival into the emergency department (ED) without receiving the colour from the triage. This choice is due to two main facts: the *a priori* colour-code assignment (following the statistical trend calculated from the data provided by the hospital database) of the model and the lack of triage in case of an emergency scenario. As matter of fact, during an emergency phase, the triage is not performed inside the emergency department: it is carried out by another special section (that is activated only during emergencies) in order to filter out patients and save time. Output data from the organizational model are always estimated in terms of WT. When the scenario changes, WT decreases or increases depending on the environmental changes (in terms of resources, arrival rate, closure of rooms, etc.). WT data are the last input included in the methodology, and are representative of all changes occurring in the performed model (scenario), which are derived from: probability functions, a semi-probabilistic failure/collapse result from non-structural components, downtimes hypothesis and choices of temporary/permanently closure of the physical system. In conclusion, WT results to be an adequate measure of the system functionality as it is intrinsically representative of all the previous steps of the method.

3.1.2 Fragility curves

Fragility curves (Fragility Curves, FC) have been historically defined as representative instruments of cumulative distribution functions. Fragility curves are therefore the expressions of probabilities that in principle, can be directly obtained from laboratory tests, analytical studies entailing simulations, and post-disaster observations of damage.

A fragility curve describes the probability of reaching or exceeding a limit state at a specified level of excitation (Badillo-Almarez et al. 2007). A fragility function can be defined as the cumulative distribution function of the capacity of an asset to resist an undesirable limit state. Capacity (C) is measured in terms of the degree of environment excitation at which the asset exceeds the undesirable limit state. For example, a fragility function could express the uncertain level of shaking that a building can tolerate before it collapses. The chance that it collapses at a given level of shaking is the same as the probability that its strength is less than that level of shaking.

In other words, a fragility curve defines the conditional probability of the seismic demand (D) placed upon the structure exceeding its capacity (C) for a given level of Engineering Demand Parameters (EDP)[3]. In principle, the development of fragility curves would require the synergistic use of the following issues: professional judgment, quasi-static analysis, damage data associated with past earthquakes or testing, and numerical simulations of the seismic response. In seismic terms, fragility curves indicate the probability for a certain system, subject to an assigned input (see Ch.4 for more details), to exceed a given limit state.

3.2 Evaluation of building response by accounting for structural and non-structural components

Structural fragility curves can be built for different limit states (indicating the probability of exceeding the specific thresholds) expressed in terms of a selected parameter.

Fragility curves can be generated for both structural and non-structural elements, using different approaches. In particular, non-structural fragility curves consist of acceleration-sensitive components and drift sensitive components. Accordingly the structural and the non-structural acceleration/drift sensitive elements can be assessed separately using their respective fragility curves. It is worth to note that only the elements being sensitive to the same parameter can be compared, say acceleration or drift.

Different approaches can be adopted, depending on the way the fragility curves are defined and constructed. Cimellaro *et al*. (2006b) developed “multidimensional” fragility curves, by including different performance parameters in the same analysis. This approach is very smart and synthetic, but it does not lead to an easy comprehension of the role of each parameter in the global performance of the system.

This work, makes use of single-parameter fragility curves in order to simplify the process. As a consequence only the elements which are known can be really assessed and compared – in terms of performance – with the structure. However, a knowledge implementation about non-structural elements and their fragility evaluation is needed since data are currently missing in this respect. The presented methodology is very simple and constitutes a kind of “pioneering” approach: although relying on the elastic behaviour of the system, it can be easily implemented in case further data are available. This approach permits an easy comparison of the performance

[3] Engineering Demand Parameters (EDPs) are structural response quantities that can be used to predict damage to structural and non-structural components and systems. Usually for expressing the Demand (D) are used the force, deformation, or other degree of loading to which the asset is subjected: an example is the peak ground acceleration in an earthquake. For defining the Capacity (C), instead, are used variables such as drift, acceleration, or other descriptive measures.

displayed by different components and reveals to be suitable for the constant innovation of architectural elements. Thanks to this procedure the road map for each component can be drawn and even modified if, as it is often the case, some changes occur in the setting of the system.

3.2.1 Seismic fragility

In performance-based seismic design, the overcoming of the performance limits related to each limit state indicates a not-acceptable condition according to the safety requirements stated by the Code.

If the intensity of the ground motion is expressed as a single variable (e.g. the peak ground acceleration or the mapped maximum earthquake spectral acceleration at short periods, etc.), a seismic fragility curve is defined as the conditional probability of failure expressed as a function of the ground motion intensity (Der Kiureghian 2005). Ideally, the assessment of the fragility curves should employ as much objective information as possible. Actually, this cognitive process is affected by many uncertainties arising from imperfections in the mathematical models, from measurement errors, and from the finite size of observed samples.

Fragility curves can be generated in an empirical or analytical way. Empirical fragility curves can be developed by using collected data about the structure (for instance, regarding previous earthquakes) or experimental data obtained from laboratory tests. Analytical fragility curves can be developed with the use of statistical data obtained by applying accurate mathematical models that represent certain physical phenomena.

Fragility curves can be used to present both structural and non-structural components, systems, or buildings. For this reason, fragility curves are used as one of the main tools in the presented methodology: they allow to make comparisons between two elements having different properties, roles and response parameters.

The relationship between structural and non-structural fragility curves is the first step of the method-chain and represents the first information regarding the physical system which is needed for assessing the final waiting time of patients. The use of fragility curves in the current procedure introduces a probability approach in the deterministic fault tree analysis presented by Jacques C. C. et al. (2013).

3.2.2 Comparing fragility curves

Fragility curves are conceived as instruments related to the overall capacity and demand for all the elements of the building; as a consequence, they collect a number of data involving all the systems the hospital consists of.

First, there needs to be full awareness of available data. It may be, for instance, that for different components, be they structural or not, there is data available which refers to different seismic input intensities. The assumed seismic input must be carefully calculated and coherently detected for all the elements evaluated at a time, i.e. simultaneously taken into account.

Another important factor is the position of the non-structural element in the structure: the position strongly affects the acceleration/drift experienced by the element. Usually the difference between the ground floor response spectrum and that displayed by another floor cannot be neglected. Accordingly, to compare two fragility curves it is necessary having the same *x* axis by considering the peak *floor* acceleration (P*F*A) instead of the classic peak *ground* acceleration (P*G*A).

3.2.3 Recovery time probability curves

Recovery time probability curves (Recovery Time Probability Curve, RTPC) have a fundamental role in the proposed methodology. They show the time needed to restore the represented element, giving important information about the downtimes the structure suffers from after a failure or damage.

Fragility curves and recovery time probability curves need to be correlated: unfortunately this correlation crucially relies on experience. According to Yao & Tu (2012) whose work refers to the response of Taiwan hospitals during the Chi-Chi earthquake, the correlation between the recovery time probability curve and the fragility curve of an element is possible if they both are expressed in terms of Time (days) versus PGA (g). This is shown in Figure 3.1:

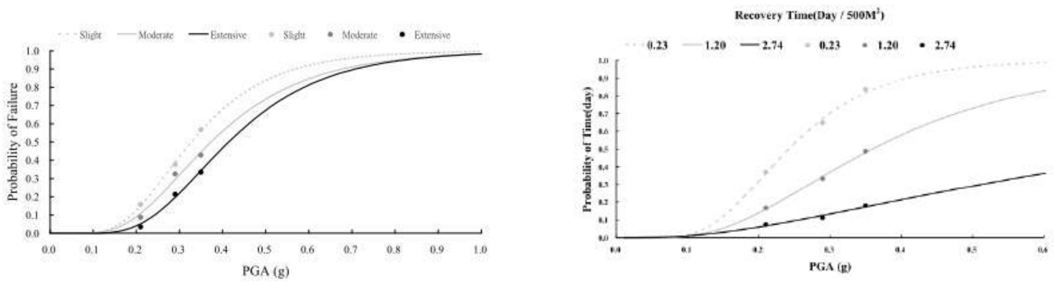


Figure 3. 1 Fragility Curve and associated Recovery Time Probability Curve of the same element (Yao and Tu, 2011).

Yao and Tu's proposal relies on the hospital's reports after the shock, i.e. downtime losses and their causes. Recovery time probability curves are derived mathematically and are not related to a specific factor: they depend on the available data; these data, however, are fundamental for future research developments.

A similar database on fragility curves, and consequently on recovery time probability curves, does not exist in Italy. To fill this gap a range of time, grouped in 12 hours, can be hypothesized as the downtime (DTs) during an emergency concerning the non-structural fragility curves. The range time of the supposed downtimes are specifically described in Ch. 4, where different groups of DTs are used to simulate damages and failures like closures. If empirical data are missing, the downtime must be hypothesized. Recent experience has shown that dysfunctions to non-structural components usually cannot be solved within the first 12 hours after the event. For instance, the prompt intervention of operators, due to difficulties to reach the affected area, the complications related to other non-structural components failures and their interconnections, is rare. In this work, for the downtime ranges classification, the possibility to represent non-structural components downtime as the sum of single DTs related to all the possible non-structural component-failures which can occur in a single room is suggested. In effect, due to the impossibility to solve all failures at the same time it is possible to assume the sum of the downtimes associated to non-structural failures, considering it as the worst case. The same procedure was adopted by Yao & Tu (2012), more details on downtime ranges are described in Ch.4.

3.3 The resilience evaluation

Each aspect of a hospital system (structural building components, non-structural components and hospital personnel) should be assessed as a part of the overall system. The main challenge for a resilience metric is to conceptualise a healthcare facility that accurately represents components and subsystems interdependencies, component and subcomponent failures, associated losses and consequences for the organizational system. To connect all these elements, a unique value representing the functionality of the system must be assumed.

The method presented in this chapter focuses on the fragility curves of structural and non-structural components: the comparison of these curves permits to establish which are the most relevant elements able to decrease the associated resilience curves by evaluating the number of emergency rooms closed after a shock. After having adopted a flow chart (cf. the following paragraphs) and made working hypotheses regarding the interaction between structural and non-structural components (Bruneau & Reinhorn 2007), the missed link between *physical* resilience and *organizational* resilience is defined. Using the described tools, it is possible to fill the gap between physical dimension and organizational dimension (see Figure 2.3) and to better define the interaction between fragility analysis and organizational model, symbolized by penalty factors (cf. MCEER approach and Cimellaro's application).

The proposed methodology allows to include all the aspects, be they technical and organizational, taken into account in the literature, and to directly connect them in a cause-effect chain. Following this procedure the organizational output data derived from scenarios defined by technical aspects can be directly linked to the process and be assessed by a statistical tool (cf. Ch. 4) associated with the data collected in the statistical database of the hospital.

Accordingly the data associated with a realistic period have been combined with the information resulting from face-to-face interviews with the hospital personnel and the organizational aspects have been statistically assessed. It is worth to emphasize that the measurement of the waiting time is intrinsically affected by possible technical causes representing a threat during an earthquake..

Choosing the mathematical application by Bruneau et al. (2003) where the waiting time is assumed as the measure of the system functionality, a logical path/route characterised by a cause-effect chain is defined.

In a sense it can be said that this methodology takes inspiration from the fault tree analysis suggested by Jacque et al. (2013) as a consequence of its cascade process, where the basic elements (cf. par. 2.3) propagate their effects to the flow chart and only one element can threaten a total failure of the functionality of the hospital; in addition, this method makes a distinction between several levels of elements. In particular, it aims at adopting the best aspects from the two main procedures available in the literature, also simplifying the mathematical model (deriving from the multi-dimensional performance limit state threshold - MPLT), using fragility curves in order to have an accessible tool, and expressing the results in terms of waiting time, which is the common denominator within a healthcare facility.

With respect to the four properties described by Bruneau (2003), this methodology takes into account: *i) robustness*, i.e. capacities and demands of structural and non-structural components, evaluated through fragility curves and considered in the organizational model as opened/closed rooms; *ii) redundancy*, i.e. the possibility to count on redundant elements; *iii) resourcefulness*, i.e. hospital personnel and recovery capacity (beds, rooms, transferability of patients, etc.), and *iv) rapidity*, i.e. the time needed to restore the system assessing the waiting time acceptable threshold during the simulations.

Assembling properties and dimensions of seismic resilience, as shown in Table 2.1 the resilience metric proposed not only explores the technical and the organizational dimensions, but also the above mentioned four properties and, in addition, considers the social dimension in relation to robustness, due to the method used for the seismic arrival rate (cf. Ch. 4). The economic dimension, which is left aside in this work, can be easily added in further improvements.

A schematic flow chart of the methodology is illustrated step by step in Figure 3. 2 .

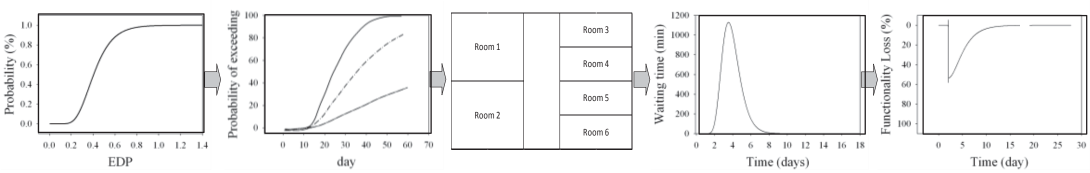


Figure 3. 2 A step by step outline of the proposed procedure

Fragility curves of structural and non-structural components, associated with their recovery probability curves and resilience curves are assessed in order to hypothesize the consequences on the physical system (in terms of closed/opened rooms). Thanks to the different system responses, waiting time curves are derived for each patient entering the hospital. Then resilience is definitely evaluated.

In this way the organizational response of the system results from the combination of structural and non-structural resilience. This technique allows the estimation of the organizational operations of a hospital as a direct result of the physical size of the (structural and non-structural)elements. Accordingly the resilience quantification is generalised from the physical dimension level to the organizational dimension level by translating the physical system resilience into operational consequences. For convenience, the all methodology is schematically represented in the following figure, where the main steps are symbolized throw shapes and captions, described below. During the explanation of the methodology, the same symbols will be defined.

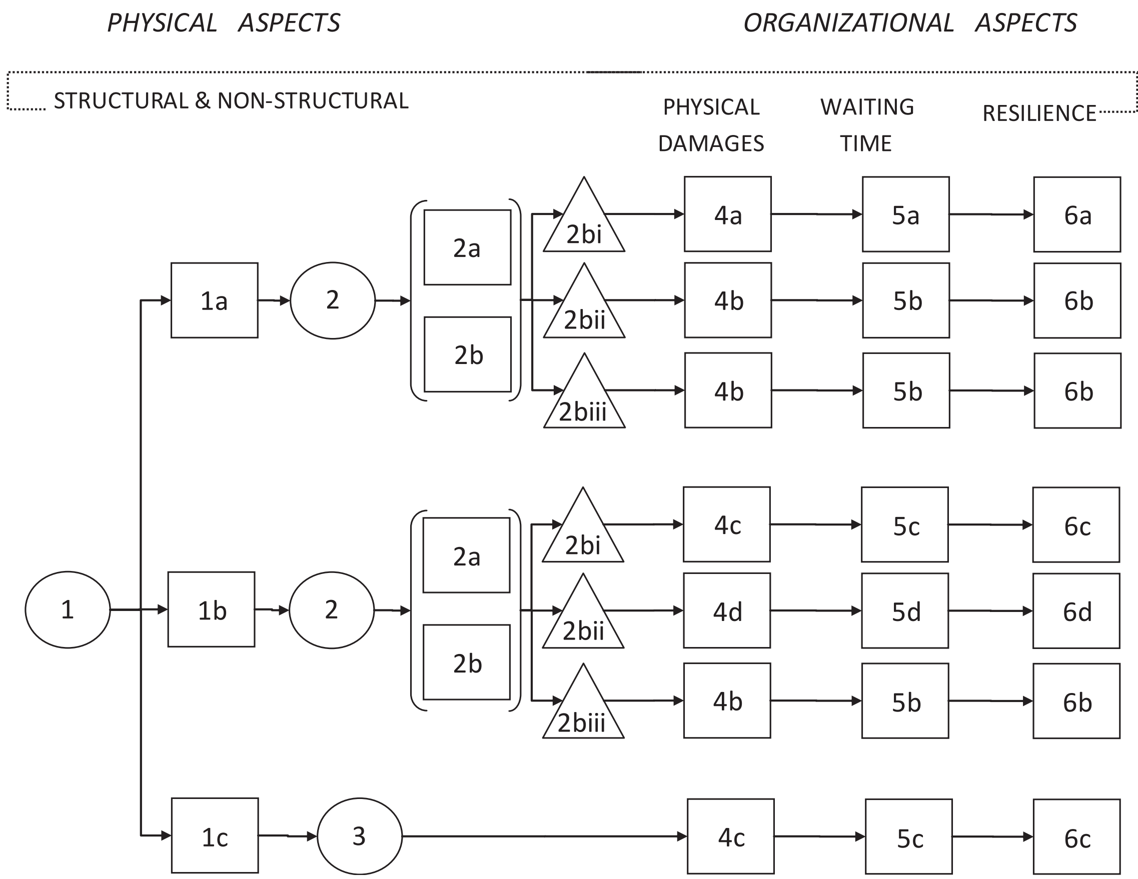


Figure 3. 3 Flow chart of the methodology, schematically represented.

A first step towards the above objectives is the definition and quantification of engineering performance and related resilience. As illustrated in Figure 3. 4 , and represented in Figure 3. 3 with the (1) different levels of integrity can be assumed as acceptable thresholds in a building. In general, three limit states are defined:

- Serviceability limit state; [1a]
- Damage limit state; [1b]
- Life Safeguard Limit State/Collapse Limit State; [1c]

Names and associated return periods (T_R) of the limit states are slightly different from code to code depending on the country. Therefore a connection/association with the return period years and associated peak ground acceleration is indispensable. In general, the first limit state is identified as the serviceability, which must guarantee the full functionality of the service. After the damage limit state, as far as this study concerns, medical service is no longer guaranteed. Therefore, in this context, the relevant thresholds are the first two. A different structural fragility curve can be associated to each limit state, and a consequent resilience curve can be derived (see Figure 3. 4).

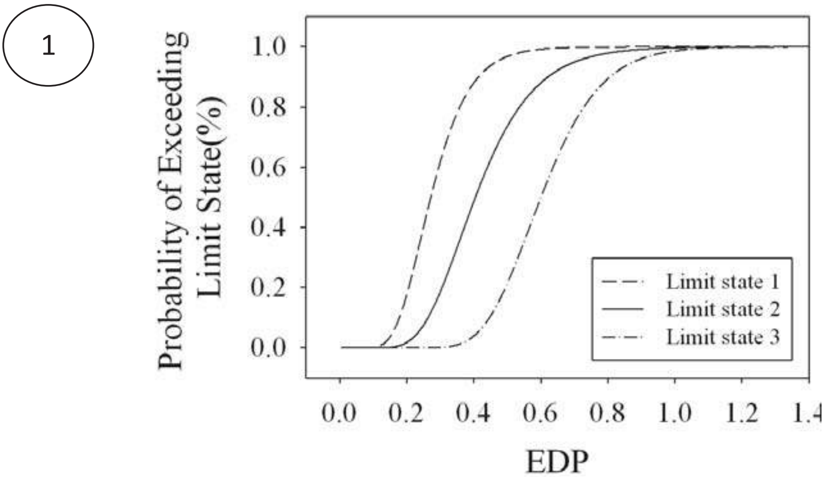


Figure 3. 4 Structural fragility curves associated with different limit states

3.3.1 Serviceability and damage limit state *VS* non-structural components

The first case presented here is the linear-elastic response of structural elements (cf. Figure 3. 5). When the response of the structure does not reach the fragility curve associated to the serviceability limit state, no damages occur to the structure. The serviceability limit state threshold is identified to include the non-structural elements behaviour that has not been identified yet in the international codes; therefore, an evaluation of non-structural components is always necessary.

An effective method to account for non-structural components is to represent their performance by means of fragility curves. In most cases they are built for the collapse limit and do not have a damage limit to be considered. Recent earthquakes have shown that healthcare facilities are usually closed even in case no structural damage has occurred. In effect, the collapse of non-structural components can occur at accelerations or drifts (depending on the EDP) differing from the threshold of non-linear elastic structural response. As a consequence it is extremely important to not underestimate their performance.

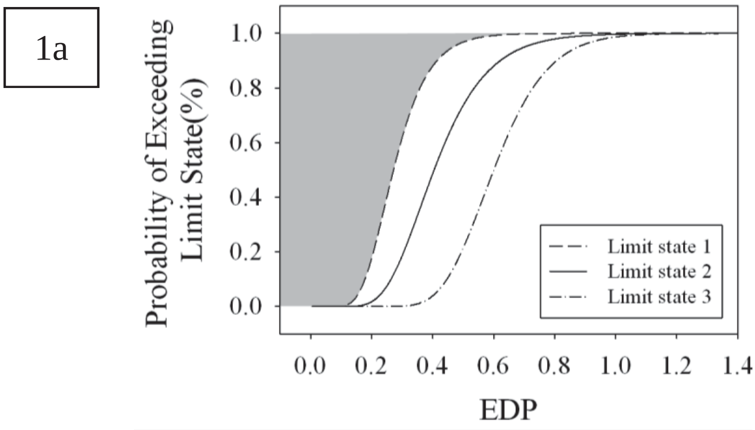


Figure 3. 5 Area of the structural linear response before the Serviceability Limit State

A comparison between structural and non-structural fragility curves is necessary to understand the behaviour of the entire system. Generally speaking, the structural fragility curves vary depending on the investigated limit state; on the contrary, the fragility curves regarding non-structural components are fixed.

In the case shown in Figure 3. ***6*** , the comparison is made with reference to a singular structural limit state and different non-structural fragility curves. Comparing the structural fragility curve associated with the serviceability limit state, the non-structural components resilience with a linear-elastic structural response is represented.

In the first case (a) the two fragility curves do not cross each other and the non-structural one (indexed by a continuous line) is shifted to the right of the structural fragility curve (indexed by a traced line). The organizational aspects are not subject to modifications and the resilience fragility curve is still linear: no loss of functionality is registered. It is possible to assume the structural fragility curve as a good threshold for describing the full operational condition.

In case (b) the two fragility curves cross at one point, corresponding to a parameter (acceleration or drift), beyond which a non-structural damage/collapse occurs before the structural threshold corresponding to the serviceability limit state. It is necessary to verify, fixing a referring PGA, the downtime associated to the corresponding probability of failure/exceeding. In this case a punctual assessment is needed (for more details see the next paragraph): thereafter the resilience organizational aspect will be modified for the determined non-structural loss.

It is worth to note that in the figure underlying, in the x-axis are specified both the EDP (Engineering Demand Parameter) referred to the structural fragility curve, and the ECP (Engineering Capacity Parameter) referred to the non-structural fragility curve. In order to compare them at the same time (non-structural and structural fragility curves) it is possible to indicate the capacity of the structural system as the demand of the non-structural components. On the base which fragility curves we are referring to, a EDP or a ECP will be taken into account.

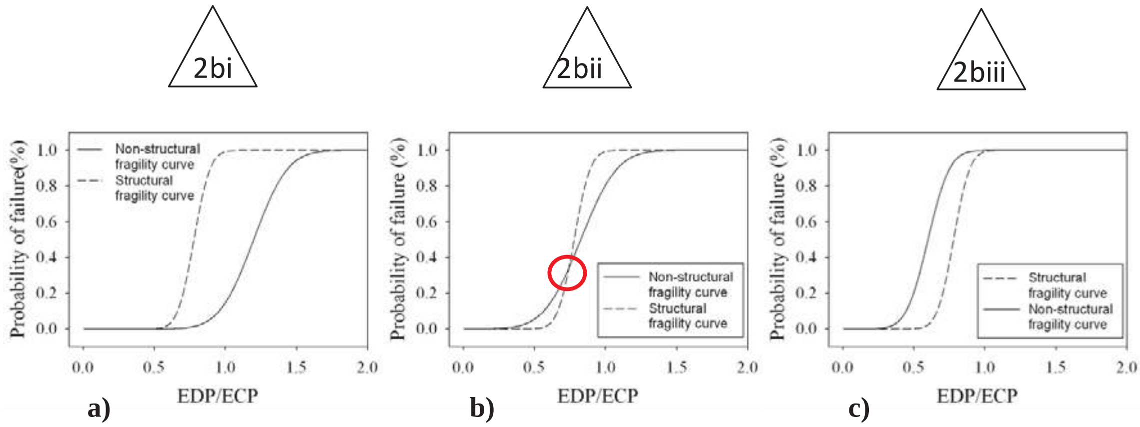


Figure 3. 6 Comparison between structural and non-structural fragility curves: (a) the two curve do not cross each other and the failure of the non-structural component occurs after the threshold associated to the chosen structural limit state (on the left); (b) the two curves cross each other for a determined EDP (in the middle); (c) the non-structural fragility curve is all shifted on the left: the non-structural failure (collapse) occurs for EDP minor than the establish structural threshold (on the right).

In the third case (cf. Figure 3. ***6*** c), a non-structural damage/collapse occurs before reaching the structural limit state. In this case the referring threshold becomes the non-structural one, in terms of down-time and number of elements involved, associated to their recovery time probability curves. Is it worth to note that this scenario – for which the non-structural behaviour is unknown and the reference threshold is underestimated – is the most frequent one. A linear-elastic response of the structure occurs also in the region between the Serviceability Limit State and the Damage Limit State. In this area, until reaching the Damage threshold for the structure, the response is still linear-elastic.

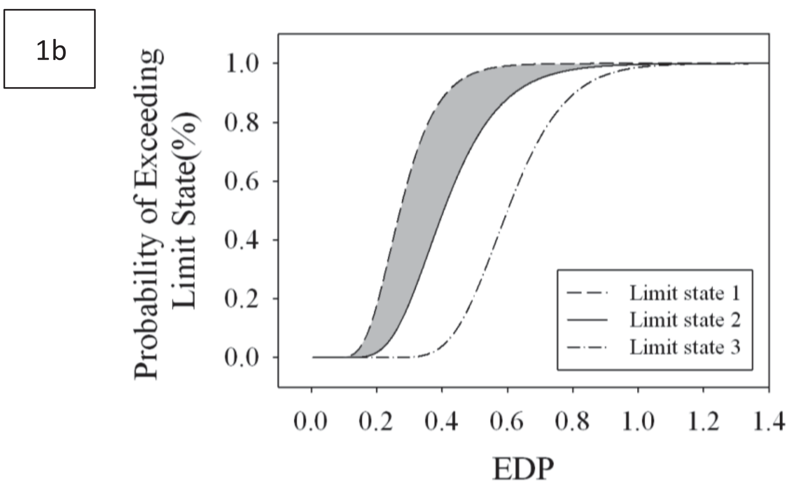


Figure 3.7 Area of the structural linear response between the Serviceability Limit State and the Damage Limit State.

As in the previous case, the interaction between structural and non-structural fragility curves displays four different scenarios about the rooms' enclosure.

In a hospital the damages that compromise its functionality are considered to depend on the failure of non-structural components. When the non-structural fragility curve is on the right of the structural one, structural damages occur, causing permanent closure of the emergency rooms. İn this case the structural damage governs the whole dramatically affecting waiting times and, consequently, the resilience curve. The percentage of damage extension can be rudely evaluated as the associated probability of exceeding the threshold in the total area of the structure. When the curves intersect each other both non-structural failures and structural damages occur, with two possible cases of closures: temporary and permanent. This state of affairs requires a more careful evaluation, as discussed in the following paragraphs.

In the last case, when the curve of the non-structural components is on the left of the structural one, the hospital functionality is governed by non-structural failures. Assuming that the structural damages govern the permanently closures, the hospital will experience only temporary closures depending to their associated recovery time probability curves. Similarly to the case presented before, the resilience curve changes as a function of the specific non-structural failure.

3.3.1.1 Resilience due to non-structural components failures

Figure 3.8 shows how rooms closure affects the waiting time curve. This happens even when the structure is not damaged, since the failed non-structural elements can jeopardize the organizational aspects: patients can experience long queues due to limited spaces available.

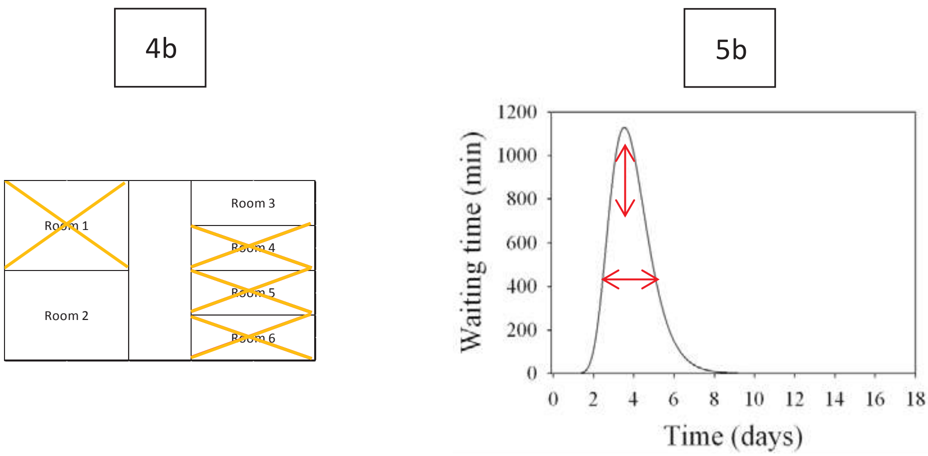


Figure 3.8 The number of closed/down rooms effects the waiting time curve, in terms of WT_{max} (peak) and size of the bell curve.

The greater the arrival rate is (number of entries during an emergency), the higher is the peak of the waiting time curve (WT_{max}) (Figure 3. **9** a): the number of patients influences the organizational response and, eventually, the vertical segment of the resilience curve (Figure 3. **9** b).

The higher the number of down rooms is, the more is the time required to bring the system back to its initial state. The size of the bell curve increases (Figure 3. **9** c) and consequently the resilience curve increases as well, with a change of the section from the peak of functionality loss to the system restoration (Figure 3. **9** d).

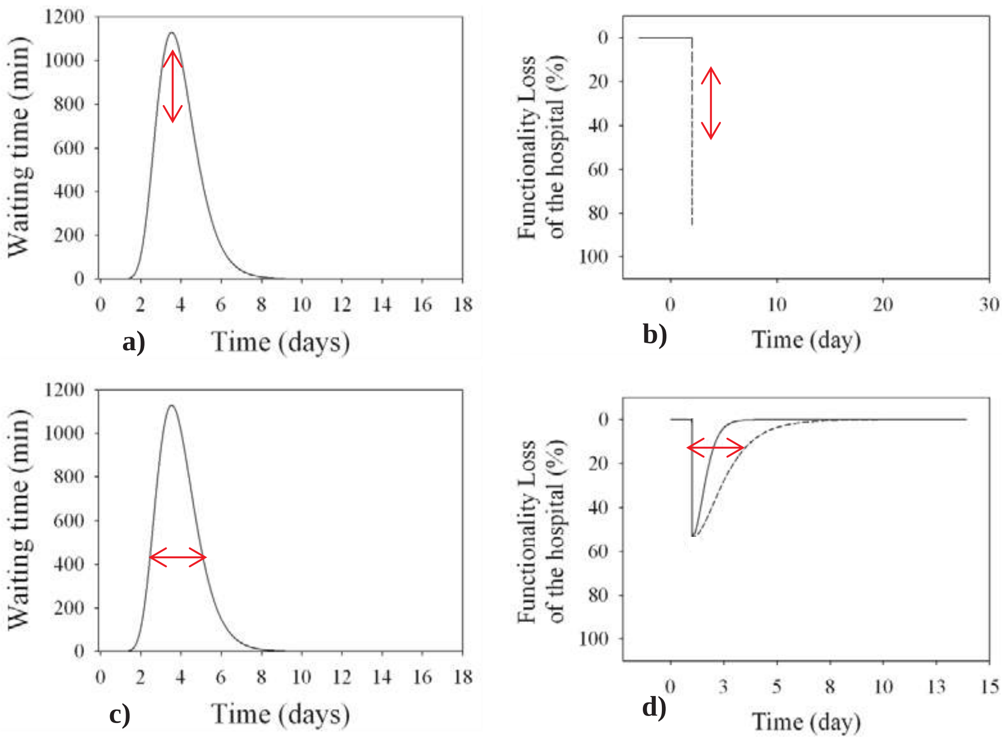


Figure 3. 9 Different non-structural components can determine changes in the waiting time curve (in the WTmax –a-, and in the size of the bell curve – c-) and, consequently, changes in the resilience curve (measure of decreasing –b- and time necessary of re-establishing –d-).

According to recent studies and direct experiences during earthquakes, to know the damages associated to the failures of non-structural components seems to be of crucial importance. In effect these damages can result in significant economic losses, i.e. temporary/partial/total loss of operation/functionality (downtime), patient and/or staff injuries, and, in some cases, even loss of life. The variable decrease of the resilience vertical segment at the time t_0 depends on various aspects:

- importance of the non-structural components;
- location and extension of the rooms,;
- conditioned functionality;
- interconnection with/dependence on other elements.

The time needed to re-establish the initial condition (or at least a satisfying condition) is related to:

- the number of failed non-structural components (NSC);
- redundancy elements;
- the time necessary to remove the failed NSC in case it is unessential for the care service.

To better quantify the time required for a satisfactory recovery, the Recovery time associated to each non-structural component must be known. The first step concerns the evaluation of a single room, comprehensive of all its non-structural components.

To quantify the effects of a possible state of damage (including the complete failure) of non-structural components in a room, it is important to know the behaviour, the function and the extension of each single non-structural component in the room.

2

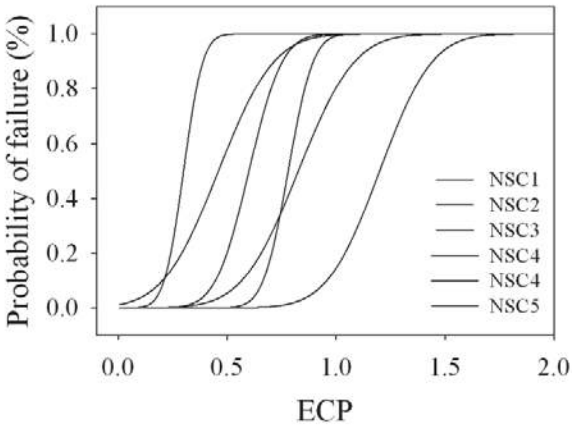


Figure 3.10 Different non-structural component fragility curves for a single room

Referring to their fragility curves, it is possible to choice for each room a certain PGA and evaluate the associated Probability of Failure/damage for all its non-structural component (see Figure 3. *11*).

2a

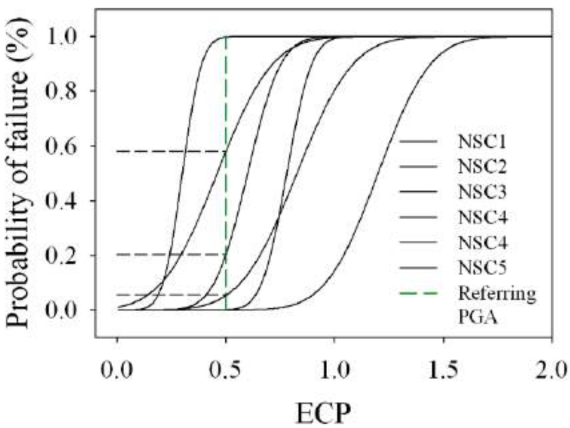


Figure 3. 11 Fixing a referring ECP (e.g. acceleration) it is possible to evaluate the failure probability for each NSC.

Accordingly for each non-structural component (NSC) it is possible to determine the Probability of Failure/Damage $Pr_{F/D}$ as follows:

$$NSC_1 \rightarrow Pr_{F/D_1} \quad \text{(Eq.3. 3)}$$

$$NSC_2 \rightarrow Pr_{F/D_2} \quad \text{(Eq.3. 4)}$$

$$NSC_n \rightarrow Pr_{F/D_n} \quad \text{(Eq.3. 5)}$$

Moreover, it is possible to associate each non-structural component with a factor *a*, the latter being equal to 0 or 1 depending on the possibility to have a redundancy referred to the specific component. Thus if a NSC is replaceable or its failure does not result in an interruption of the service, *a* is equal to 0 and the component is not taken into account inside the room.

Figure 3. *12* shows the effects of the redundant component on the POF representation. Non-structural components, which are considered "in parallel" by other scholars, are considered as redundant in the current approach and therefore they are not evaluated together with the other room elements since they are replaceable in a short time. Conversely, if a non-structural component is placed in series and it fails, also the other non-structural elements linked to it must be considered failed: they are perceived as a system where the failure of the most fragile element makes the whole system fail. As illustrated in (Eq.3. 6, *a* factor can be 0 or 1:

$$NSC_n \rightarrow Pr_{F/D_n} * ɣ_n \quad \text{(Eq.3. 6)}$$

with: ɣ =1 when the element is redundant or connected in parallel;
ɣ =0 when the element is not redundant or is connected in series with the others. In this case the elements which are connected in series with this element are considered failed in case the first fails.

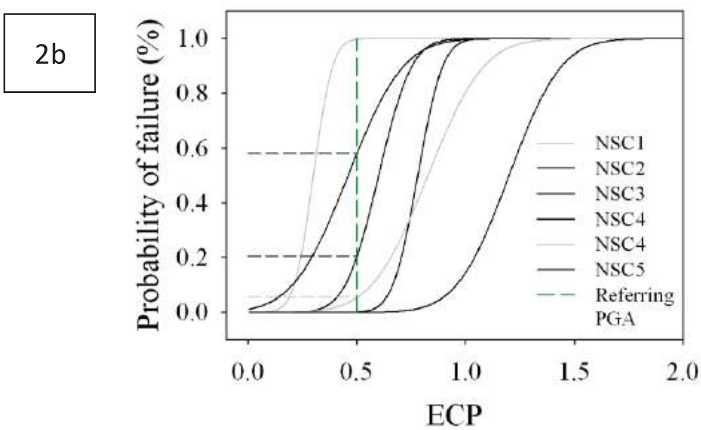


Figure 3. 12 Non-structural components really implicated in a resilience room.

$$NSC_{room} = NSC_2 + NSC_3 + NSC_5 + \cdots + NSC_n \quad \text{(Eq.3. 7)}$$

As illustrated in Figure 3. *13* , the installation of non-structural components compromises the entire system (the term “system” here refers to the group of non-structural components that are linked together, both in series and in parallel). On the one hand, if NSC_1 fails, also the other non-structural components linked in series with it will fail and, consequently, the entire system will fail; on the other hand, if NSC4 or NSC5 are redundant, i.e. they can replace each other, and one of them fails, the other non-structural components connected with them, will not necessarily fail.

The knowledge about the mutual relationship among different systems is essential for a good planning, for the management of the single non-structural component, and for the prevention of big jeopardy.

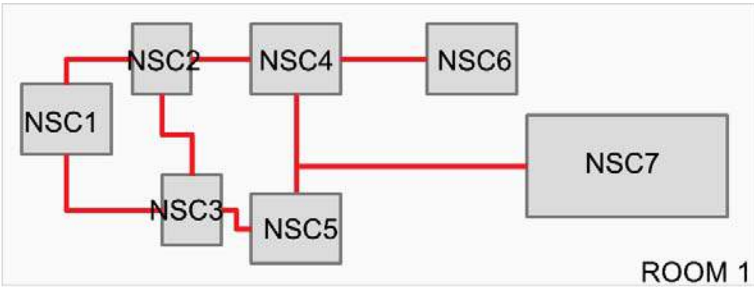


Figure 3. 13 Non-structural component realized in series and in parallel into a generic room.

According to Yao & Tu (2012), it is possible to derive the Recovery time probability curves from the fragility curves of the components, and to associate each of them, for a specific PGA, to the corresponding downtime (cf. (Eq.3. 8).

$$NSC_n \rightarrow Pr_{F/D_n} * a_n \rightarrow RT_n \quad \text{(Eq.3. 8)}$$

Then it is possible to assess a total recovery time as the sum of the obtained partial recovery times, as displayed in (Eq.3. 9:

$$RT_2 + RT_3 + RT_5 + RT_n = RT_{tot} \quad \text{(Eq.3. 9)}$$

This procedure can be used to evaluate the Recovery Time needed for the non-structural components in a room. In this case the structure is assumed to have undergone no damages.

This technique whose main purpose is to assess the downtime associated with an individual emergency room, can be extended to several rooms and, consequently, to an entire Emergency Department. Therefore it is extremely important to recognize the “most fragile” non-structural component in order to prevent a total loss of functionality deriving from its failure. Some significant examples from recent earthquakes are the collapse of the “Emergency Department” signal in front of the entrance causing the complete block of the hospital (L’Aquila, 2009), the fall of the roof onto the parked ambulance, with the consequent block of all rescue missions (S. Fernando 1971). As evident, the collapse of a singular non-structural component can affect the entire resilience of the hospital: this is the reason why particular attention must be paid to the assessment of non-structural elements.

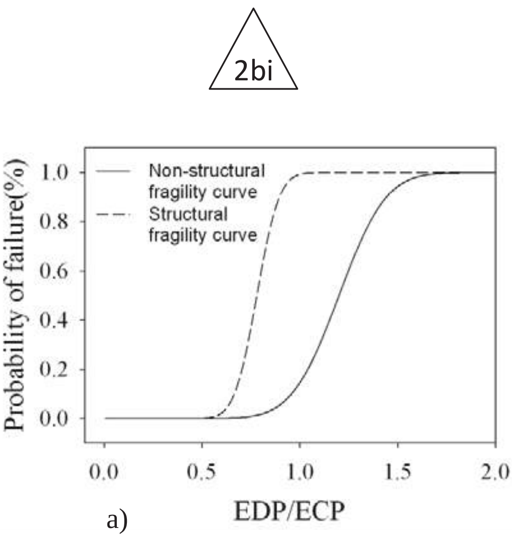
3.3.2 Physical system response and related waiting time and resilience curves

This section offers a more detailed analysis of the cases discussed above in order to check the effects of the different physical system scenarios on organizational aspects. These cases indicate that the comparison of structural (dotted line) and non-structural (full line) fragility curves permits to identify the "global" fragility curve (in red), to establish – by following the illustrated procedure – the downtime of the rooms, the waiting time and the resilience curve.

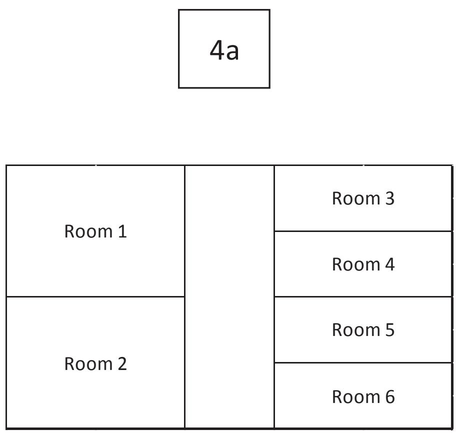
3.3.2.1 Linear elastic structural response

The following paragraph refers to the structural limit state defined in Figure 3. 5. In case of a non-structural component curve entirely on the right of the structural fragility curve (Figure 3. ***14*** , a), the associated resilience curve (Figure 3. ***14*** , d) is linear and no structural damages are registered (Figure 3. ***14*** , b). In this case the organizational model is not changed and the correlated organizational aspects are the same as under normal conditions (i.e. in a normal scenario when no earthquakes strike). The waiting time under normal conditions does not vary and it meets the hospital standards (Figure 3. ***14*** , c). In this case the structural fragility curve governs the global behaviour of the hospital system.

Even if an earthquake strikes, the consequences will not disturb the system: the performance displayed under normal conditions remains unvaried. If the emergency procedures are activated, they are not determined by failures or closures of rooms. The waiting time value will increase, depending on the organizational protocols.



a)



b)

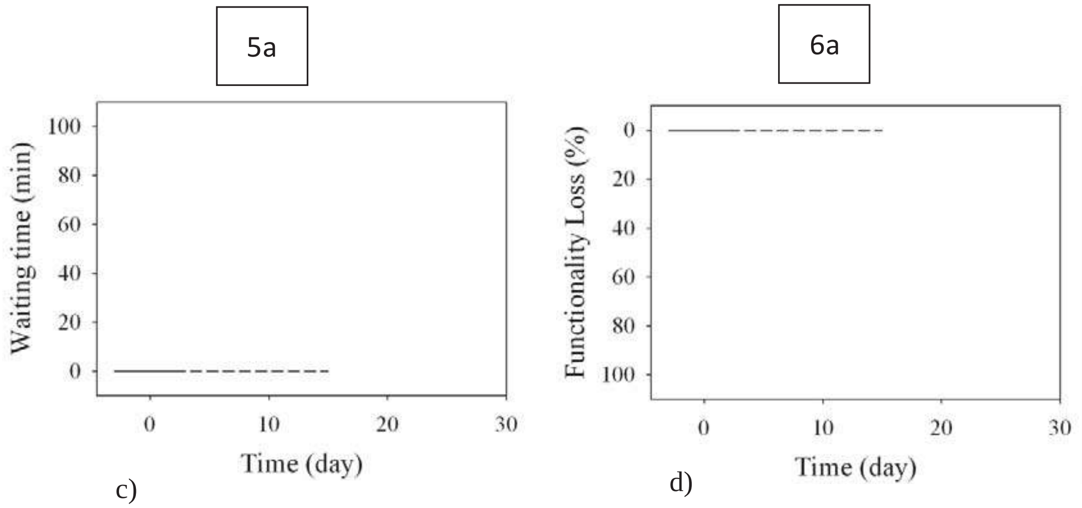


Figure 3. 14 Area of the structural linear response (a); schematic plan of a hospital with all functioning rooms (b); waiting time associated to a normal scenario (c) and resilience curves (d).

The second case occurs when the fragility curves cross each other (Figure 3. *15* , a). The new limit curve is an envelope of the two, and the closure of the rooms is a direct consequence of the more restrictive limit (Figure 3. *15* ,b). As in the previous case, the associated waiting time depends on the number of closed rooms and on their downtime, and the consequent resilience curve is still associated only with non-structural failures. In this case it is essential to consider the referring peak *floor* acceleration (PFA) and the consequent percentages of non-structural and structural failures. This specific case is discussed in more detail in the following paragraph.

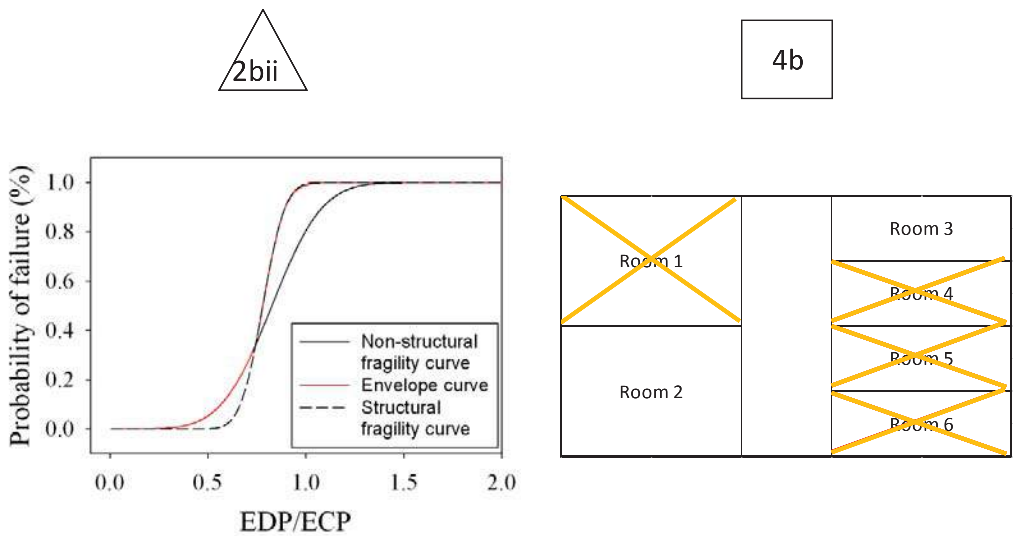


Figure 3. 15 Comparison between structural and non-structural fragility curves (a); schematic plan of a hospital with some permanently closures (red) and temporary closures (yellow) of the rooms (b)

The last case is represented by a non-structural component fragility curve located on the left of the structural one: the first becomes the new “Full Operational Limit State” (Figure 3. *16* , a), despite the structural response. Only non-structural failure occurs in the system (Figure 3. *16* ,b) resulting in a temporary closure of the rooms to the related recovery time. The associated waiting time depends on the number of closed rooms and their downtimes: the relative resilience curve depends on non-structural failures.

The weakest element fragility curve is taken into account as a new limit for determining a complete functionality, also depending on the role it assumes into the emergency room and the probability for it to compromise other essential non-structural components for the emergency procedures.

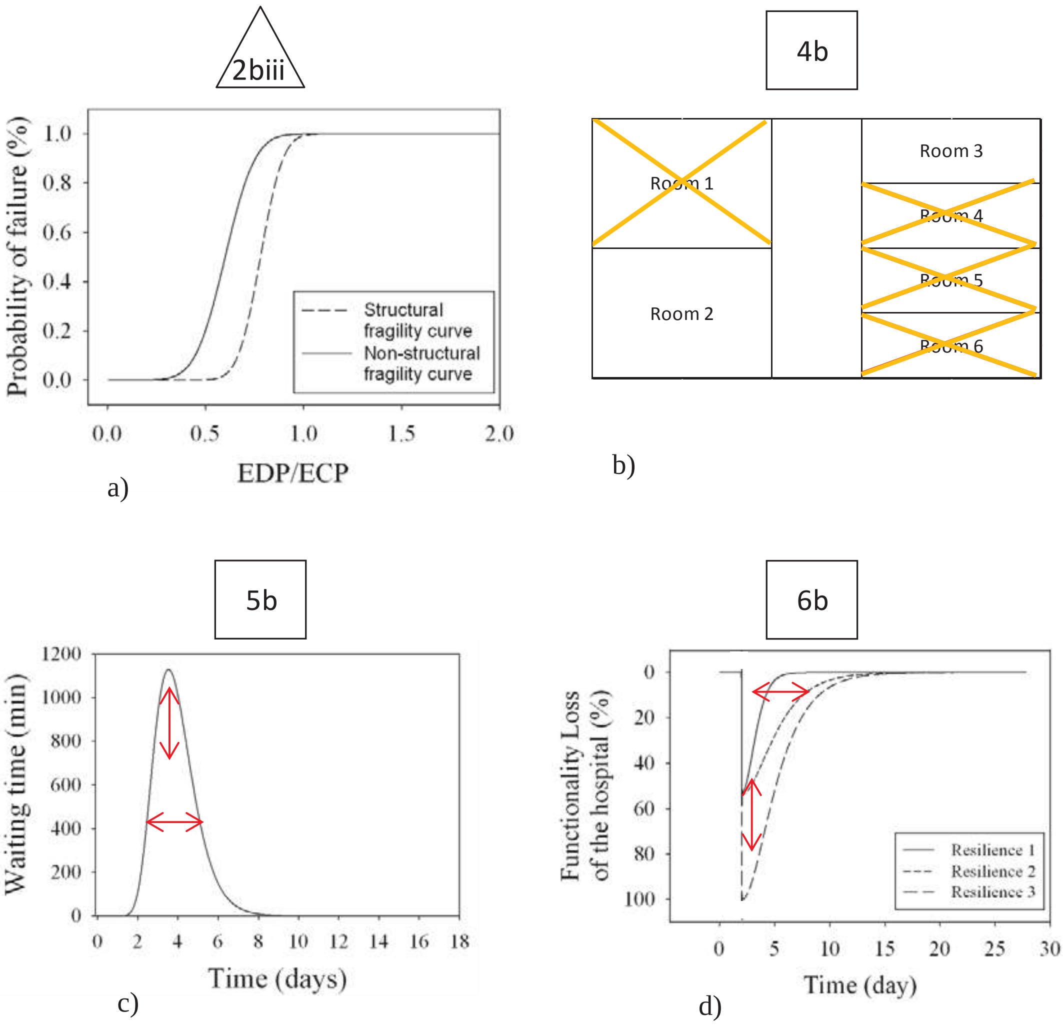


Figure 3. 16 Comparison between structural and non-structural fragility curves (a); schematic plan of a hospital with all functioning rooms (b); waiting time associated to a normal scenario (c) and resilience curves (d).

3.3.2.2 Non-linear inelastic structural response

The following paragraph refers to the structural limit state defined in Figure 3.7 (named as the "1.b" label into methodology flowchart in Figure 3. *3*). Non structural components cases are discussed above, in relation to the structural limit state.

By fixing a certain PGA, it is possible to represent this case as a partial closure of the ER, depending to the associated probability of damage which is calculated as a percentage of the entire area covered by the emergency rooms.

Eventually also the resilience curve shape will change, in particular regarding the length of the descending trait and in the scale of the trait after the shock time (represented as t_0 in Figure 2.4).

In case of non-structural components failure, fragility curves cross the damage limit state but still appear in the grey area (see Figure 3.7), without crossing the next structural fragility curve. Accordingly it is possible to fix a PGA of reference in order to establish two main cases.

The first one occurs when the probability of failure for the non-structural component (or the curve representing the most fragile NSC) is lower than the probability of exceeding the damage limit state (Pr_{STR}), as shown in Figure 3. *17* . In this case it is possible to assume the Pr_{STR} as the closed percentage area of the Emergency Room, and the Recovery time probability function associated with the Probability of Failure of non-structural components ($Pr_{F/D\ n}$) as the temporary time of emergency room downtime. Accordingly the damage the structure suffers from is assumed as equal, in terms of surface, to the percentage of probability of exceeding of the damage limit state. For instance, with a fixed PGA (green dotted line in Figure 3. *17* and Figure 3. *18*) if the Pr_{STR} is 0,72 the damaged area of the Emergency rooms will cover its 72%. Then the non-structural components recovery time will be added to the ER damaged area percentage.

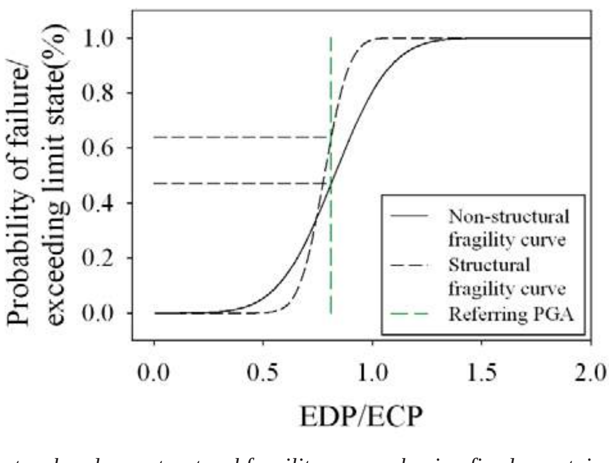


Figure 3. 17 Crossing structural and non-structural fragility curves: having fixed a certain PGA the probability to fail for non-structural component ($Pr_{F/Dn}$) is lower than the probability of exceeding the damage limit state (Pr_{STR}).

The same procedure can be followed when the probability of failure for non-structural components is higher than the probability of exceeding the damage limit state, as shown in Figure 3. *18* .

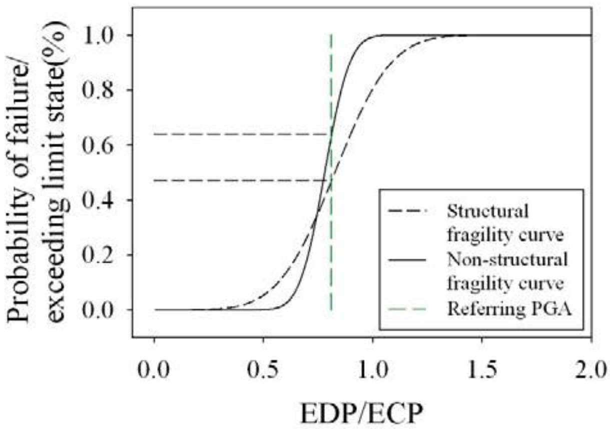


Figure 3. 18 Crossing structural and non-structural fragility curves: having fixed a certain PGA the probability to fail for non-structural component ($Pr_{F/Dn}$) is higher than the probability of exceeding the damage limit state (Pr_{STR}).

With respect to the structural damage fragility curve and its comparison with the non-structural ones, the three cases previously presented are further discussed. A reference non-structural fragility curve is taken into account.

The first case corresponds to the downtimes/interruption of the room(s) due to non-structural failure according to the fragility curves comparison. As matter of fact if the non-structural fragility curve is entirely to the left of the structural one (Figure 3. *19* a) only temporary downtimes occur (according to the recovery time probability curve of the non-structural component), represented in Figure 3. *19* b with yellow shape cross.

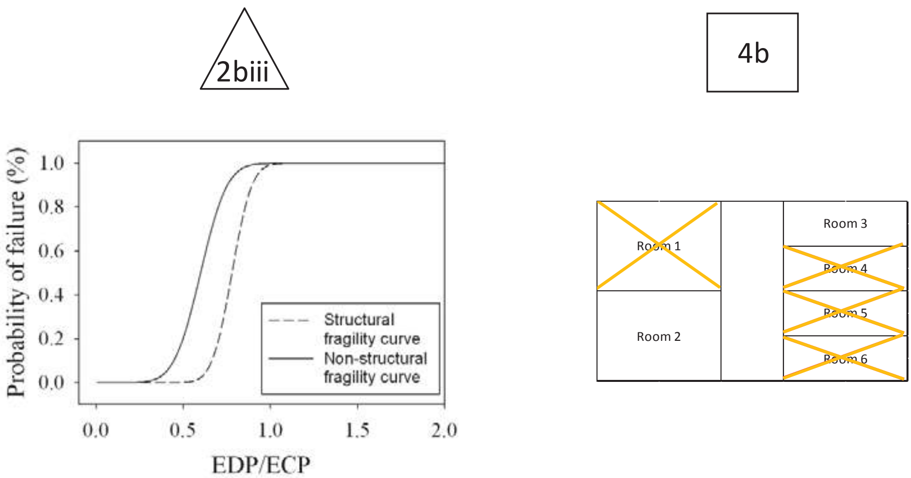


Figure 3. 19 Comparison between structural and non-structural fragility curves (a); temporary closure of the rooms (b).

In case of crossing fragility curves, the above mentioned procedure must be applied to evaluate the damaged area and the consequent recovery time of NSCs. Accordingly both structural downtime (permanently in the damaged area) and non-structural downtime equal to the associated recovery time, due to non-structural failure (Figure 3. *20* a) will occur. The waiting time curve is affected by both systems and the resilience curve presents a disruption as a result of both structural and non-structural effects (Figure 3. *20* b, represented with cross shape in yellow for temporary, and in red for permanently closures).

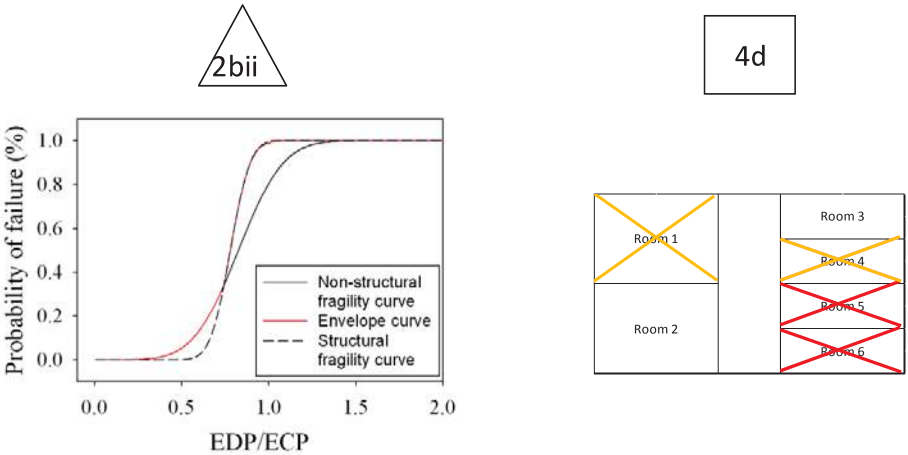


Figure 3. 20 Comparison between structural and non-structural fragility curves (a); schematic plan of a hospital with some permanently closure (red) and temporary closure (yellow) of the rooms (b).

If the intercepted fragility curve is only the structural one, the room downtime can be calculated by associating the percentage of the damage with the total area of the emergency rooms (Figure 3. *21*). In this case the inoperability will result in a permanent downtime.

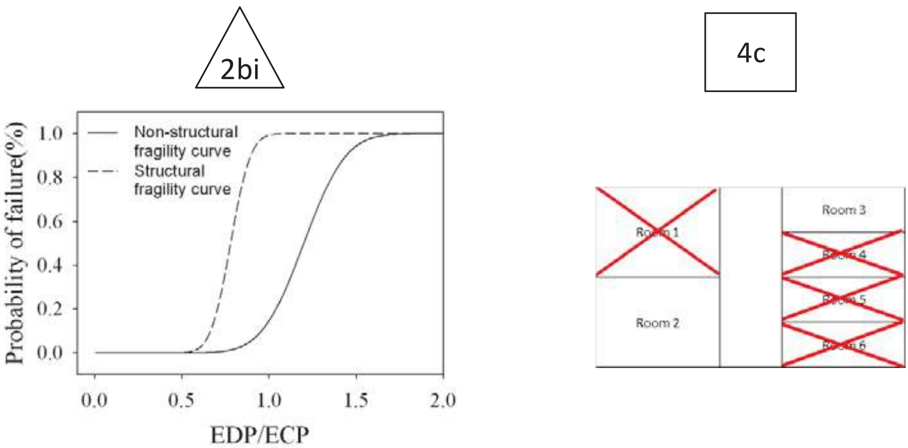


Figure 3. 21 Comparison between structural and non-structural fragility curves (a); schematic plan of a hospital with some permanent closures (b).

The fragility curves related to the other limit states are representative of the thresholds associated with the damage level until the collapse of the structure (Figure 3. ***23*** a). In between these two thresholds, several different types of damage can occur.

The organizational aspects strictly depend on the loss of integrity of the structure. Following Bruneau & Reinhorn (2007) it can be assumed that, in case of structural damage, the resulting probability of losses will increase, with a corresponding higher loss of non-structural resilience, possibly up to a total loss. In case of non-linear-inelastic structural response, the corresponding impact of structural damage on the fragility and resilience curves of non-structural components is rather unknown. As a consequence, it is useful and more precautionary/preventive to figure out a total loss of non-structural components as soon as any structural damage occurs (a structural damage threshold is achieved). Subsequently, the structural damage will determine the non-structural losses.

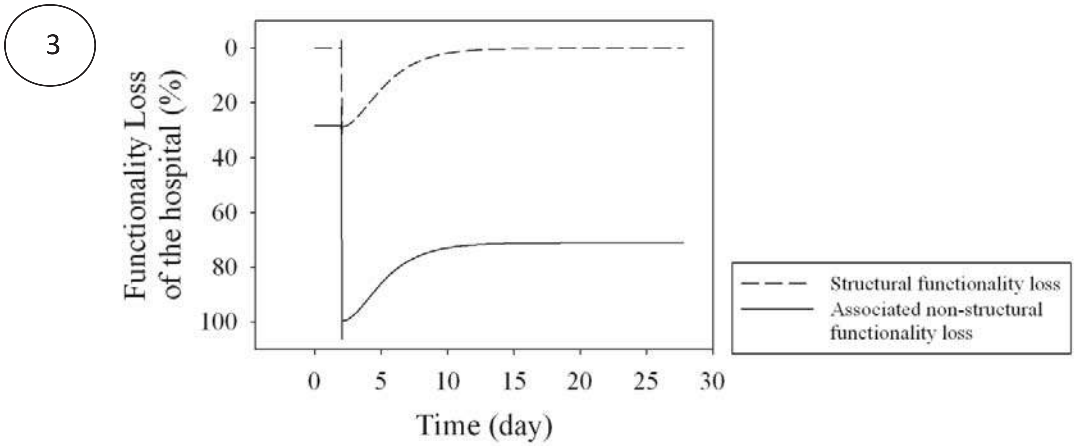


Figure 3. 22 Corresponding shift in non-structural seismic resilience curve in case of non-linear-inelastic structural response.

This is translated into the organizational model of the hospital as the permanent closure of some areas (in this specific case a different number of emergency room, i.e. ER) because of the direct relationship between waiting time and treated patients. With structural damage, in effect, are opening of the emergency room is not guaranteed and the structure will need restoration after the shock-days. Therefore the waiting time of the hospital in case of an emergency is affected by the number of closed (down) emergency rooms; besides, it can vary depending on the intensity of the seismic arrival rate. In principle, it is possible to suppose a permanent closure of the rooms depending on the length of the emergency phase. In this respect it is worth to specify that in this work the term "permanent closure" in connection with the length of an emergency phase refers to a timespan of three days.

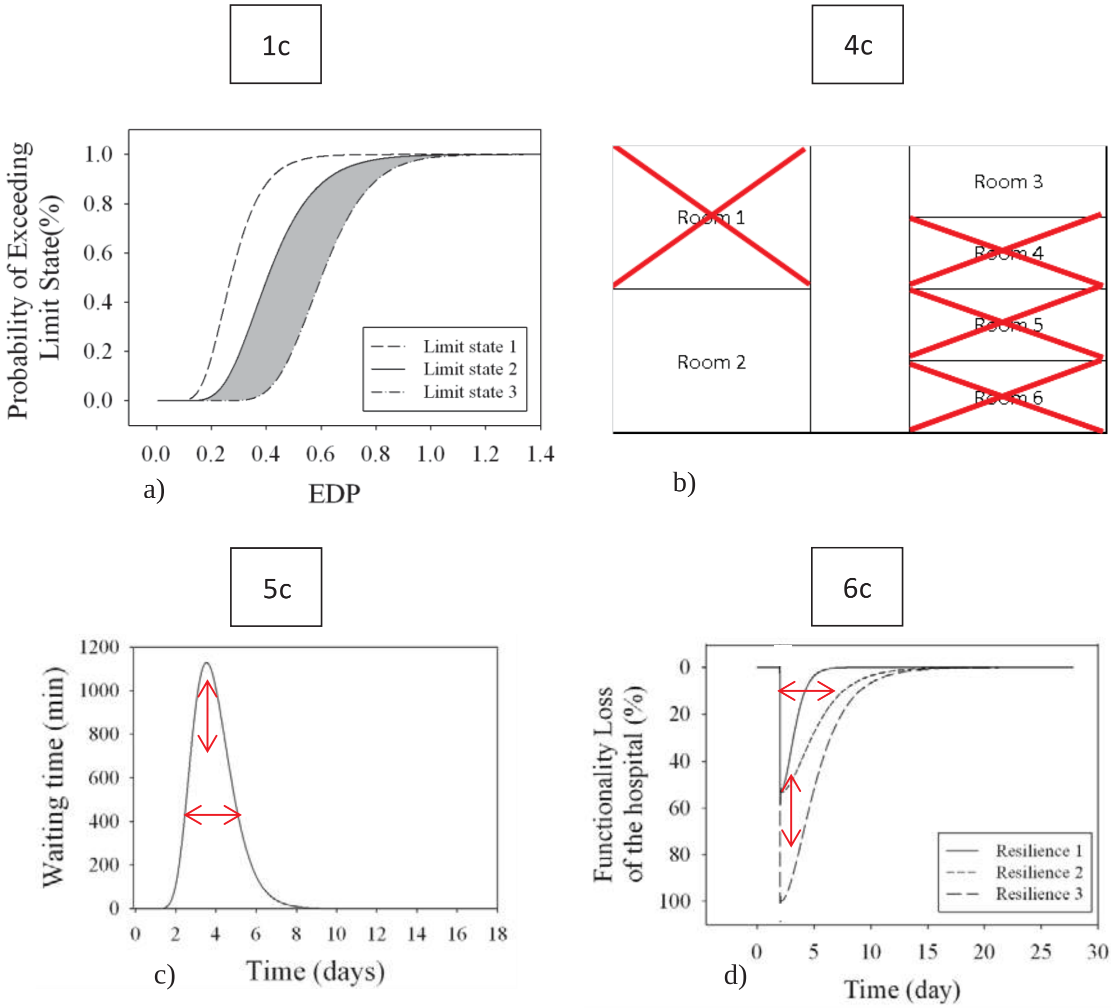


Figure 3. 23 Area of structural damages (a); permanently closure of several Emergency Rooms (b) and consequently increasing of WT registered (c) for the patients treated with a general decreasing of functionality of the system (d).

Figure 3. ***23*** shows the structural fragility curves ranging between the damage and the final collapse. In this case, several different forms of structural damage can occur, with a consequent closure of emergency rooms. Those cases affect the waiting time curve, which can decrease or increase both in terms of pick and size of the bell. Of course this implies a variation of the WT_{max} and of the time necessary to restore the original functionality.

3.3.3 Integrating components' resilience

The "road map" in Figure 3. *3*, where all steps are identified through labels, allows to represent the resilience of all components (from the structural to the singular non-structural ones) and, therefore, to determine all the essential mutual dependencies. The same road map is represented below, from Figure 3.24 to Figure 3.28, focusing on different steps of the procedure, in order to better explain the logical passages.

Figure 3.24 shows the importance of distinguishing different thresholds for the structural components, from which the procedure changes the results. Consequently, each non-structural component can significantly change the organizational behaviour of the entire hospital (Figure 3.25). The identification of the most essential non-structural components can be of great help not only for making appropriate management choices, but also as a decision tool enhancing the seismic resilience of healthcare systems.

This approach emphasizes the pivotal/fundamental need of information regarding the fragility of non-structural building components in terms of capacity and recovery time. It is worth to note the importance of comparing the structural performances with the non-structural ones, especially considering that even in case an immediate occupancy performance level (serviceability limit state) is achieved after a seismic shock, the failure of non-structural components can cause the total interruption of the medical services.

First, the possibility to simulate the organizational response to variable losses of emergency rooms in terms of numbers and downtime, results in an essential method to check and identify critical points and elements. Secondly, such a method allows the association of a singular resilience curve with every component, depending on the recovery time probability function related to non-structural components, and their further combination to estimate a resilience curve in different scenarios.

Furthermore, it is relevant to distinguish the physical aspects from organizational ones; depending on the hospital plan and staff organization, on the base of the number (due to structural damages) and downtime closure (due to non-structural recovery time probability functions) of the rooms, the system will display different responses to the shock. Emergency plans, staff preparation and human resources crucially influence the hospital behaviour. Nevertheless thanks to the organizational model it is possible to statistically estimate the organizational response in terms of waiting time; besides, multiple scenarios can be tested.

To estimate the resilience of the healthcare facilities, the knowledge of the system, the hospital plan, the hospital staff preparedness, the non-structural element and extension are the major elements to be taken into account together with their associated recovery time fragility functions (after a punctual assessment of the structure).

This method can be used for a singular room, for comparing a non-structural component with a determined structural limit state, but can also be applied to the entire hospital campus.

Last but not least, this approach improves and completes the methodologies presented in the literature (see Ch. 2 for more details) in that it statistically quantifies the organizational aspects by means of a unique value, i.e. the waiting time. With respect to the probabilistic approach proposed by Cimellaro et al. (2008), this methodology can not only simplify the procedure, but also permit a better management of each single non-structural element to identify the resilience of the system.

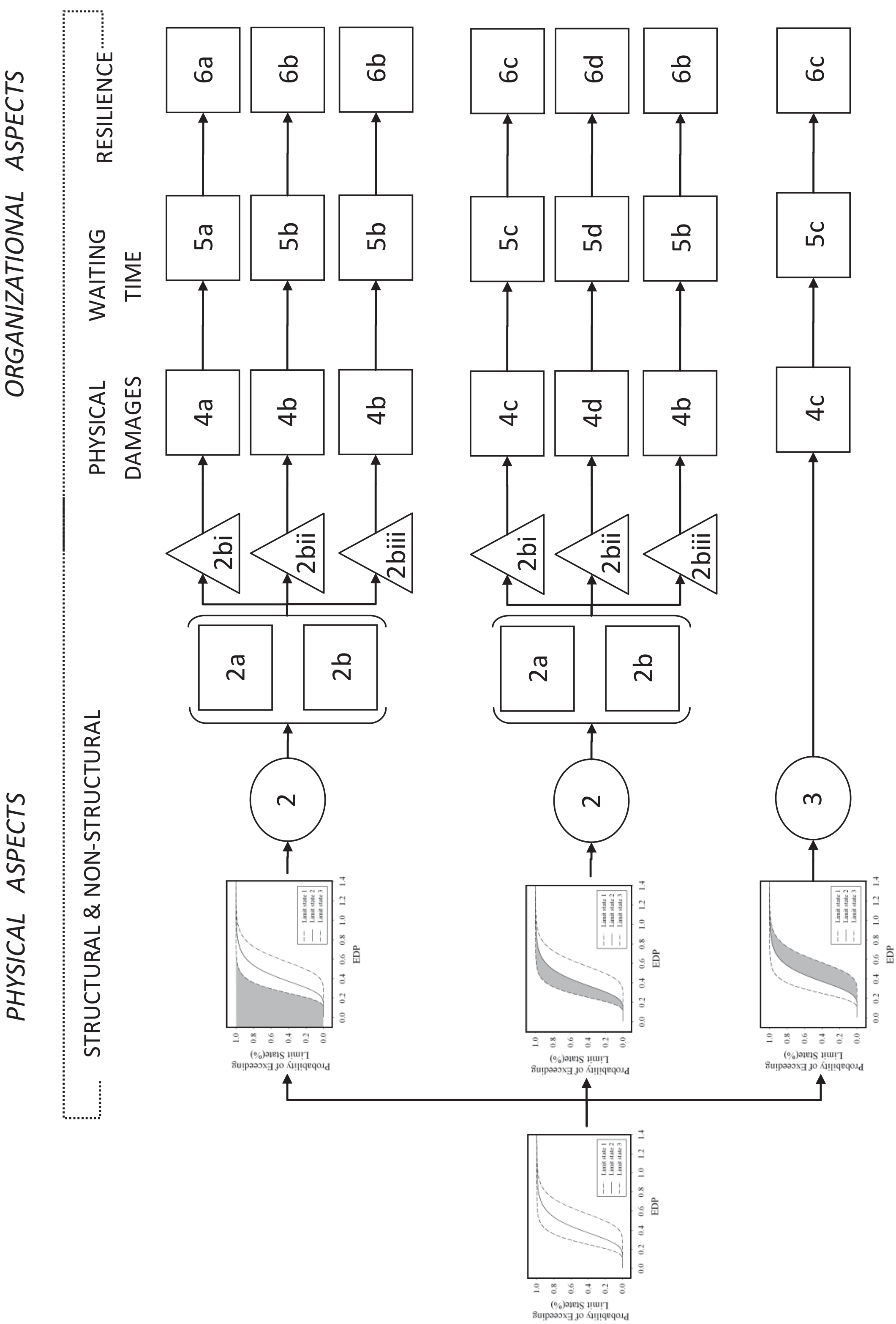


Figure 3. 24 Methodology roadmap, with focus on the structural assessment and limit states.

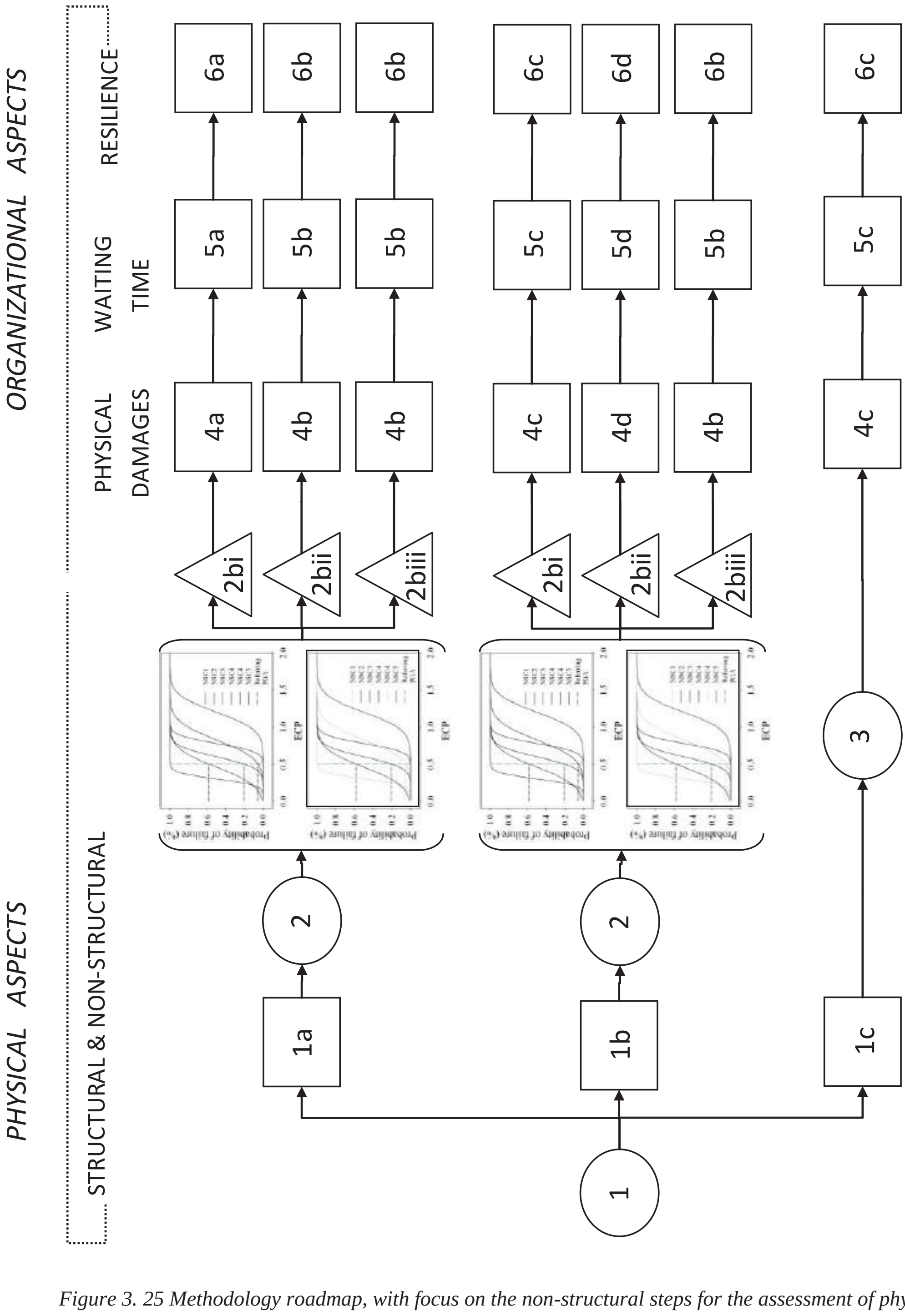


Figure 3. 25 Methodology roadmap, with focus on the non-structural steps for the assessment of physical aspects.

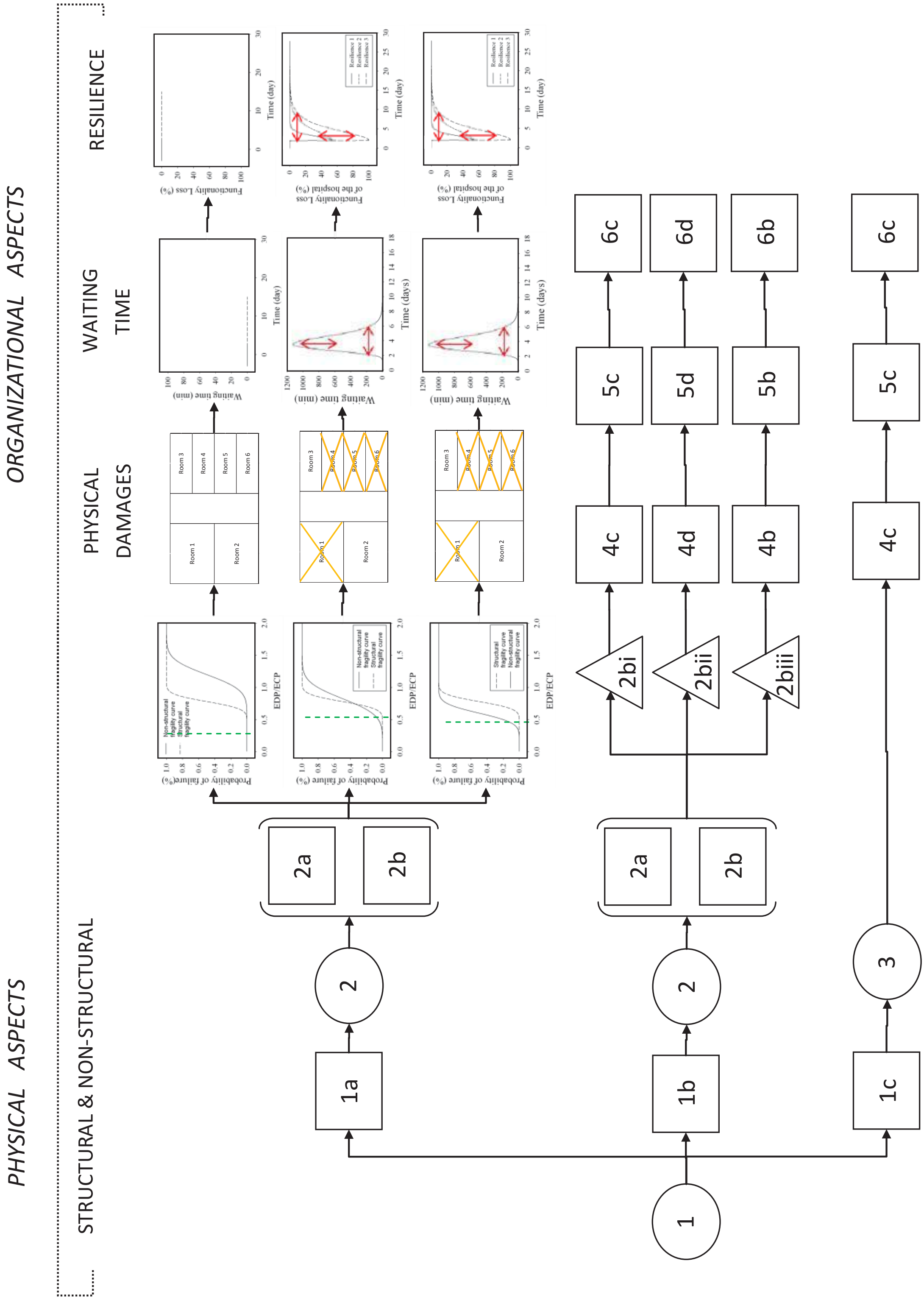


Figure 3. 26 Methodology roadmap, with focus on different cases of the linear elastic structural response.

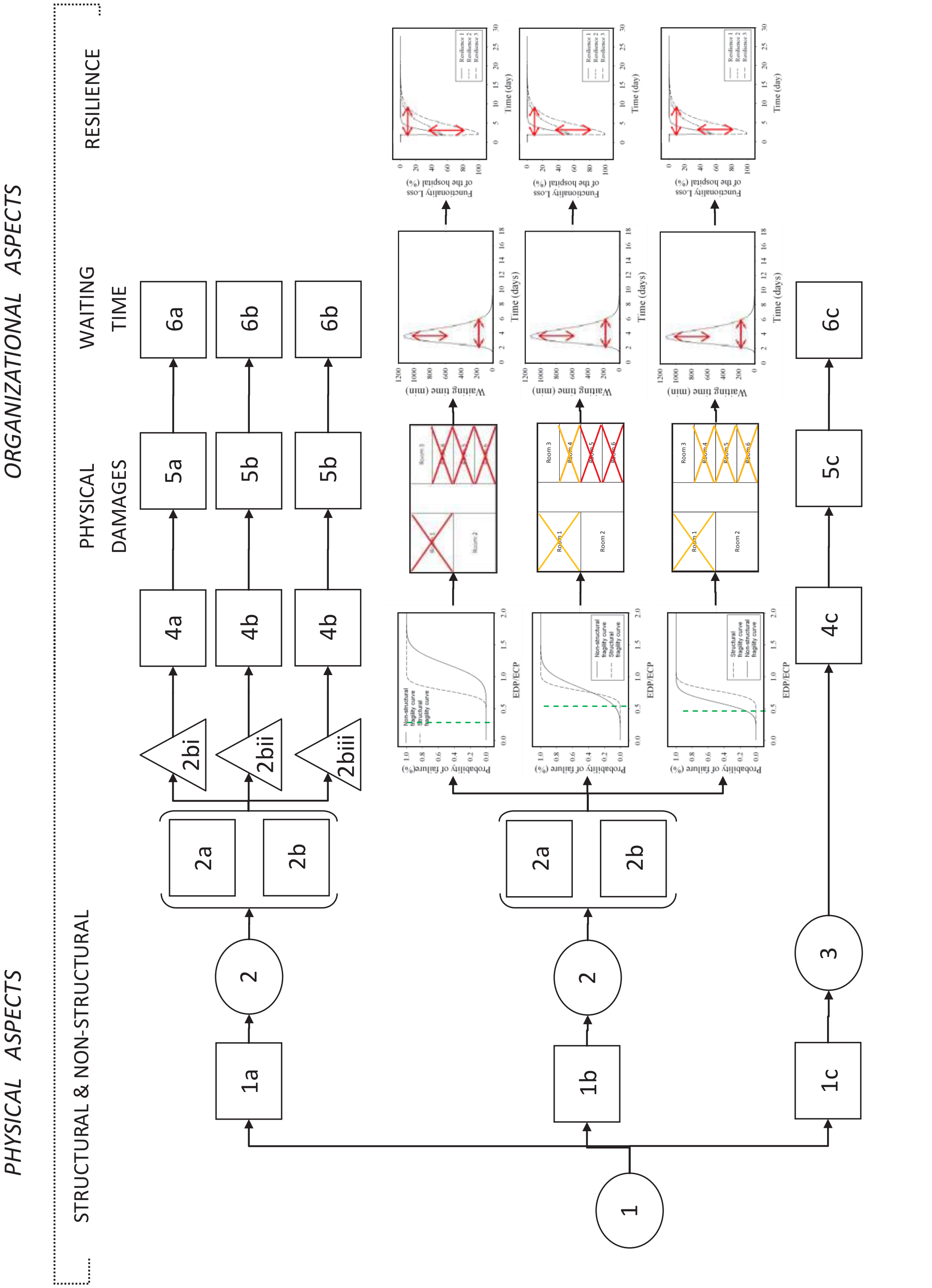


Figure 3. 27 Methodology roadmap, with focus on different cases of the non-linear inelastic structural response.

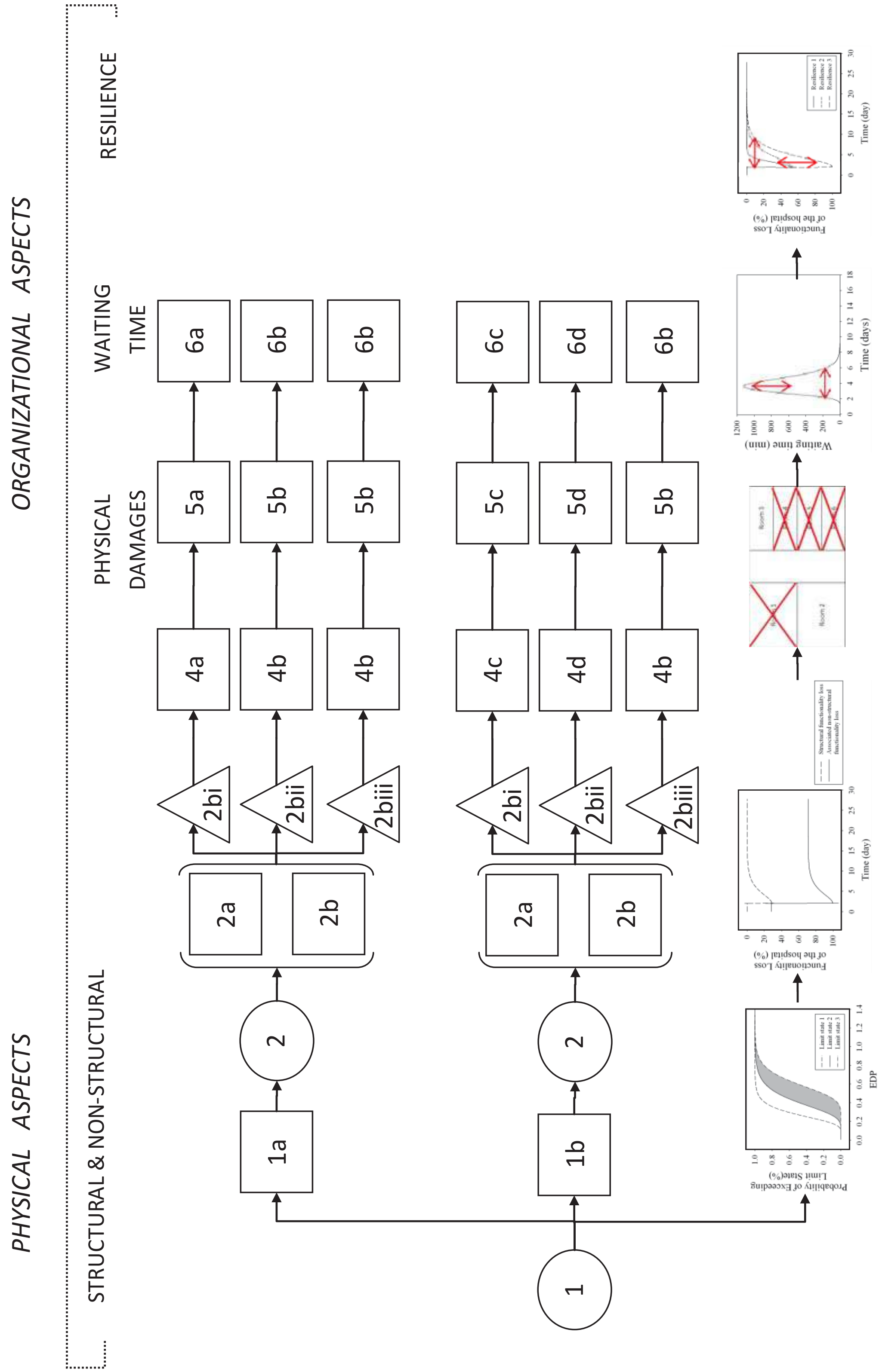


Figure 3. 28 Methodology roadmap, with focus on different cases of the inadequate structural response.

Chapter 4

Case study: the Sansepolcro hospital

4.1 Physical aspects of the Sansepolcro hospital

The Valtiberina Hospital complex[4] is situated in the Sansepolcro town, in the province of Arezzo, Tuscany (Figure 4. 1). According to the regional healthcare service this hospital is categorized as a “third category hospital”, due to its capacity and the population supported.

This campus has a complex configuration with two main sticks, having a roof terrace, pointing downstream, and connected through other perpendicular units. The whole hospital, located at the bottom of a hill, consists of four levels following the slope of the land, and is surrounded by parks and gardens. The main façade – in stone and exposed concrete – looks towards, the valley and is characterized by the alternation of windows and balconies, an d the emergency department access that consists of two vehicle ramps. A little portico located at the left side of the complex constitutes the main entrance to the hospital. The hospital is variously articulated, both for the structural and functional relationship between the different structural units

[4] This work is the result of an agreement stipulated in March 2012 between the University of Florence and the Tuscany Region and contributes to the Research Program “Valutazione del Rischio Sismico delle Strutture ospedaliere in Toscana” (“Assessment of the seismic risk in healthcare facility in Tuscany”). The research started with the material mechanic characterization and the static stability of the hospital complex according to the Italian Code (NTC2008). The documentation was found at the civil engineering office of Arezzo (Italy) and at the hospital archive of Sansepolcro (AR).

Figure 4. 1 Geographical location of the Sansepolcro hospital: national view (left), regional view (middle), satellite view of the complex (right).

4.1.1 Summary description of the building complex

The hospital is characterized by around 50000 cubic meters and is constituted by 18 independent structural units. These structural units, occasionally divided from each other by ground/floor-to-roof joint on average of 10 cm size, have been built in consecutive ages: the original project was outlined in 1962 and completed in 1979; then numerous restorations and reorganizations followed.

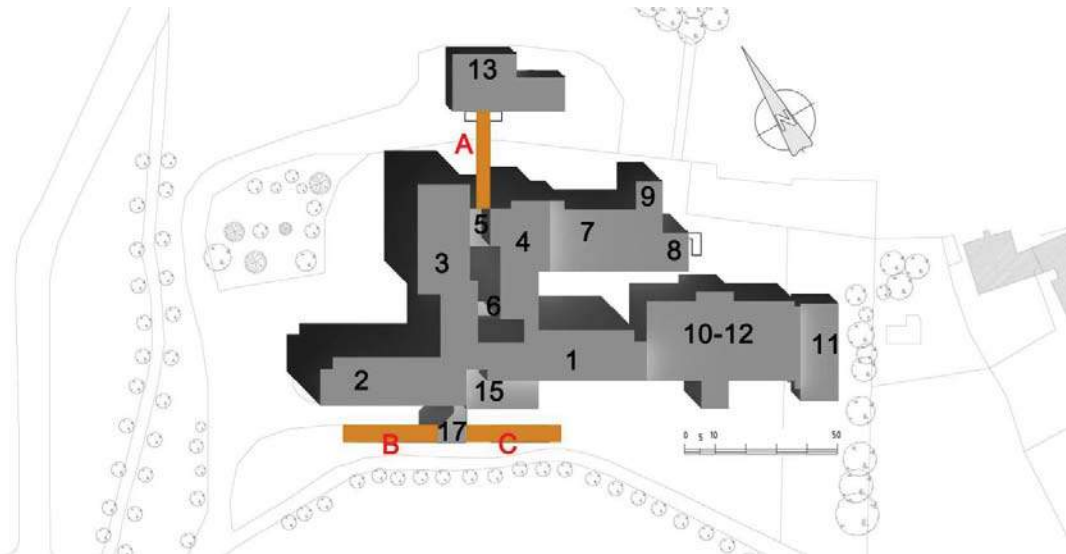


Figure 4. 2 Inner space of the emergency department (ED): corridor.

All the various blocks have a reinforced concrete (Rc) frame structure, except for the last extension (in Rc walls and steel structure), which overlaps an existing building still remaining independent. The various structural units have an average of three or four floors, with another upper floor without infill walls, which is often equipped with special spaces for contents and medical equipment.

The site morphology determines the “slope distribution” of the complex, with a height difference of up to almost two floors, between the basement of the Emergency Department access and the “morgue” structural unit. The main entry of the hospital is located at an intermediate height on the long side of the structural unit (cf. Figure 4. 2, nr. 3). The administrative and reservation services are located into the newest building (cf. Figure 4. 2, nr. 12).

The structural units designated for the recovery service are located around the two courts, while the “service structural unit” (morgue, emergency department, technological system) are situated in a marginal position. The building which allocates the thermal systems is identified as structural unit nr.11 and is connected by a tunnel (exclusively for the medical personnel) to the basement level of another building. On the contrary, the morgue building is connected by a bridge-corridor to the rest of the hospital complex.

4.1.2 Geological framework

The study area belongs to the Tuscany layer and as such follows the Northern Apennines evolution. The land consists of Arenarie of Monte Cervarola sandstones. The local lithologies consist of alterning turbidites (fine-grained sandstones) interbedded with silty marls. The maximum thickness varies between 1000 and 1500 meters and its age can be related to Aquitanio-Langhiano period. In the area under consideration it is clearly observable a sequence of about 10 meters showing irregular alternation of silty marls and sandstones in layer of variable size.

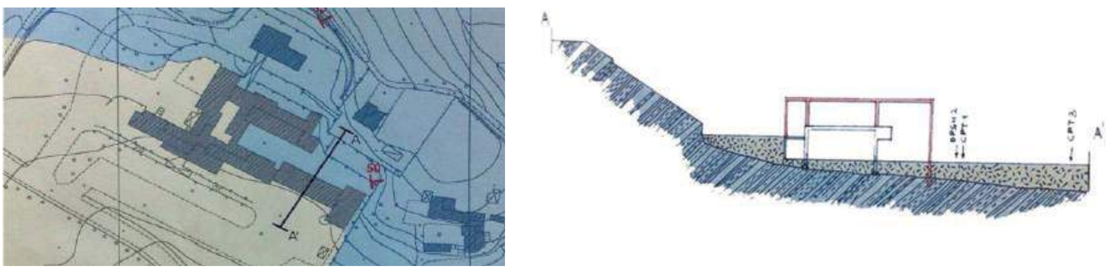


Figure 4. 3 Geological overview: plan (left) and section(right). The blue colour identifies Arenarie of Monte Cervarola sandstones area, while the grey colour identifies the layout of alternation of turbidities sandstones and fine silt marl

4.1.3 The emergency department

The investigated structural unit named n°15, is a two-story building with a dimension of approximately 19.5x12 meters located in the south part of the building complex. It consists of reinforced concrete frames with two spans of 5.88 meters and 2.88 meters length in direction X (Figure 4. 5), and three frames (primary ones) in direction Y, measuring 6.0 meters, 3.22 meters and 10.06 meters in length. Columns have different section sizes at different levels: in the basement floor they are 0.35x0.35 meters except for the four central columns having a dimension of 0.40x1.2 meters decreasing in section as it goes above to the ground level; on the first floor the columns are all 0.30x0.30 meters (Figure 4. 4).

The primary beams on the first floor have section size of 0.3x0.6 meters, except those at the ground floor which are larger in size and have a different configuration. The heights of the first and second floors are 3.7 meters and 3.4 meters respectively.

Figure 4. 4 Outdoor space of the structural unit n°15: the basement.

The main entrance to the ground floor is set back with respect to the perimeter of the building. The first floor allocates a portion of emergency department area: the vehicular access is guaranteed by two ramps. On the southern front there are also terraces built with cantilever slabs.

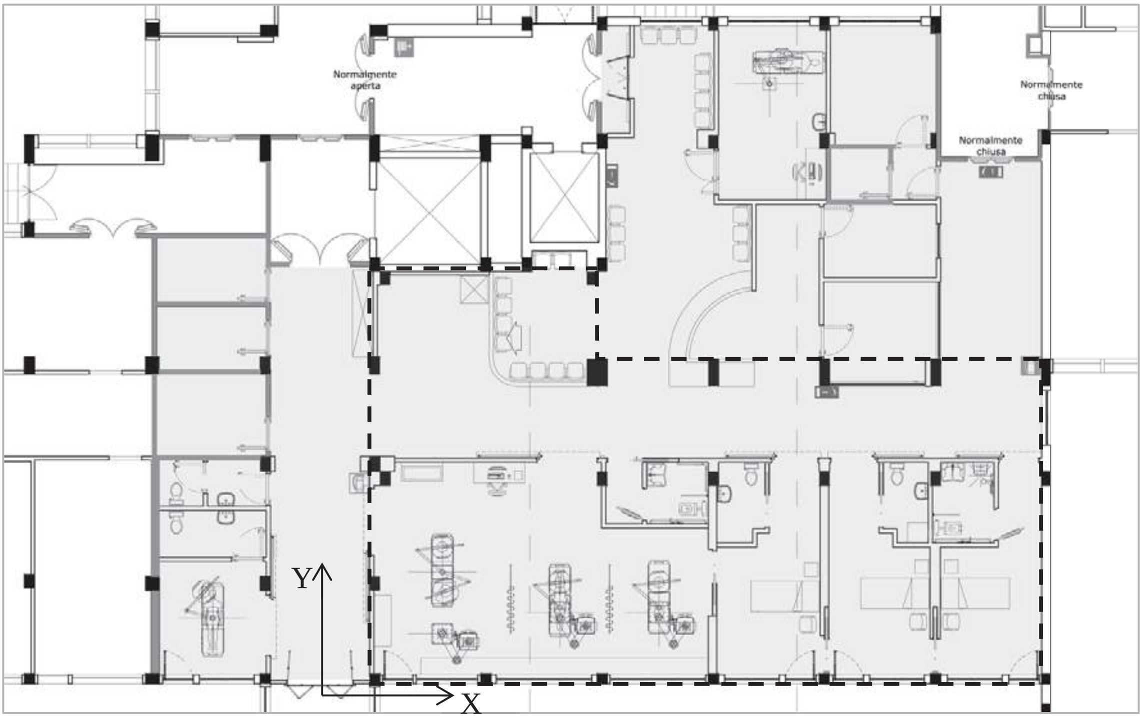


Figure 4. 5 Architectural plan extracted from the hospital (in shadow the Emergency Department).

4.1.3.1 Structural details of the emergency department

The plan view of the two floors and the two architectural sections of building n°15 can be seen in Figure 4. 6: column members are shown in solid black and beam members are outlined with black. The dotted line represents the overhang of the balcony. All dimensions on the plan drawings are given in meters.

The hospital structure features a hollow-brick slab (it. 'laterocemento') on the first floor and roof level. The slabs were constructed *in situ* with the beam members. Both slabs have a thickness of 20 centimetres. Furthermore, the first floor slab has a 4 centimetres thick layer of concrete on top of it; therefore the first floor slab has a total thickness of 24 centimetres

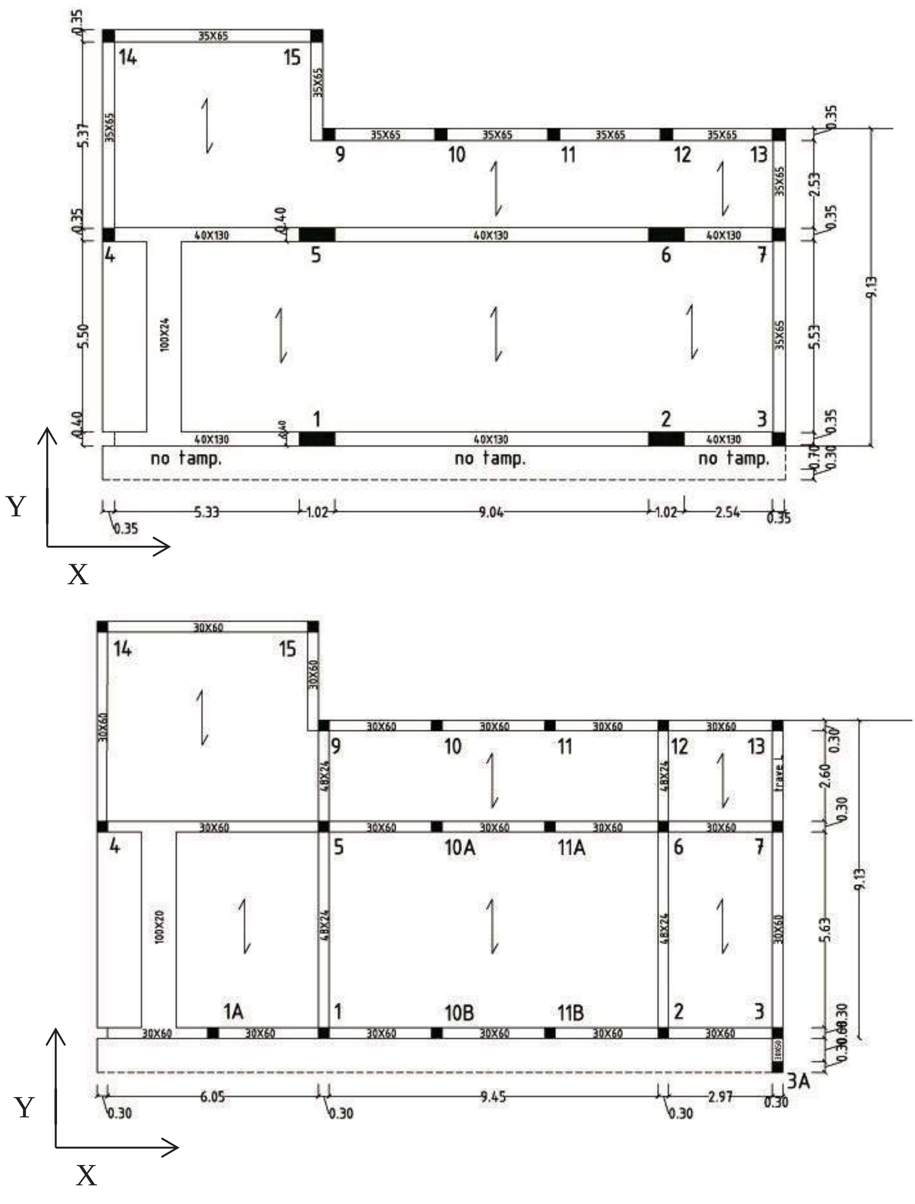


Figure 4. 6 Plan overviews of the ground and first floor of the emergency department (ED).

Column section details can be found in Figure 4. 8 (for the ground level) and Figure 4. 9 (for the first level). The transverse reinforcement for the beam and column members varies in size from 6 millimetres, 8 millimetres, to 10 millimetres spaced at 200 millimetres; but exact transverse reinforcement sizes for every member are unknown. To solve this issue a uniform transverse reinforcement size of 8 millimetres spaced at 200 millimetres intervals was assumed for all members. Concrete cover to longitudinal bars is 40 millimetres for columns and 30 millimetres for beams (Przelazloski 2014). Details for the beam section and reinforcement are shown in Table 4. 2.

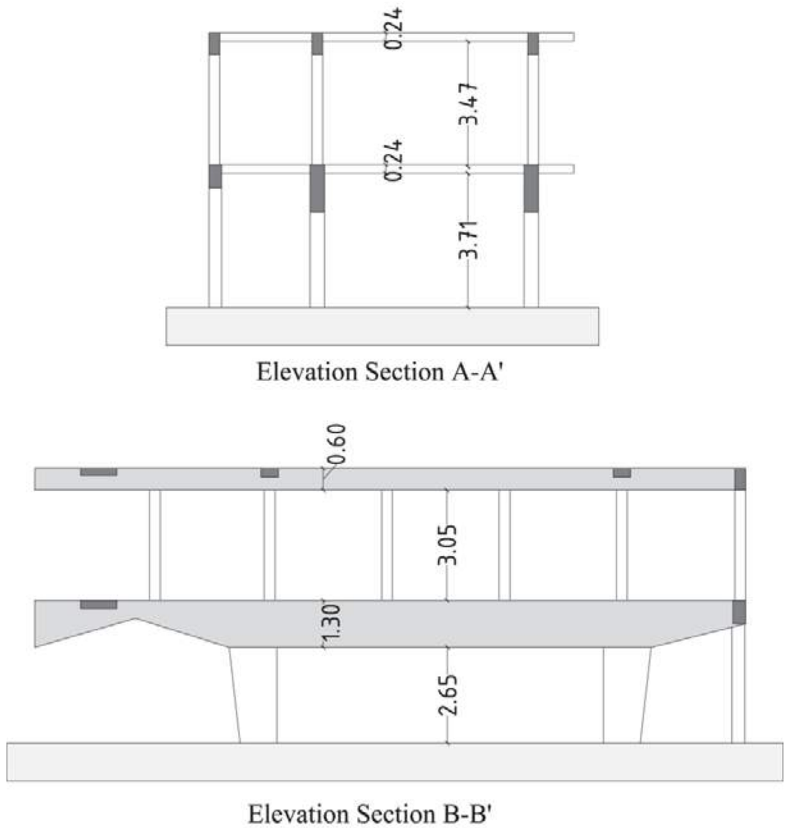


Figure 4. 7 Elevation sections of the emergency department (ED).

***Table 4. 1**: Column section and reinforcement details for the case study building*

Column section	Dimensions (cm)	Longitudinal reinforcement	Transverse reinforcement
1	40 x 102	18 ϕ24mm	ϕ8 at 200mm
2	35 x 35	4 ϕ16mm + 4 ϕ14mm	ϕ8 at 200mm
3	30 x 30	8 ϕ14mm	ϕ8 at 200mm
4	30 x 30	4 ϕ12mm	ϕ8 at 200mm

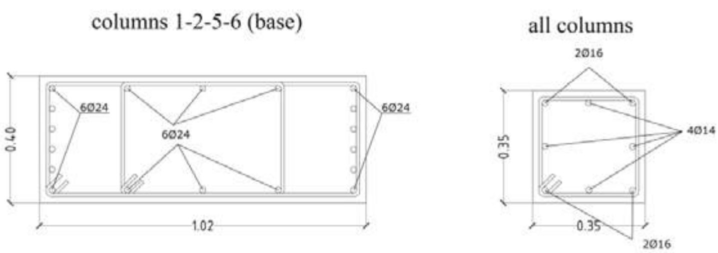


Figure 4. 8 Column details of the ground storey of ED.

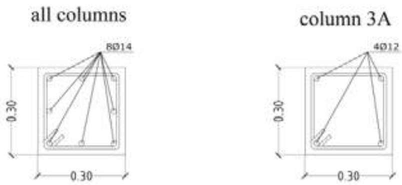


Figure 4. 9 Column details of the first floor of ED.

Table 4. 2: Beam section and reinforcement details for the case study building

Beam section	**Dimension (cm) (Depth x Width)**	**Top longitudinal reinforcement**	**Bottom longitudinal reinforcement**	**Transverse reinforcement**
A	100x24	12 ϕ20	4 ϕ20	ϕ8 at 200 mm
B	100x24	4 ϕ20	8 ϕ20	ϕ8 at 200mm
C	100x20	12 ϕ20	8 ϕ20	ϕ8 at 200mm
D	30x60	8 ϕ20	8 ϕ20	ϕ8 at 200mm
E	30x60	6 ϕ16	2 ϕ16	ϕ8 at 200mm
F	30x60	2 ϕ16	4 ϕ16	ϕ8 at 200mm
G	40x130	6 ϕ16	2 ϕ16	ϕ8 at 200mm
H	40x130	2 ϕ18 + 6 ϕ20	2 ϕ20	ϕ8 at 200mm
I	35x65	2 ϕ18	9 ϕ18	ϕ8 at 200mm
K	35x65	2 ϕ14 +2 ϕ16	2 ϕ14	ϕ8 at 200mm
L	40x130	2 ϕ14	2 ϕ14 + 2 ϕ16	ϕ8 at 200mm
M	40x130	12 ϕ20	4 ϕ20	ϕ8 at 200mm
N	40x130	4 ϕ20	8 ϕ20	ϕ8 at 200mm
P	40x130	8 ϕ20	4 ϕ20	ϕ8 at 200mm
Q	40x130	10 ϕ20	3 ϕ20	ϕ8 at 200mm
R	40x130	3 ϕ20	7 ϕ20	ϕ8 at 200mm
S	40x130	7 ϕ20	3 ϕ20	ϕ8 at 200mm
T	40x130	4 ϕ24 + 7 ϕ20	4 ϕ24	ϕ8 at 200mm
V	40x130	3ϕ20	8 ϕ24	ϕ8 at 200mm
Z	40x130	7 ϕ24 + 3ϕ20	4 ϕ24	ϕ8 at 200mm
W	30x60	2ϕ24 + 2ϕ16	2 ϕ14	ϕ8 at 200mm
J	30x60	2ϕ14	2 ϕ14 + 2 ϕ16	ϕ8 at 200mm
AA	15x50	2ϕ16	4 ϕ16	ϕ8 at 200mm
BB	30x50	2ϕ14 + 2ϕ16	2 ϕ14	ϕ8 at 200mm
CC	48x24	3ϕ16	3 ϕ16	ϕ8 at 200mm
DD	35x24	3ϕ16	3 ϕ16	ϕ8 at 200mm

Material strengths and deformation limits are presented in Table 4.1. Concrete compressive stress was determined through the use of destructive (crushing cylindrical core samples) and non-destructive (ultra-sonic) tests. Data sets from both types of tests were used in calculating the concrete compressive stress. Steel yield stress was determined through tensile tests on bar samples. Testing procedures were done as specified in the Italian standard NTC 2008: Norme Tecniche per le Costruzioni. Other material properties are unknown but established within the guidelines provided by the NTC 2008 or assumed based off typical values. Material properties not verified through testing are marked with an asterisk (*) in Table 4.1.

Table 4. 3: Material proprieties for building

Median concrete compressive strength (f_{cmed}) (MPa)	35.7
Concrete modulus of Elasticity* (E_c) (GPa)	32.22
Concrete Compressive Strain at Peak Stress* (ε_{co})	0.002

Median steel yield stress (f_{ymed}) (MPa)	412
Median steel ultimate stress* (E_c) (GPa)	473.8
Maximum steel strain* (ε_{cu})	0.12

The seismic masses are shown in Table 4. 4. The masses were calculated according to the specifications provided by the NTC 2008.

Table 4. 4: Seismic masses of building n°15.

Level	Translational Seismic Mass (metric ton)	Rotational Seismic Mass (metric ton-m2)
Ground Storey	226	9826
First Floor	139	6029

4.2 Structural assessment of the Sansepolcro emergency department

A three dimensional Ruaumouko model was developed for the two stories concrete frame hospital structure in Sansepolcro in cooperation with the *Istituto Universitario di Studi Superiori (IUSS)* of Pavia, Italy (Przelazloski 2014; Pianigiani et al. 2014). Beams and columns have been modelled with line elements with concentrated plastic hinges at their ends. Due to the age of the structure and concerns about the construction practices, the effects of the transverse reinforcement in terms of confinement has been neglected both in beam and column deformation capacities. The behaviour of the joints columns have been modified to take into account the joint shear mechanism.

4.2.1 Structural fragility curves for the collapse limit state

After a modal analysis and pushover analyses carried out on the structure, the model was analysed using incremental dynamic analysis (IDA) for two sets of records of ground motion

(FEMA and Site Specific set). The IDA has been done until the achievement of the collapse condition, which is the physical situation that involves either excessive deformations leading and approaching collapse of the structural component under consideration or the structure as a whole, as relevant, or deformations exceeding pre agreed values. It involves of course considerable inelastic (plastic) behaviour of the structural scheme and residual deformations. The data from the IDA results were equipped with a lognormal distribution to build fragility curves. The first set is the same time history contained in the FEMA P695 document [FEMA P695, 2009]. This record set consists of 22 pairs of ground motions, so a total of 44 time histories and therefore 44 IDAs. Each record is normalized by their peak ground velocity via the factors given by Table A-4D of the FEMA P695 document [FEMA P695, 2009]. The second record set to be used in the IDAs is a record set that was developed specifically for the site of the hospital structure [Christovasilis, 2013]. The ground motion set consists of four subsets of 22 pairs of records each. The time histories in each of the subsets correspond to a different probability of exceedance in 50 years; the four probabilities considered are 22%, 10%, 5%, and 2%. The records in these subsets were matched to the conditional mean spectra of the site at a fundamental period of 1 second. A period larger than the actual natural period of the structure was deemed reasonable as it accounts for a fundamental period shift (lengthening) as the structure deforms. The four subsets of records each have a different median spectral acceleration at the natural period of the building, which is higher for lower probabilities of exceedance. As a result, to fully cover the range of spectral acceleration for the IDAs, each subset needs to only be scaled slightly up or down. The advantage of this procedure this is to reduce the uncertainties associated with the use of large scale factors on the time histories.

Figure 4.11 shows how the fragility curves assessed for the structural collapse and referred to the ground level must be assessed for both the right limit state and the right level where the non-structural component to be compared with is allocated.

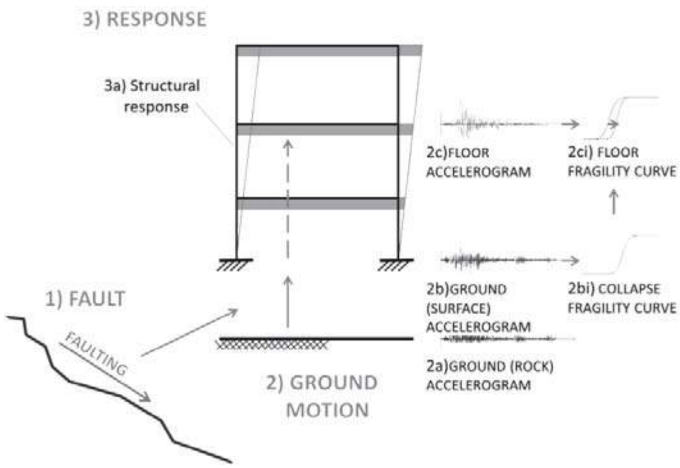


Figure 4. 10 Schematization of the behaviour of a structure during an earthquake.

Figure 4. 11 shows that the curves are relatively similar in value with the FEMA fragility curve tending to give lesser collapse probabilities. The site specific set seems to have some impact on the fragility curve results. However, considering that this is a probabilistic assessment, the

difference in fragility curves is not absolute and it can be affected by the uncertainties in modelling and assessment as well as by the record selection. Without considering the differences between the two curves, from an assessment standpoint, they both represent undesirably high collapse probabilities.

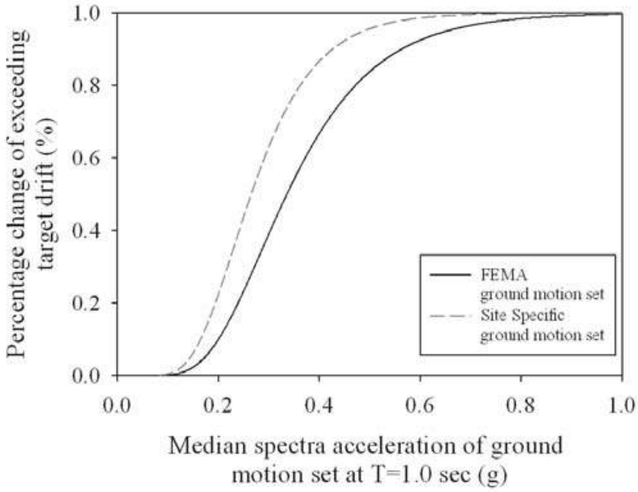


Figure 4. 11 Comparison of Site Specific set fragility curve and the FEMA fragility curve.

4.2.2 Structural fragility curves for other limit states

The estimation of structural fragility curves performance, for different limit states, is a fundamental step within the procedure. Actually the most common way to proceed is to assess the collapse fragility curve at the ground level; in this case the collapse limit state is not significant (as the research is referred to the functionality of the hospital), but it is necessary the comparison between curves related to the serviceability limit state (called SLO in Italy) or to the damage limit state (called SLD in Italy). Therefore even the structural fragility curves must be estimated at the right limit state and at the right level (floor) associated to the non-structural element position.

For this reason the median peak floor total acceleration of each floor has been extracted in order to allow a comparison between the median peak total acceleration of the floor taken into account and the relative fragility curve associated to different limit states. The latter are calculated in relation to the maximum drift allowed, which in the Italian code is equal to 2/3 of the 5‰ of the height of the floor. This limitation is established for the serviceability limit state, for allowing to the non-structural components to be functional even under seismic actions. The acceleration of the floor is reported as the total acceleration and it is correlated to the control node in the model, which is close to the centre of the floor plans. This is a good representation of the total acceleration of the whole floor. Moreover, the median peak floor acceleration is established only using record results with no structure collapse. For a better comparison, the ground motion intensity used to build the graph is the median spectral acceleration of the ground motion set used in the analysis, scaled to the median spectrum for a period of 1 second.

Figure 4. 12 shows the collapse fragility curve and the median peak floor acceleration of each floor: more specifically the graph related to the FEMA record set is on the left and the graph related to the Site Specific record set is on the right.

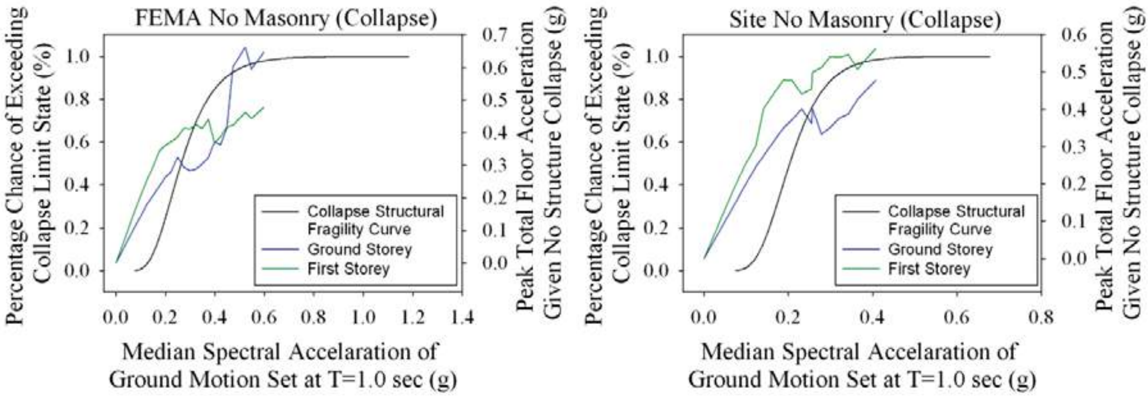


Figure 4. 12 Multiple graphs with the median peak floor total acceleration of each floor versus the ground motion intensity from the incremental dynamic analysis (FEMA record set on the left and Site Specific record set on the right).

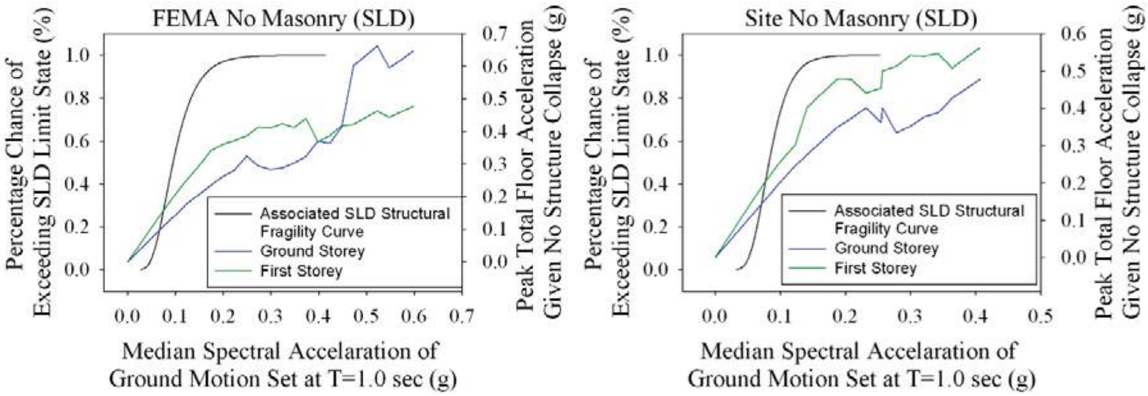


Figure 4. 13 Multiple graphs with the median peak floor total acceleration of each floor versus the associated damage limit state fragility curve (FEMA record set on the left and Site Specific record set on the right).

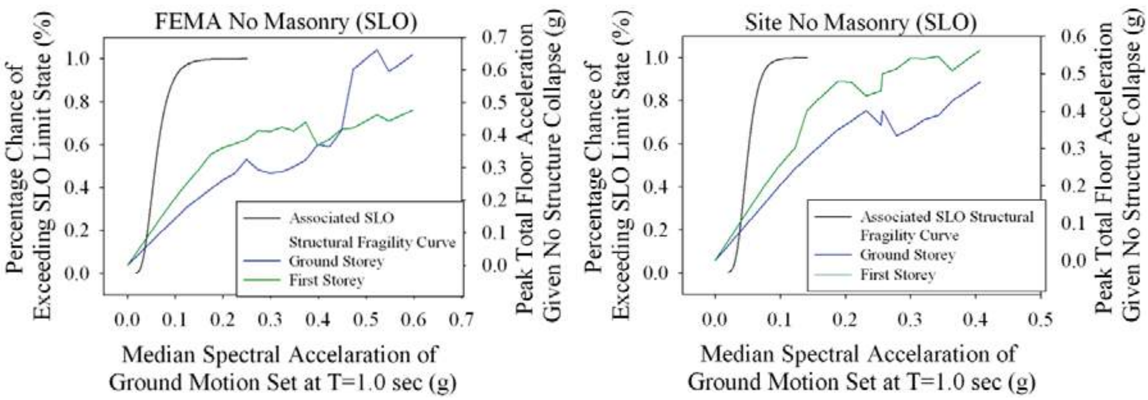


Figure 4. 14 Multiple graphs with the median peak floor total acceleration of each floor versus the associated serviceability limit state fragility curve (FEMA record set on the left and Site Specific record set on the right).

Plotting on the graph the fragility curves related to other limit states – as illustrated in Figure 4. 13 and Figure 4. 14 (e.g. serviceability limit state and damage limit state) – it is possible to derive the fragility curve of peak total floor acceleration for each floor. As matter of fact reading the acceleration on the vertical axis on the left related to the green and blue curves, the associated percentage of exceeding probability is given (related to a certain limit state). By plotting at the end the peak total floor acceleration versus the percentage chance of exceeding a chosen limit state, step by step it is possible know all the points. Figure 4. 15 shows the steps for assess the fragility curves by proceeding point by point.

The figure representing the fragility curve for the collapse limit state of the structure with the plotted acceleration for the first and the second floor, shows to find one point. Starting from the percentage chance of exceeding the collapse limit state, the corresponding median spectral acceleration of the ground motion is found; the latter point corresponds to a certain peak total acceleration for a determined floor of the structure. In this way, the median spectral acceleration is common to the two points with which is possible to build fragility curves where the percentage chance of exceeding a certain limit state is referred to the peak floor acceleration.

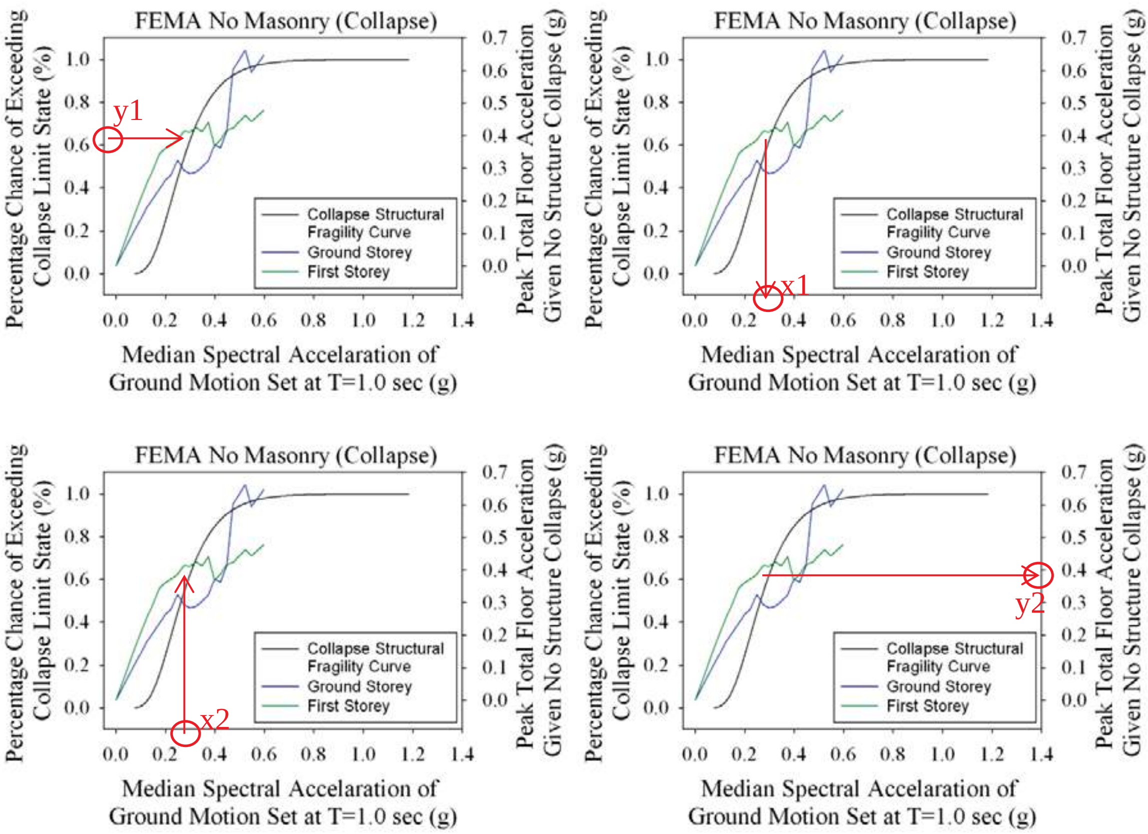


Figure 4. 15 Necessary steps for the derivation of the x-value and y-value from the collapse fragility curve and the peak total floor acceleration given by no structure collapse of the first and second floors.

In this process the y1-value begins the new y-value for the new curve, while the y2-value the new x-value of the point. It is possible because the two plots have a common value, and it is assumed that to a referring percentage chance of exceeding the limit state corresponds a peak a value of the peak total floor acceleration.

In this sense, for the new fragility curves associated to different floors, a certain number of “common” points are assessed, and then fitted.

Figure 4. 16 shows the peak total top-floor acceleration fragility curve related to the serviceability limit state for both records, while Figure 4. 17 shows the graphs related to the damage limit state.

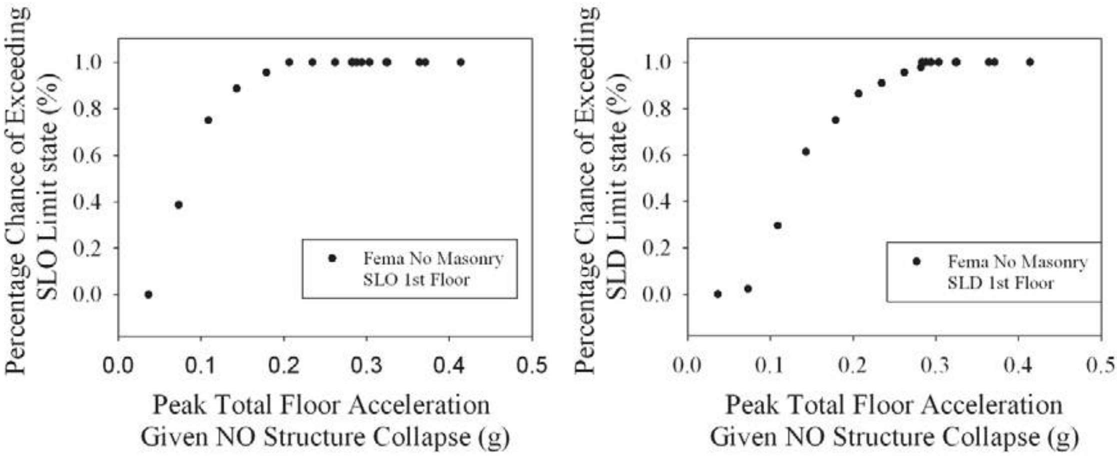


Figure 4. 16 Peak total top floor acceleration data for the serviceability limit state (FEMA record set on the left and Site Specific record set on the right).

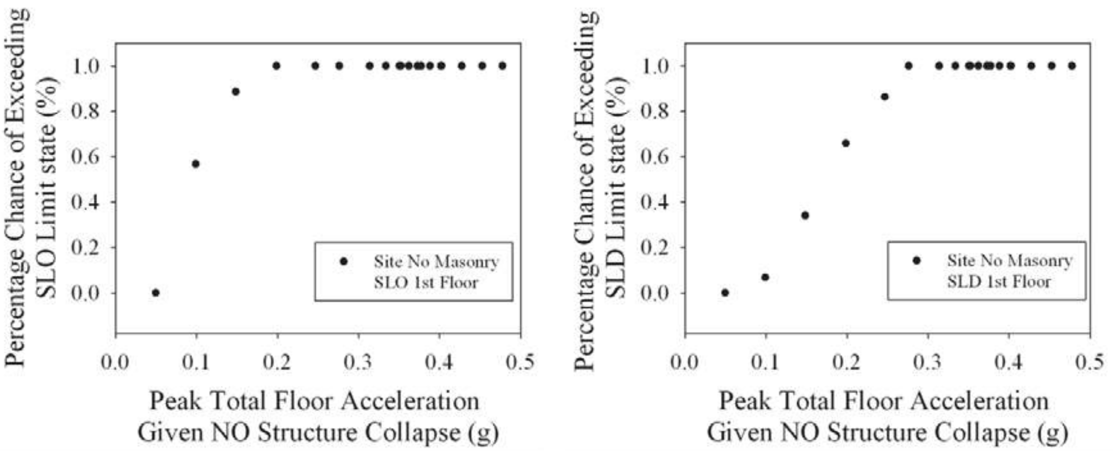


Figure 4. 17 Peak total top floor acceleration data for the damage limit state (FEMA record set on the left and Site Specific record set on the right).

These new acceleration points refer to the floor acceleration on the second floor of the building, where some acceleration-sensitive non-structural components will be evaluated. In effect in order to compare the capacity of the non-structural elements, it is obligatory to assess the real acceleration on the floor where they are allocated. The points derived for the top-floor, associated with both the FEMA and Site record set, and for the serviceability limit state (SLO) and the damage limit state (SLD) are to be fitted in order to have a continuous fragility curves.

4.2.3 Maximum Likelihood Estimation (MLE) fitting procedure

In order to account for the non-constant variance of the observed fractions of collapse, a more appropriate fitting technique is the one relying on the method of maximum likelihood (Baker 2014). This procedure is used where different ground motion groups (in this work for the

Multiple Stripe Analysis MSA) are defined as input for the IDA. The procedure is fully explained into Chapter5.

Such a procedure has some implications, for instance: it is not necessary to get an "intensity measure (IM) at collapse" for a given ground motion; it does not always get increasing fractions of collapse with increasing IM and, above all, it is not essential to perform analyses at high enough IM levels for it getting 100% collapse. The latter reason is very important because the peak floor acceleration points are registered for record which did not give a collapse. Therefore the main objective is to find Θ (median) and β (standard deviation) to define the fragility function that has the highest probability of having produced the observed data. Assuming n independent observations of "collapse or no-collapse:

$$P\left(z_{,j}\ collapses\ in\ n_j\ ground\ motions\right) = \binom{n_j}{z_j}\ {p_j}^{z_j}\ (1-p_j)^{n_j-z_j} \qquad \text{(Eq.4. 1)}$$

where p_j is the true probability of collapse at $IM = x_j$ (from the unknown fragility function).

Substitute in the fragility function for p_j in the previous equation:

$$P\left(z_{,j}\ collapses\ in\ n_j\ ground\ motions\right) = \binom{n_j}{z_j}\left(\frac{\ln(x_j/\Theta)}{\beta}\right)^{z_j}\ (1-\Theta\left(\frac{\ln(x_j/\Theta)}{\beta}\right))^{n_j-z_j} \qquad \text{(Eq.4. 2)}$$

To consider multiple IM levels, takes the product of these probabilities for each IM level (assuming independence of collapse realization from level to level). This gives a likelihood function:

$$Likelihood = \prod_{j=1}^{m}\binom{n_j}{z_j}\left(\frac{\ln(x_j/\Theta)}{\beta}\right)^{z_j}\ (1-\Theta\left(\frac{\ln(x_j/\Theta)}{\beta}\right))^{n_j-z_j} \qquad \text{(Eq.4. 3)}$$

It is possible to find the best estimates of Θ and β by maximizing this likelihood function. The parameters which maximize this likelihood function will also maximize the log of the likelihood, and numerically it is typically easier to optimize this log likelihood function":

$$\{\widehat{\Theta},\ \hat{\beta}\} = \underset{\widehat{\Theta},\hat{\beta}}{\arg\max}\prod_{j=1}^{m}\binom{n_j}{z_j}\left(\frac{\ln(x_j/\Theta)}{\beta}\right)^{z_j}\ (1-\Theta\left(\frac{\ln(x_j/\Theta)}{\beta}\right))^{n_j-z_j} \qquad \text{(Eq.4. 4)}$$

The information on the right hand side of this formula is all readily available from dynamic analysis results, and the optimization to determine the maximum value is performed in this case with the Excel program (the values for the MLE procedure compared with the traditional values are into Appendix e).

The following figures represent the fitting for the second floor acceleration data derived from the median peak floor total acceleration of each floor versus the associated damage limit state fragility curve graphs (Figure 4. 12-Figure 4. 14).

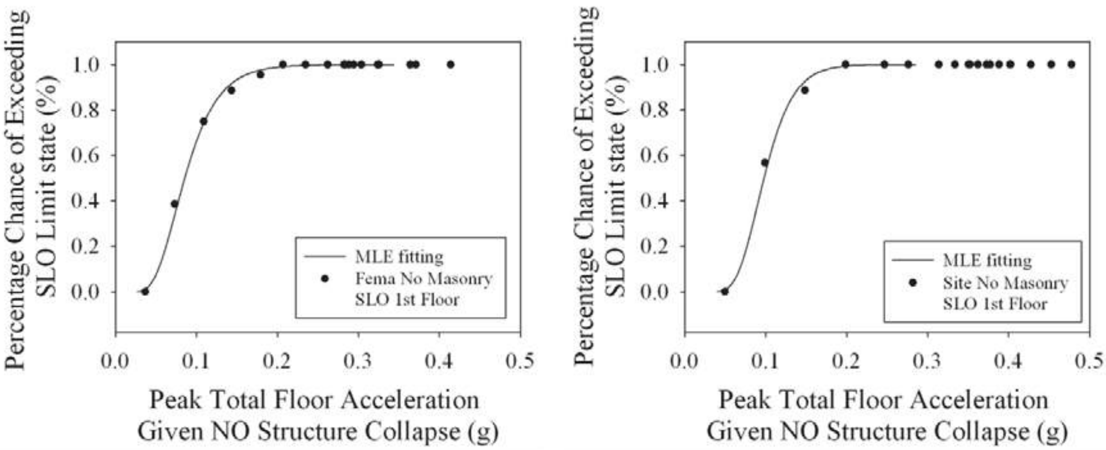


Figure 4. 18 Peak total top floor acceleration fragility curve for the serviceability limit state (FEMA record set on the left and Site Specific record set on the right).

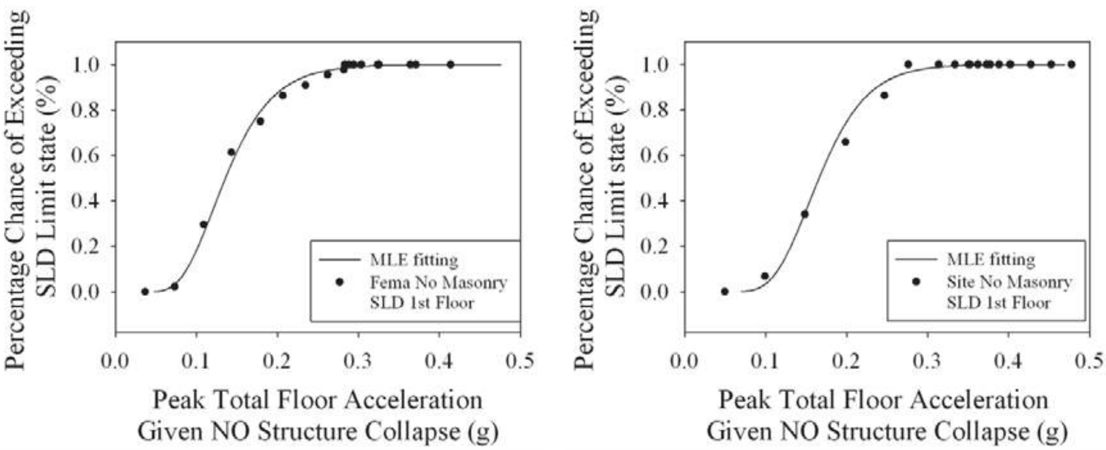


Figure 4. 19 Peak total top floor acceleration fragility curve for the damage limit state (FEMA record set on the left and Site Specific record set on the right).

4.3 Non-structural components

The non-structural components within a facility are all those parts of a building that do not lie in the primary load-bearing path of the building itself and are not part of the seismic resisting system (Figure 4. 21). The number and the complexity of non-structural systems and components of a building far outnumber its structural components.

They are connected to the floors of the building, which are not, however, part of the carrier system. The list of non-structural components is nearly endless and is constantly evolving as new technologies alter our built environment. Many agencies and organizations have scheduled and organized non-structural components depending on the building typology, outlining three main categories:

a) architectural components;

b) building utility systems;
c) building contents.

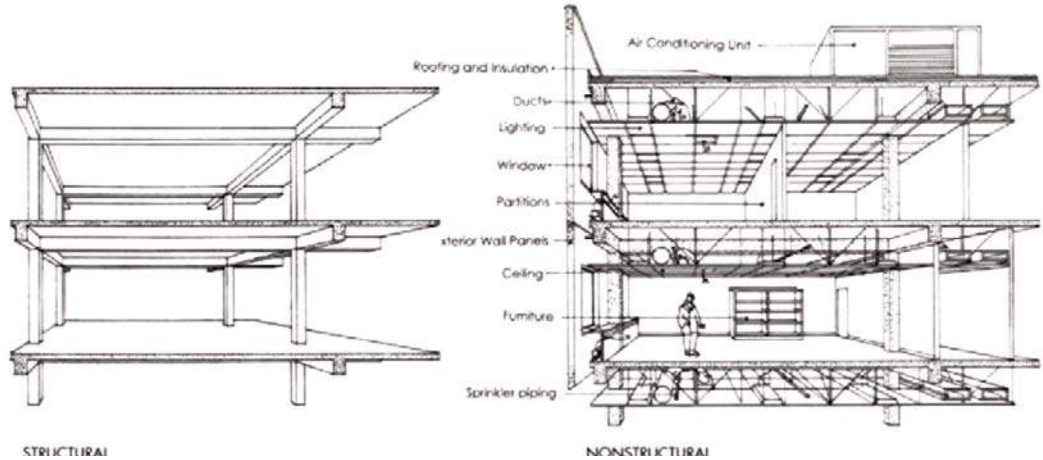


Figure 4. 20 The basic structural system (left) and the non-structural components (right). Picture extrapolated from FEMA

The first category includes: partitions and ceilings, windows, doors, lighting, interior or exterior ornamentation, exterior panels, veneer and parapets. The second group includes: mechanical and electrical equipment and distribution systems, water, gas, electric and sewerage piping and conduit, fire suppression systems, elevators or escalators, HVAC systems and roof-mounted solar panels. The latter category comprises: computers and communication equipment; cabinets and shelving for record and supply storage; library stacks; kitchen and laundry facilities; furniture; movable partitions; lockers; and vending machines. An example of grouped NSCs is fully presented in Appendix a.

Non-structural components are far from being of minor importance, both in economic terms and in terms of continued service: past experiences like the earthquakes of Christchurch in February 2011, and L'Aquila in November 2009, showed that a significant portion of the functional interruption can be attributed to non-structural components and contents' damage, resulting in a safety hazard also hampering the safe movements of evacuating occupants and of rescuers entering the building. Such damages to non-structural components can occur at seismic intensities which are much lower than those leading to a structural damage. Nevertheless they can lead to similar hazards, especially due to the multiple effects that earthquake ground shaking causes on non-structural components, for instance: inertial or shaking effects causing sliding, rocking or overturning; the building deformation interconnected with the failure of non-structural components; the separation or pounding between separate structures which may damage non-structural components crossing each other; the interaction between adjacent non-structural components like the change of their original location (this is particularly relevant for hospitals since the architectural disposition is frequently modified and the building can undergo further restoration over time).The latter characteristic is crucial for the performance evaluation of non-structural components in terms of fragility curves. Figure 4. 22 shows the schematic representation of the elements which have been taken under consideration in this study.

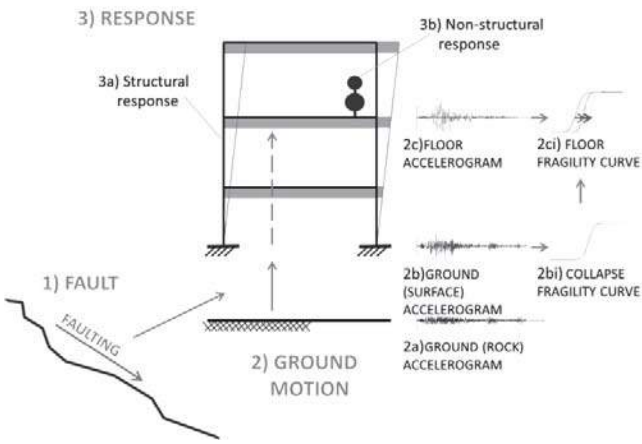


Figure 4. 21 Schematization of the behaviour of the ceiling of a building during an earthquake.

Compared to structural components and systems, there is much less information available and giving specific guidance on the seismic design of non-structural building components for multiple-performance levels.

4.3.1 Identified non-structural components within the emergency department (ED) of the Sansepolcro hospital

Among the many non-structural components which generally contribute to the hospital functionality, this study identifies some particularly important elements of the emergency department. The general architectural plan in Figure 4. 23 show the most important elements, while specific non-structural components are pinpointed in the following architectural plans and photos.

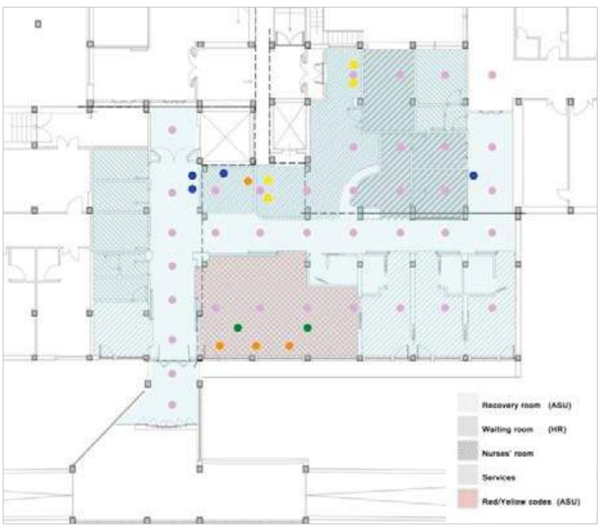


Figure 4. 22 Non-structural components location into the emergency department.

It is evident that the massive presence of non-structural components may jeopardize the emergency department in all its extension. Within the general location of non-structural components, the infill-walls are not taken into account; although they are considered as secondary elements, they are able to influence the seismic behaviour of the structure. Therefore in an accurate analysis they may be introduced as part of the structural model. The non-structural elements taken into account here are (see also the following Figures Figure 4. 24 - Figure 4. 27):

- Surgery Lamp;
- Multi-parameters monitor;
- Electrocardiogram;
- Microscope;
- Endoscope;
- Defibrillator;
- Surgical Aspirator;
- Pulmonary fan;
- Autoclave;
- Cabinets;
- Technical cabinets;
- Electronic control units;
- Suspended ceiling system.

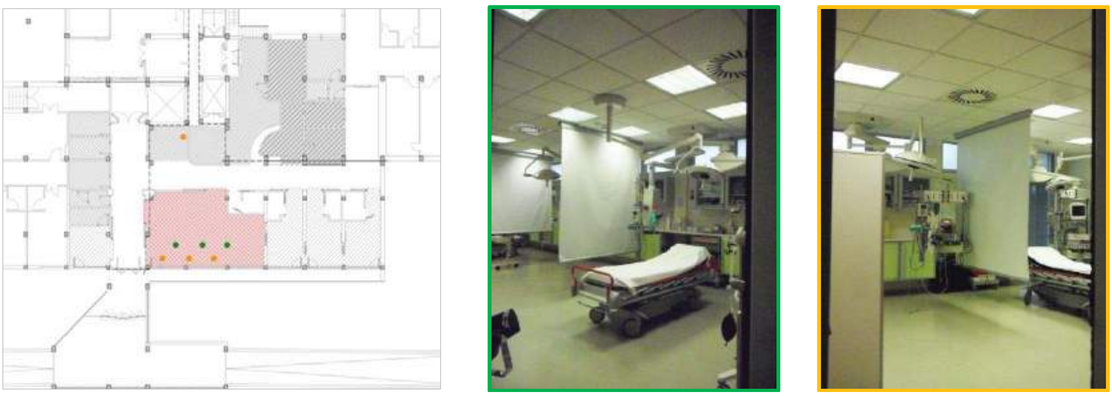


Figure 4. 23 Non-structural components inside the emergency room: Surgery Lamp, Multi-parameters monitor, Electrocardiogram, Microscope, Endoscope, Defibrillator, Surgical Aspirator, Pulmonary fan, Autoclave, cabinets.

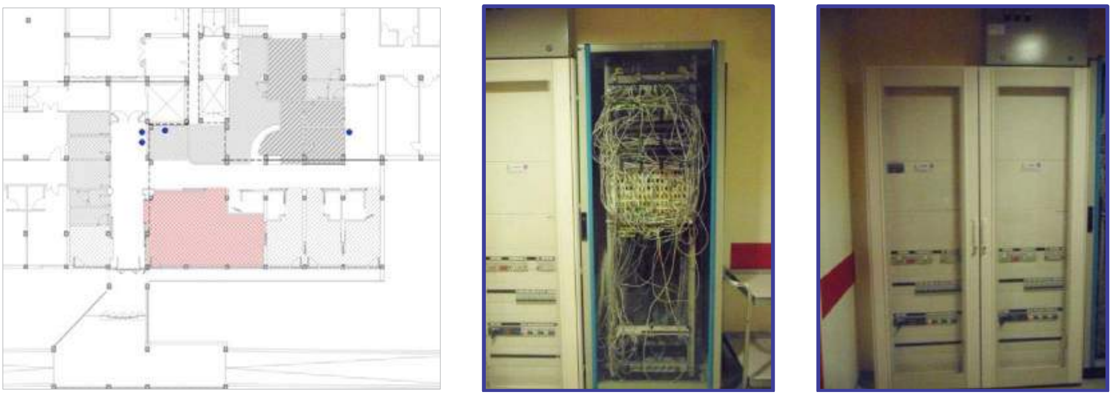


Figure 4. 24 Non-structural components: technical cabinets.

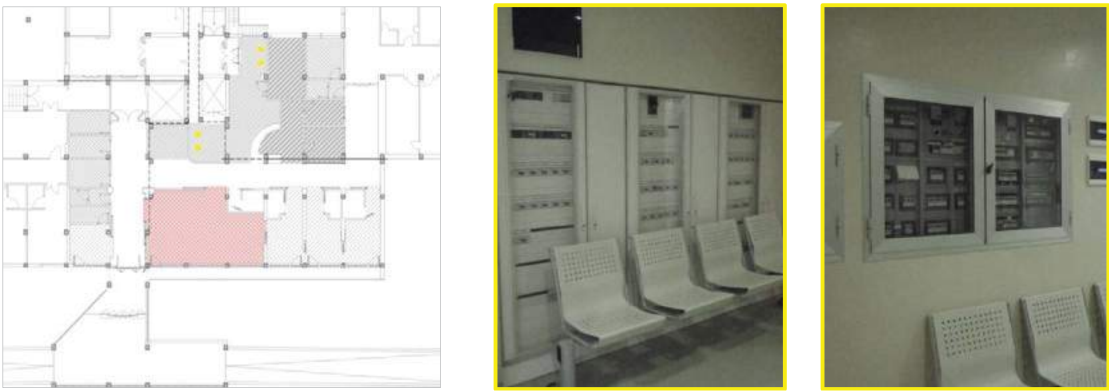


Figure 4. 25 Non-structural components: electronic control units.

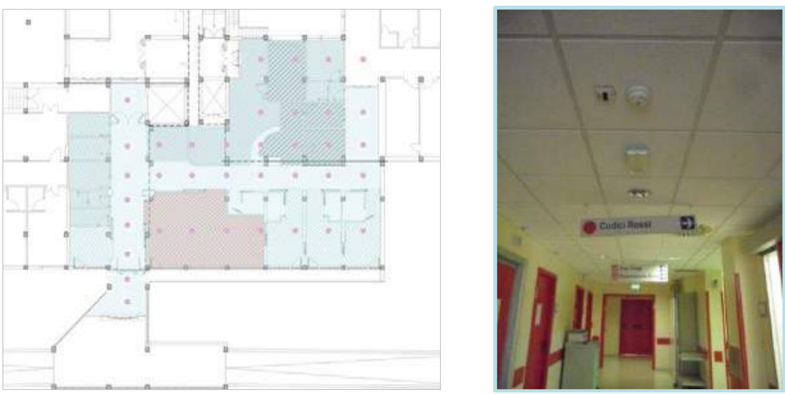


Figure 4. 26 Non-structural components: suspended ceiling system.

The latter non-structural component extends for all the emergency department area, and it was chosen as the main case study for the non-structural part in the emergency department. Suspended ceiling can lead many failures in case of an earthquake: for instance during the 1987 Whittier Narrows earthquake as well as during the most disruptive recent earthquake in New

Zealand (2010) most of the building had to be evacuated due to damages related to this non-structural element[5].

4.3.1.1 Suspended ceiling system into department

This section mainly compares the capacity of this unit's ceilings with different levels of seismic demand in order to evaluate the healthcare facilities response to earthquakes. This procedure relies on data obtained from tests performed at the Canterbury University in Christchurch, and guidelines for installators provided by the construction agencies. This expedient was obligatory given the lack of data on this kind of component.

Despite several studies on this subject, neither robust fragility data for suspending ceiling systems nor proven strategies to increase the seismic strength of suspended ceiling systems have been provided. Till now most research on suspending ceiling has focused on the full scale testing of this system on shake tables, while very little research has been accomplished regarding the capacities of individual sections within the ceilings. To the first category belong the tests carried out by Anco Engineers Inc. (1983), Shephard & Shepphird (1990), and Amstrong World Industries Inc. in 1993. Analytical shake table studies were conducted by Yao (2000), Badillo-Almarez et al. (2007), Gilani (2008), Matsuoka et al. (2008), and Magliulo et al. (2012) who by means of a performance analysis studied the behaviour of non-structural components under seismic actions. In 2012 Ryu et al. performed a full scale dynamic testing on different surface size of ceilings at the University of Buffalo (within the UB-NEES program).Other researchers such as Hoehler et al. (2012) developed fragility functions, while laboratory tests on singular components of suspended ceiling system to derive fragility curves were carried out by Paganotti (2010).

This section mainly compares the capacity of this unit's ceilings with different levels of seismic demand in order to evaluate the healthcare facilities response to earthquakes. Despite the fully extension of the suspended ceiling system in the area, only some specific rooms of the emergency department are considered:

- the Emergency Room (ER), where severely injured patients are located;
- the Short Intensive Observation Room (OBI), where patients needing in-depth examination can wait without being disturbed.

In the following paragraph the compositions and the characteristics of the suspended ceiling system are defined.

4.3.1.1.1 Suspended ceiling system composition

Suspended ceilings typically consist of a grid system, hanger or bracing wires, perimeter supports and lay-in tiles. The grid system investigated in this study is made up of hot-dipped galvanized inverted T-sections that form square or rectangular shaped frames for supporting the tiles. They are two main categories: main tees and cross tees. Main tees come in higher capacity and bigger

[5] Much current literature (Tally ,1988; EERI, 1990;Griffin & Tong 1992; Freeman et al. 2001; FEMA 2004; Lo et al. 2004; Chrstopoulos et al. 2001; Magliulo et al. 2012; Paganotti 2010) discusses – with plenty of concrete examples – the most common damages that occurred during recent earthquakes.

length, while cross tees provide the transverse restraint for the main tees. The ceiling systems can be either "perimeter fixed" (surrounding confinement) or "floating" (not connected to the perimeter but supported by means of diagonal bracing wires to the top floor). In the first case inertial forces on the ceiling are transferred to perimeter connections, whereas in the second system braces provide the resistance. The seismic force – which depends on the weight of the ceilings and the horizontal earthquake acceleration – activates a horizontal in-plane diaphragm action in both directions; while the vertical component of an earthquake excitation causes an out-of-plane vertical force (transverse to the plane of the ceiling).

The lengths of the rooms are indicated in Figure 4. 28, which also shows the direction of suspended ceiling elements, the main tees (MT) and the cross tees (CT).

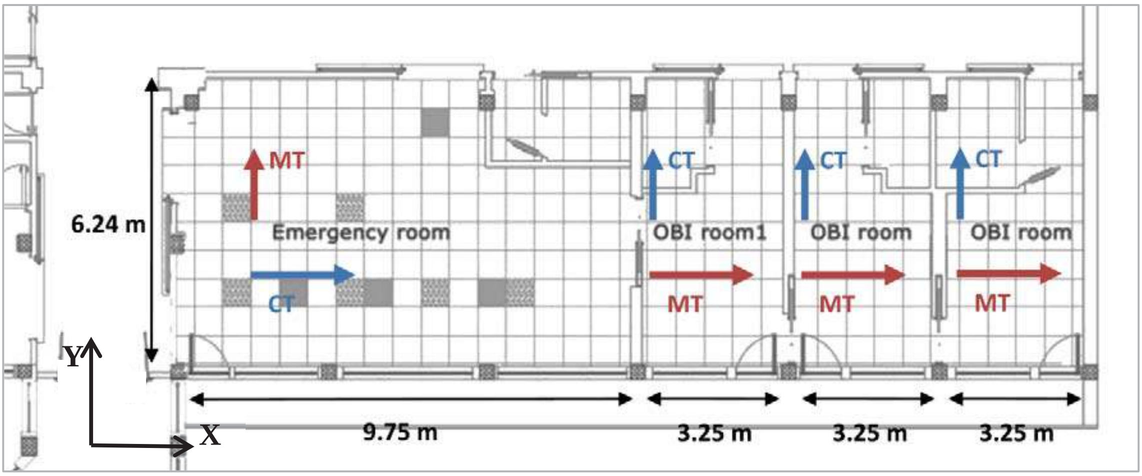


Figure 4. 27 Dimensions and direction of main tees (MT) and cross tees (CT) in different rooms

The area of major interest is the ER Room, both due to its the size and its functions. The areas and perimeters of the rooms are listed in Table 4.5. Since the ER and OBI rooms are located at the same level of the building, their seismic demands are the same. However, due to their difference in size, the overall capacity of the ceilings in different rooms will vary. It is expected that the capacity of the ceiling in the ER room will be lower than in the OBI rooms, making the first more vulnerable during an earthquake.

Table 4.5 Size of the different rooms in the Emergency Department

ZONE	AREA [M^2]	PERIMETER [M]
STRUCTURAL UNIT AREA	189.8	62
EMERGENCY ROOM (without toilet)	53	32
OBI ROOM1 (without toilet)	14	18
OBI ROOM2 (without toilet)	14.5	18
OBI ROOM3 (without toilet)	18.5	14

Due to the dearth of information about the components and the characteristics required for the derivation of fragility curves, assumptions have been made about the directions (MT and CT) and the type of elements used. It is to be noted that the assumptions made regarding the capacity of the system investigated has a considerable impact on the outcome. The onsite observations show that the characteristic of the ceiling components installed in the hospital display a satisfactory proximity to the ceiling system studied by Paganotti (2010). Further evidence by closely reviewing the actual size and mechanical properties of the ceiling components is required to establish their actual capacity.

4.3.1.1.2 Description of the suspended ceiling used

The installed ceiling is defined as a sub-ceiling, having a cavity space between the fixing base and the basic ceiling. The system used in the hospital is perimeter-fixed, provided by Knauff and consisting of different elements as shown in Figure 4. 28. The primary structure is composed of different elements: suspension flanges, spiral suspensions and regulation springs. The hanger wires are fixed through a hole in the bulb of the section and wrapped around themselves, spaced in accordance with the manufacturer and project conditions required. A metal grid (distribution class) is suspended from the underside of the floor above and is made up of long and short intermediate tees. The panels installed in the hospital have a dimension of 0.59x0.59x0.018 meters and weigh 4.56 kg each. These elements are modular and removable and hide the space between the metal grid on which they are seated and the floor above.

N.1: tees PP 24/38 (primary tees)

N.2: tees IC 24/38 (short intermediate tees)

N.3: tees IL 24/38 (long intermediate tees)

N.4: suspensions: suspension flange (FS); spiral suspension (SS42 90); suspension x PP (SPP), regulation spring (MRU).

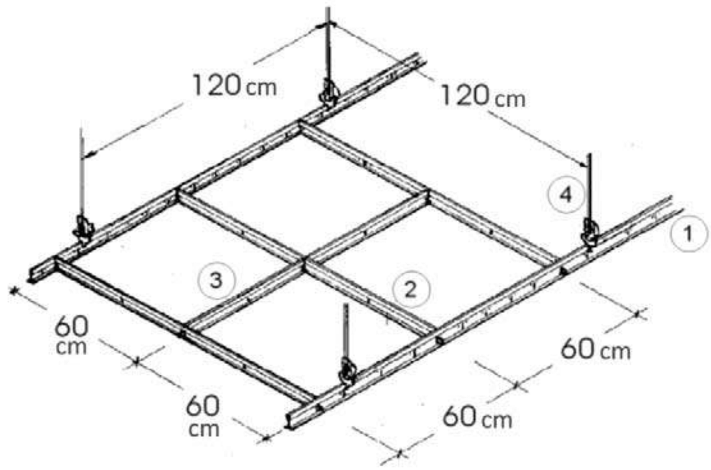


Figure 4. 28 Schematic ceiling components installed in the emergency department.

4.3.1.2 The cabinet non-structural component

No many data are available for assessing non-structural components and the generation of their fragility curves is the rare product of a complex laboratory and analytical work. However, thanks to the work by Cosenza et al. (2014), another non-structural component could be added to this study: the cabinet.

Cosenza et al. carried out several experimental tests on hospital building contents and established the limit states for a typical healthcare room. In particular, their experiments assessed the influence of the distance between the cabinets and the wall. This study takes into account the last analytical manipulation representing the fragility curve of a cabinet, considering variations in mass and space between the cabinet and wall (Figure 4. 31).

To realistically complete the present case study, these data can be included as representative for the cabinets.

4.3.2 Seismic vulnerability of suspended ceiling system

To assess the performance of the ceilings, the capacity of the suspended ceiling systems installed needs to be compared with the seismic demand on the floors of the hospital building. Due to the scarcity of available data, assumptions have been made regarding the capacity of the system. Following quantitative comparisons, the system elements used in the hospital have been compared in terms of size and material. Since the components of the system provided from the hospital resulted of same size and material, it has been concluded that the ceiling system used in the emergency area is similar to the suspended ceilings manufactured in New Zealand, which were tested in a previous study at the University of Canterbury (Paganotti 2010). Therefore, it has been concluded that the fragility curves resulting from these experiments could be used to represent the capacity of the ceilings in the current study.

The ceilings located in the ER area were designed on the base of the guidelines provided by the manufacturers of the system, and the allowable size of the main and cross tees were checked. Fragility curves were then derived for the most critical components of the system – Rivets on both tees (R3.2mm), connections in Cross tees (CT-con) and splices in Main tees (MT-Sp) – with floor acceleration as the intensity measure. Since the system is considered a failure as soon as any of its components reaches its capacity, it is possible to assume that the weakest element governs the capacity of the whole. Accordingly an envelope curve, as shown in Figure 4. 29, was drawn on the far left side of the graphs: this curve indicates the overall fragility of the ceilings. The enveloping fragility curves were compared with the demand acceleration resulting from the numerical analyses of the hospital. For the ER Room, the envelope is considered as the curve of the weakest element (see Figure 4. 29), while for the OBI Room, where the curves of the elements cross each other, an overall failure envelop is derived from the individual component fragility curves (see Figure 4. 30).

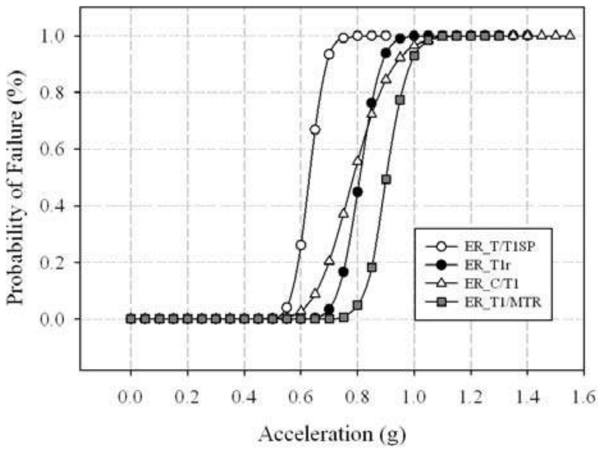


Figure 4. 29Fragility curves of the elements and envelop curve for the ER Room: rivets of the main tees (ER_T/T1SP); main tees(ER_T1r); cross tees(ER_C/T1) and rivets of the cross tees(ER_T1/MTR).

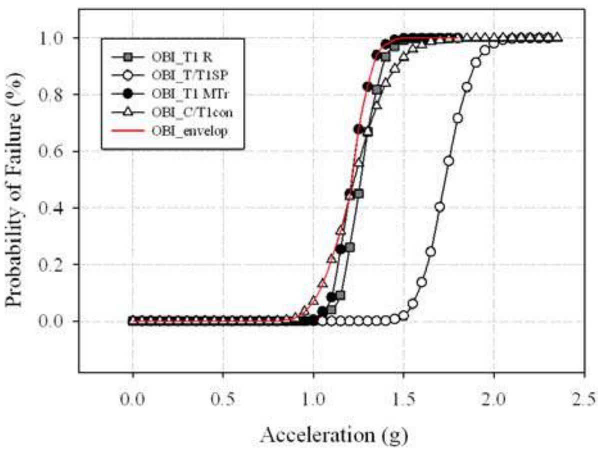


Figure 4. 30 Fragility curves of the elements and envelop curve for the OBI Room: main tees (OBI_T1R); rivets of the main tees(OBI_T/T1SP); cross tees (OBI_T1MTr); rivets of the cross tees (OBI_C/T1con); and envelop curve (OBI_envelop).

4.3.3 Seismic vulnerability of cabinet elements

The cabinet non-structural component is considered for the overturning limit, due to the lack of data in other damage limit states, and because the change of position does not cause big problems into the emergency room. Other damage limit states could be considered for example in the pharmacy, where medicine faults can cause greater consequences. Figure 4. 31 illustrates the fragility curve derived by Cosenza et al. which for the present work have been assumed as reliable data.

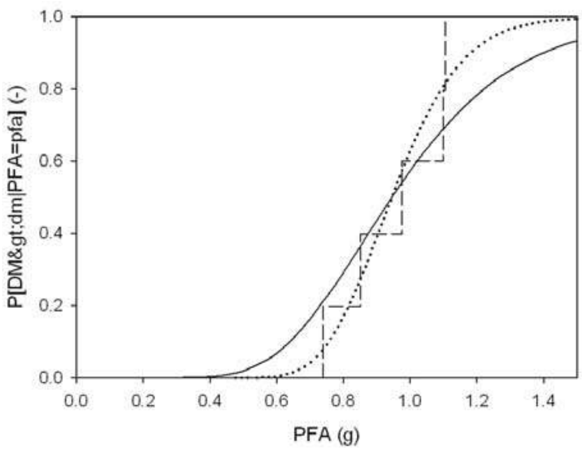


Figure 4. 31 Last fragility curves analytically derived from the laboratory tests at the University of Naples (Cosenza E. et al.) for the sample cabinet non-structural component.

4.4 Organizational aspects of the case study

The emergency department is one of the most critical areas/functions of a hospital. For this reason, in order to provide the highest possible level of service to the community with the available resources, it is important to maximize the efficiency and the use of the emergency department. Accordingly the main aim is to carry out an investigation using the Discrete Event Simulation (DES) model, which permits to statistically verify the behaviour of the hospital by performing several cases of organizational setting and occurring events.

4.4.1 Computer simulation use

The use of computer simulations has been recently increasing, both regarding the design and the operational aspects of healthcare facilities. One of the reasons leading to this development is the desire to maintain a high level of quality of the services together with the decrease of the associated costs. In addition, thanks to the improvement of the software used, , the limitations of computational simulation models for practical applications of heath care, is no longer an insurmountable constrain.

Simulations are statistical experiments that allow us to model in detail the internal operation of a hospital. This kind of evaluation permits to answer “what if” questions before making any real change; in this sense, computer simulations also allow the optimal use of healthcare resources subjected to various constraints.

A large amount of studies in healthcare industry are the result of such simulations. Cote (1999) developed a simulation model for performance evaluation in an outpatient clinic. He investigated the influence of examination room capacity and patient flow on four performance measures: room usage, room queue length, occupancy of the examining rooms and patient flow time. Cahill & Render (1999) used computer simulations to analyse the flow of patients through the intensive care unit (ICU), telemetry and medical floor beds, and to assess the effects of the planned phased construction. Weng & Houshmand (1999) made use of computer simulations to find the best staff size able to maximize the patient throughput and to minimize patient flow time and cost. Fitzpatrick et al. (1993) used a simulation model to assess the performance of different scheduling for operating rooms based on throughput, waiting time, and facility utilization. Iskander & Carter (1991) developed a simulation model to simulate the operations of the same day care unit (SDCU) and to evaluate the system performance under various patient load conditions. The model was used to successfully identify the facility needs at the SDCU in order to optimize patient care and accommodate projected growth in patient volumes.

4.4.2 Organizational modelling approach

The objectives of this study – which relies on the Discrete event simulation model – are: (1) to assess the level of the emergency department chosen as the case study in normal condition; (2) to determine the impact of a patient inflow due to a seismic shock; (3) to assess the influence of increasing resources following the existing emergency plans; (4) to assess the response of the structure in case of different failures due to structural and non-structural components in an emergency. According to Law & Kelton (2000), a systematic simulation steps involves the following steps:

- Comprehension of the objectives and study planning;
- Assumption of the performance measures;
- input and analysis data collection;
- simulation model construction;
- model validation;
- simulation of scenarios;
- outputs interpretation;
- to draw conclusions;
- resilience assessment.

4.4.3 Emergency department functioning

The emergency department (ED), whose general location in the hospital campus is shown in Figure 4. 32 and which is illustrated in more detail in Figure 4. 33, Figure 4. 34, and Figure 4. 35, is dedicated to the emergencies and urgencies which need dedicated spaces (see Figure 4. 37 and Figure 4. 38); moreover, it makes use of spaces dedicated to the short observation of those patients needing more time to have their conditions checked (see Figure 4. 36).

The access to the emergency rooms and consequently to medical cares, does not depend on the relative time different patients arrive at the hospital, but on the severity of their health condition. In the case under consideration, this procedure is evaluated through a practice called “triage” (Figure 4. 35), which allows to assign to each patients, upon their arrival, a degree of urgency represented by a “colour code”.

Such a practice is used in Italy by those healthcare structures that reach more than 15000 entries a year. Even though our hospital does not reach this amount of entries, the same procedure has been adopted also in the current case study since the personnel knows this practice and employs it in order to fasten the emergency department procedures.

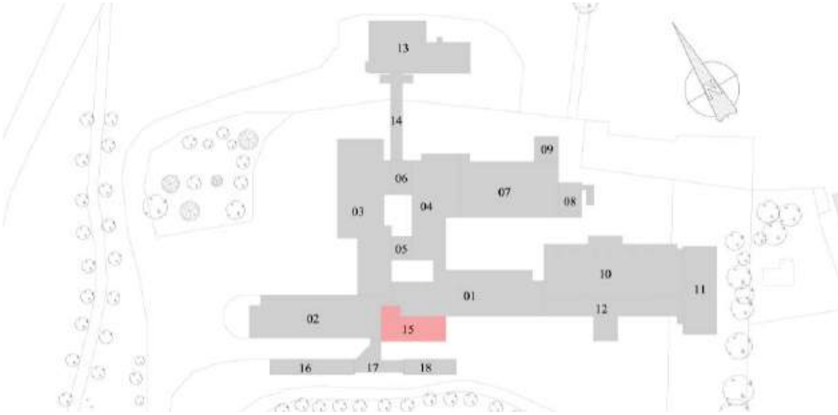


Figure 4. 32 The Emergency Department (ED) location within the other structural units of the hospital campus.

Figure 4. 33 Inner space of the ED: corridor.

Figure 4. 34 Inner space of the ED: corridor toward the OBI rooms.

Figure 4. 35Inner space of the ED: triage desk.

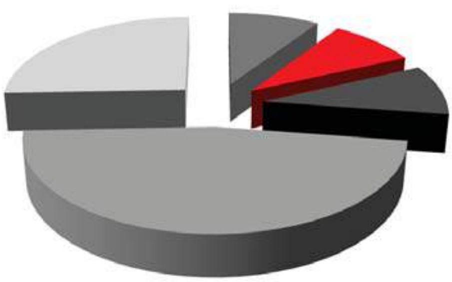
Figure 4. 36 Inner space of the ED: OBI room.

Figure 4. 37 Inner space of the emergency room (ER): the yellow code beds.

Figure 4. 38 Contents of an emergency room (ER).

Figure 4. 39 shows the rate of patient entries in the province of Arezzo, where the case study is situated. As briefly described in par. 4.1, the Tuscan hospital located in Sansepolcro belongs to the third category. This categorization is due both to its dimensions and to the number of recovery beds, i.e. the population to which it must take care of. The graphs illustrate the percentage of entries in comparison with other hospitals belonging to the same regional health framework.

As evident from Figure 4. 39, the number of entries in the emergency department of the case study hospital is less than 15000 people; the same it happens for the Casentino and Valdichiana hospitals; on the contrary, the structures of Arezzo and Valdarno, serve a greater number of patients. Although, the hospitals with less than 15000 entries a year do not provide the triage service, the Sansepolcro hospital train its personnel to this service that is considered as an essential one for the good treatment of patients. Accordingly the current study reports data that could have been drawn from any other "normal" hospital.



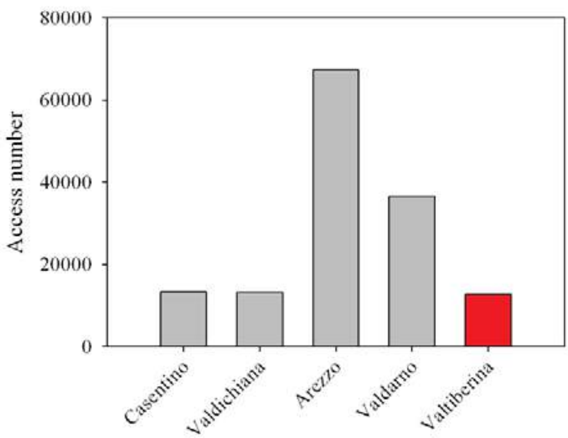
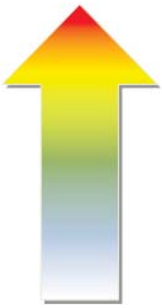


Figure 4. 39 Number of entries in the year 2012for the case study hospital among the other hospitals in the region network.

In Italy there are different colour codes to be assigned to a patient at the *triage* moment. Normally there are four different colour codes, but the Tuscany Region added a new one in order to give priority to urgency and emergency patients. When a patient arrives to the reception, the nurse starts the procedure in order to identify the most appropriate colour code on the base of the definitions listed in Table 4.6:

Table 4.6 Colour codes definition



RED CODE (RC) – emergency	IMMEDIATE ACCESS: the patient is in imminent DANGER of life.
YELLOW CODE (YC) – urgent	QUICK ACCESS: not deferrable urgent, potentially life-threatening condition.
GREEN CODE (GC) – urgent deferrable	Urgency deferrable, the PROBLEM is acute, but non-critical.
BLUE CODE (BC) – low emergency	The problem is acute, but of little clinical relevance.
WHITE CODE – not urgent	The problem is not acute, MINIMUM of relevance.

Patients who are given the Major (yellow and red) Codes come in through the driveway entrance of the emergency department: they gain a rapid access by ambulance or by car. . On the contrary, the Minor Codes can reach the acceptance area through the north-west located crossover. On their arrival all patients have to register to get the code assigned by the nurse on duty: this does not apply to Red Codes that skip the queue and with immediate priority enter the emergency rooms.

Once they are assigned the colour code, patients have to follow a specific procedure according to their own colour code. Minor Codes wait in the waiting room (WR) before entering the clinic for minor codes (ACM – *Ambulatorio Codice Minore*): here they are seen by a doctor who allocate them to the Discharge (DISCH) or to the short intensive observation rooms (OBI – *Osservazione Breve Intensiva*), depending on the outcome of the medical examination.

Major Codes, after the triage (directly made by the hospital personnel or by other medical personnel) pass into the emergency room (*Sala del Pronto Soccorso*) where they are examined by a nurse (and often by another medical figure – the OSS – *Operatore Socio Sanitario*, who helps her during the medical treatment), and then by a doctor.

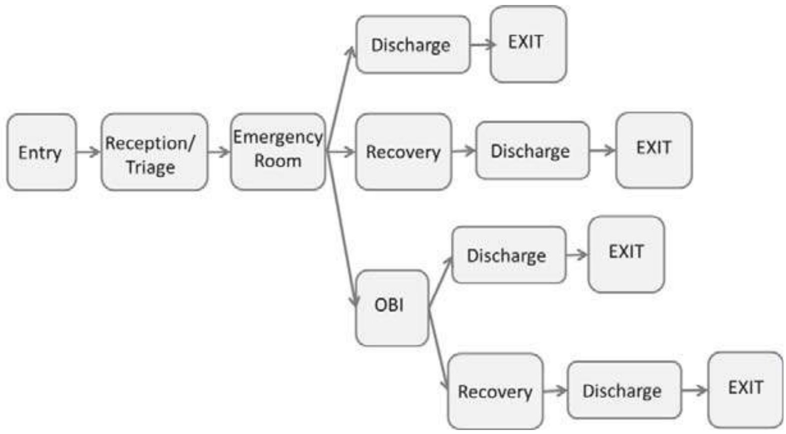


Figure 4. 40 Flow chart of "Major Codes" patients

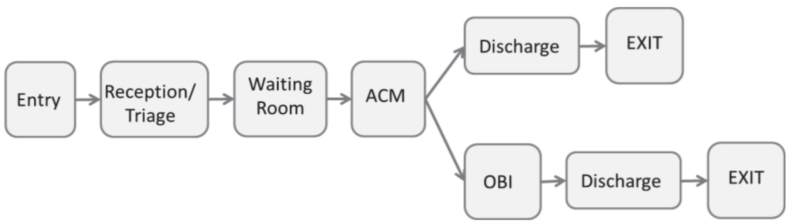


Figure 4. 41 Flow chart of "Minor Codes" patients

Depending on the patient's conditions, the hospital personnel can decide to move the patient to the OBI, the Recovery area or the Discharge. The patients' flow charts and the various operations in different locations follow the diagram represented in Figure 4. 41 and Figure 4. 40.

Patients who arrive at the Emergency department of the Sansepolcro hospital are rarely Red Codes: this hospital belongs to the Tuscan hospital network and therefore people in critical conditions are generally transferred to other hospitals by ambulance. However, the access of Red Codes cannot be excluded a priori : for this reason – in the predicted emergency scenarios– they have been included into the organizational model. In addition, the hospital has a room dedicated to infected patients: in case all other rooms are occupied this room is used as an alternative OBI room.

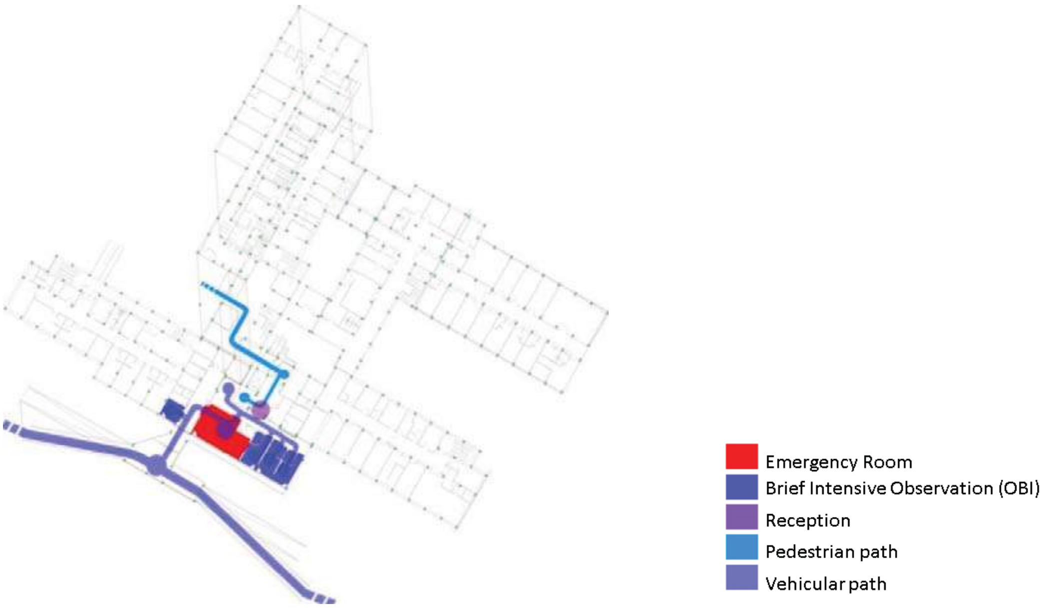


Figure 4. 42Patients' paths and main locations of the emergency department in the normal scenario

4.4.4 Procedures and data analysis

The data to set the simulation model were collected on the base of the patients' rate of arrival, the various types of treatments for different color-codes, the resources and the time necessary for carrying out the procedures associated with the health service, the hospital personnel's working hours and the nurses and doctors' activities. Some of the data were collected through face-to-face interviews with key hospital personnel, while other data (like the patients' rate of arrival and the duration of the cycle of services provided) were collected from different existing electronic databases. The data refer to a trimester (January-March 2012).

Among the main data for the construction of the model there are the patients' flow charts and the data regarding the medical staff. Number of resources (doctors and nurses) and work time, with the locations that the resources can visit are presented in Table 4.7, where the scheduled work time and the locations interested by each resource are specified, such as the medical personnel confirmed during the periodic meetings.

The model accounts for the unidirectional or bidirectional paths associated with each resource. In the construction of the model it is possible to allow or not allow the entrance of a specific resource in the specific locations. In this case it is assumed for the medical personnel to work through the entire emergency department, while the "other" resources (in particular the transporters) are limited to some locations (e.g. it is not permitted the transit through the OBI rooms and the ACM room). The shift rotation of nurses and doctors covers the whole day since the emergency department constitutes a 24 hour service for the community; while other medical personnel such as the OSS – that are support (but not indispensable) personnel – have reduced schedules.

Table 4.7 Nnumber and scheduled work time of Emergency department personnel.

RESOURCES	N°	SHEDULED WORK TIME	PATHS AND LOCATIONS
NURSES	2	7-13 13-21 21-7	Entry, Reception, ACM, Waiting Room, Recovery, Discharge, Emergency Room, OBI Room
OTHER MEDICAL OPERATOR (oss)	1	1-13 13-21	Entry, Reception, ACM, Waiting Room, Recovery, Discharge, Emergency Room, OBI Room
DOCTORS	2	h24	Entry, Reception, ACM, Waiting Room, Recovery, Discharge, Emergency Room, OBI Room
OTHER	2	h24	Entry, Reception, Emergency Room, Discharge

In normal scenarios OSS operators help the nurses to take care of the patients before they are seen by a doctor; moreover, they can help the patients to move from one location to another; however, they are not allowed to make the triage: this operation is strictly reserved to nurses and doctors who have been trained for that. Accordingly even in case there are no OSS workers the personnel of the Emergency Department can fulfil their duties.

Table 4.8 resumes the time needed by the hospital personnel to perform standard medical operations in different locations.

Table 4.8 Time needed for triage and medical procedures by different colour codes in different locations

	ENTRY	TRIAGE (Reception)	EMERGENCY ROOM	OBI	OTHER BEDS	RECOVERY	ACM	WAITING ROOM
RED CODES	X	around 2-5 minutes	around 5-10 minutes with nurse and 10-20 minutes with doctor	-	-	to ask	-	-
YELLOW CODES	X	around 2-5 minutes	around 5-10 minutes with nurse and 10-20 minutes with doctor	from 4 hours to 48 hours	-	to ask	-	-
GREEN CODES	X	5-10 minutes	-	-	30-90 minutes	-	10-20 minutes	?
BLUE CODES	X	5-10 minutes	-	-	-	-	10-15 minutes	?
WHITE CODES	X	5-10 minutes	-	-	-	-	5-10 minutes	?

It is worth to notice that the triage of the Major (red and yellow) Codes needs less time than that of the minor codes: this is due to the urgent and serious conditions of the first category of patients whose triage is directly carried out by the medical personnel during the transfer to the hospital.

It is difficult to exactly estimate the time spent by a patient into the emergency room; there are, however, some mandatory medical operations requiring the time expressed in the table for the red and yellow codes. Additionally, patients are moved as soon as possible to the OBI rooms: this procedure is meant to reduce queues and to keep emergency beds free for other patients who need to be examined. For the same reason even the OBI beds have time restrictions: they can accommodate patients for no more than 48 hours. Then patients have to be discharged or recovered. The average time for a medical examination carried out by a doctor in the ACM ambulatory is 20 minutes, but it crucially depends on the patient's condition. Patients' arrival data are used to outline the daily arrival pattern in a month and the trends concerning the hourly arrivals in a day.. The identified empirical probability distribution is used to simulate the patients' arrivals in the model. Figure 4. 43 and Figure 4. 44 show the probability distribution of daily patient volumes, as well as the hourly percentage of patients' arrivals at the Emergency department.

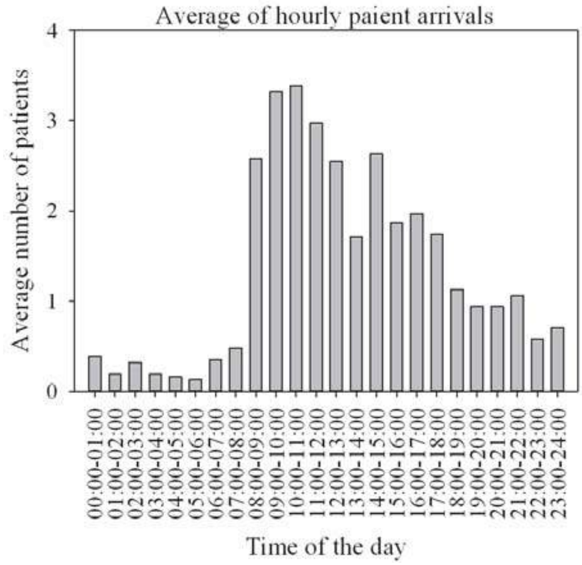


Figure 4. 43 Average of hourly patient arrivals

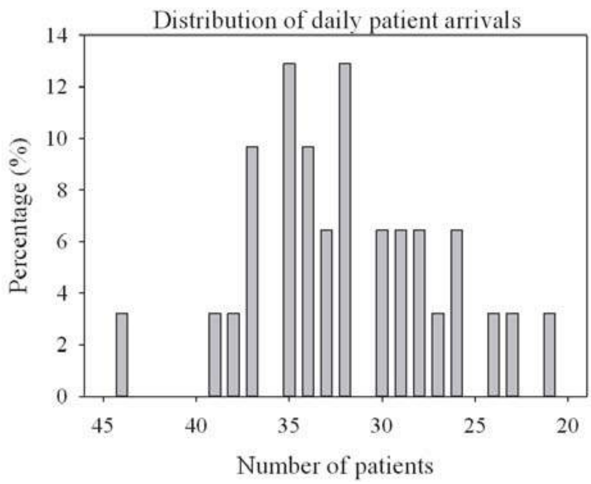


Figure 4. 44 Distribution of daily patient arrivals

Figure 4. 43 shows that on 13 days out of 100 days, the number of patients arriving at the Emergency Department is 35. Figure 4. 44 shows that the number of patients arriving at the Emergency department after 9:00 am represents 10,41% of the total arrivals in a day.

As mentioned above, the five types of codes are divided into two major groups: the “Minor Codes” are assigned white, blue or green colour, while the “Major Codes” the yellow and red ones. This classification is made especially for planning purposes, both for the location management and for the hospital personnel involved. From a functional point of view the grouping of these two categories of patients takes into account the resources involved and is useful to estimate the timing of service delivery according to the emergency.

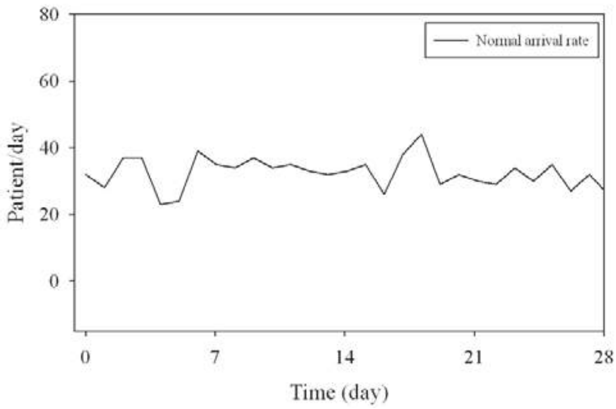


Figure 4. 45 Arrival rate at the Emergency Department in a normal scenario.

Besides, such classification permits to operate with the same distinction in a maxi-emergency phase, in which the Major Codes will have the highest priority, while the Minor codes will not be taken into care and will be transferred to other structures (for more details see par. 4.4.5.2.1).

In the emergency model additional data are taken into account, that is: the time duration of surgeries, the increased inflow of patients to the Emergency Department, the availability of more resources and the opening of Operating Rooms (ORs).

To capture the time required to transfer patients from one place to another, a matrix of distance has been prepared (see Table 4.9). This type of data are needed to estimate the time spent for transportation within the system. All distances are in meters and are derived from the architectural draws of the hospital. It must be noted that the path of the patients during the two scenarios (the normal and the emergency ones) varies widely: in the setting of normal operations all functions are carried out on a single level, while in a changing scenario, once the emergency procedures are activated, the patients are moved to the Operating Rooms located on the second floor. Only a vertical connection is installed between the two level by means of a dedicated ED elevator.

The model accounts for the possibility to simulate a downtime during the path, such as in case of damage occurred at the elevator.

Table 4.9 Distance matrix for the Emergency Department in a normal scenario

	ENTRY	RECEPTION	EMERGENCY ROOM	WAITING ROOM	ACM	OBI
ENTRY	0	20	9	25	25	25
RECEPTION	-	0	10	3	10	10
EMERGENCY ROOM	-	-	0	12,5	17,5	13
WAITING ROOM	-	-	-	0	12	12
ACM	-	-	-	-	0	18
OBI	-	-	-	-	-	0

* All distances are in meters, measured from layout drawing.

Moreover, in order to make the organizational model as realistic as possible, it is necessary to take into account the possibility for patients to “change colour”. This process occurs frequently in the Emergency department structure. As matter of fact, after the first triage, patients can be stabilized waiting for the doctor’s examination and further investigations (in case of Major Codes), or they can wait until they are examined by a doctor and then have to undergo further analyses. Therefore after the doctor’s examination (in the ER or the ACM ambulatory) or after further analyses the patient’s condition can get better or worse.

Data provided from the hospital database demonstrate a large rate of “changed colours”. For the simulation to be realistic, the model takes into account this possibility: since a patient . can be assigned to different colours according to his/her varying health condition, the model gives priority to those patients whose condition is getting worse. The model includes the percentages referred to each colour code shifting to another level of severity, according to the data provided by the health system. The patients’ paths, ideally shown in Figure 4. 41 and Figure 4. 40, change significantly and follow the diagrams represented in Figure 4. 46.

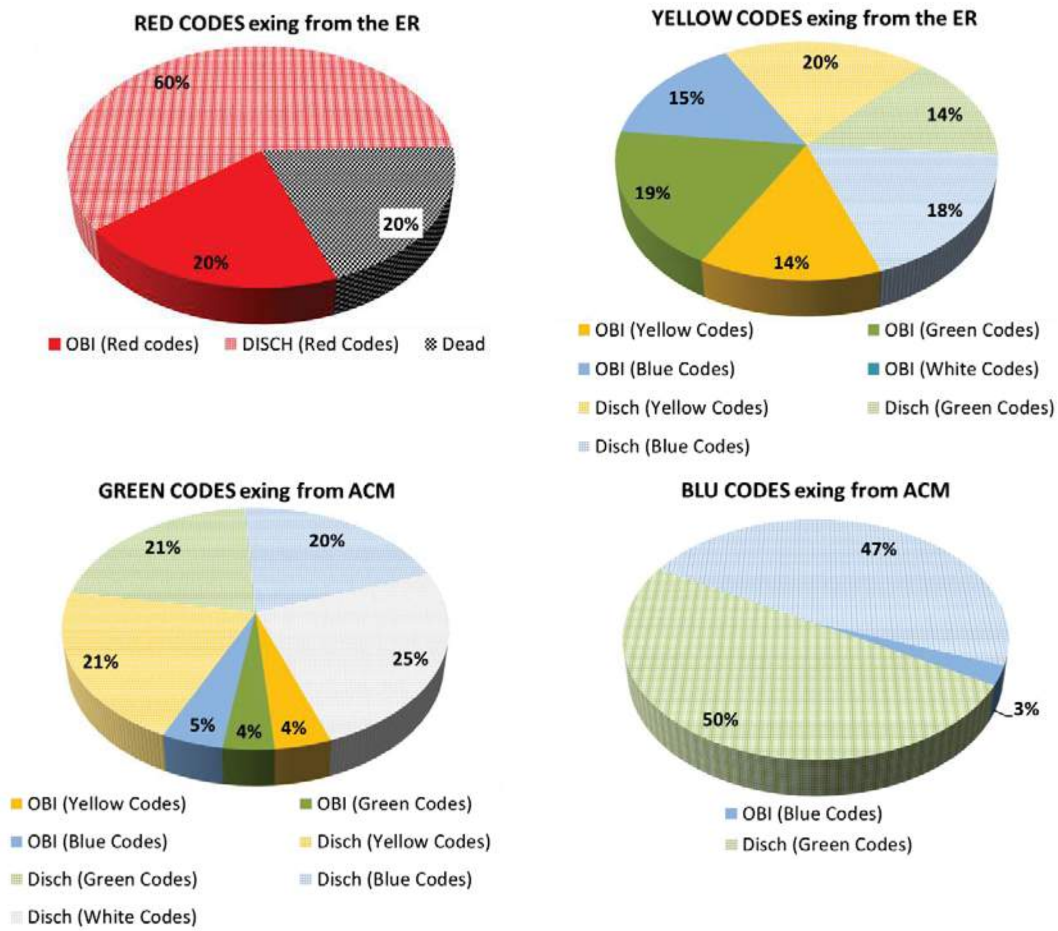


Figure 4. 46 Percentages referred to each code taking into account the possibility for a patient to change his/her colour after having been examined in the Emergency room (Red and Yellow Codes) or in the ACM ambulatory(Green and Blue Codes).

These data indicate that patients can be assigned different colours after the first medical examination (by a doctor), or after further analyses. For instance a patient who has been given a green code can get another colour once his/her conditions have been verified. Otherwise in case the patient's condition remains stable the color code does not change. As a consequence, the patients' flow charts both for Major and Minor codes are not necessarily fixed, but can change due to further re-assignments.

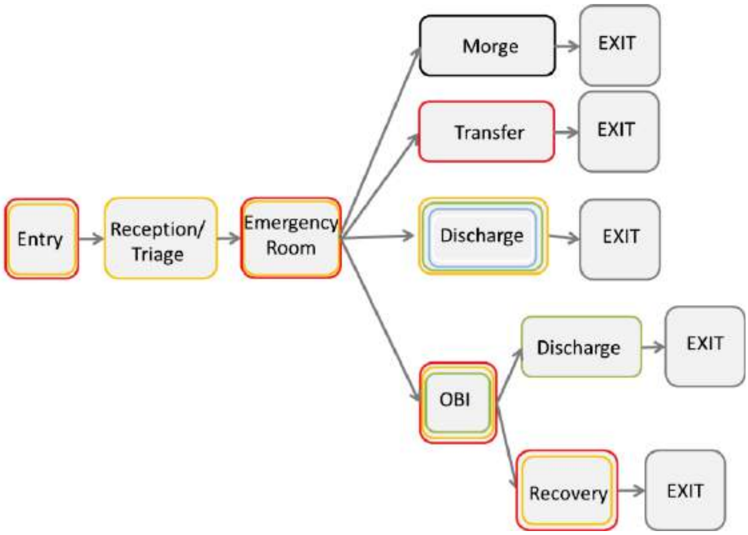


Figure 4. 47 Realistic patients' flow charts for Major Codes ("changed colours" included).

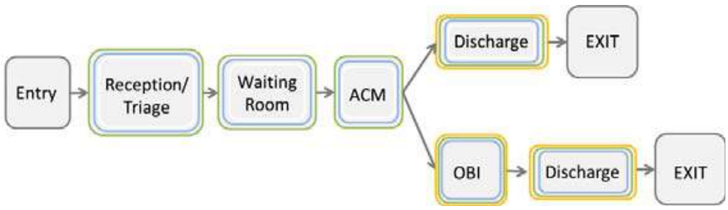


Figure 4. 48 Realistic patients flow chart of Minor Codes, including "change colour".

4.4.5 Simulation model description

The activities performed in the ED can be summarized as follows: to make the triage; to transfer the patients to the Emergency room, to move the Major-Codes from the Emergency room (ER) to the OBI rooms, to move the patients from the ER to the Recovery beds, to accommodate the walking patients from the Waiting room (WR) to the ACM ambulatory and/or to the OBI beds. Given these activities as well as the routes, process times, transportation times and staff's schedules, an animated simulation model is able to show how patients are taken care of in the ER, ACM, OBI rooms and other beds.

The dynamic nature of the patients' flow towards the hospital is captured by altering the time between their arrivals at different times during a day. The total number of arrivals in a day follows the distribution shown in Figure 4. 44. Parameters and attribute values are assigned upon arrival for each patient. The most important attribute value – the patient group (i.e. severity code) – is assigned according to the probability of occurrence of the cases shown in Table 4.10.

Table 4.10 Patient groups and probability of occurrence.

WHITE CODES	BLUE COSED	GREEN CODES	YELLOW CODES	RED CODES	DEAD E	tot
416	17	447	105	5	1	991
0.419	0.017	0.451	0.105	0.005	0.001	1
0.42	0.02	0.45	0.11	0.01	0.00	1.0 0
41.98%	**1.72%**	**45.11%**	**10.60%**	**0.50%**	**0.10%**	**1.0 0**

The patients are routed through a sequence of units according to their types (see Figure 4. 48 and Figure 4. 47). For each unit, the appropriate staff resources and schedules are incorporated according to both location and patient group. Process time in each unit is also generated according to the appropriate distribution at the time a patient arrives at the unit (see Table 4.11). When two or more patients attempt to enter the same unit, a FIFO (First In- First Out) rule is used. In case a unit is full, patients who need to be treated in that unit will experience a waiting time.

The transportation time is modelled with the help of the path network that captures the information in the from-to distance chart. Speeds of gurney movement (with and without patients) are specified.

The software model calculates and adds the movement time where applicable.

The following modelling assumptions have been made: each patient benefits from the priority assigned by his/her colour code; if a patients changes his/her colour code such a priority changes as well; all personnel of the same type have the same skill levels; the Brief Intensive Observation (OBI) rooms have limited capability (3+2 beds), as well as the Emergency room which accommodates one bed for the Red-Codes and two for the Yellow-Codes. The Waiting Room is considered as an infinity capability room.

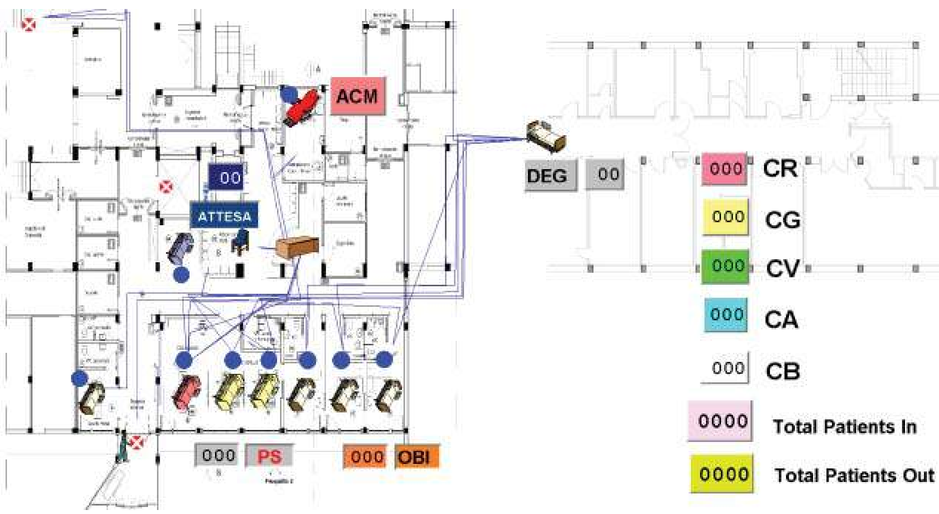


Figure 4. 49 Screenshot of the simulation model.

Equipment/instruments are not explicitly modelled: at this state there is some chance for explicit modelling in structural and non-structural elements. Their failure and/or damage is simulated by assuming the closure of the rooms that implies an inoperability to provide medical services.

The simulation model is capable of modelling the Emergency department for 24 hours a day. All entries (patients entering into ED), included those at night, are considered with full operation of the medical staff (with the only exception of the OSS operators). The simulation lasts one month.

Table 4.11 Mathematical distribution representing the time spent by the colour code patients in different locations of the model

	ENTRY	TRIAGE (Reception)	EMERGENCY ROOM	OBI	OTHER BEDS	RECOVERY	ACM	WAITING ROOM
RED CODES	X	N(3.5;0.5)	N(7.5; 0.833) + N(15; 1.66)	-	-	?	-	-
YELLOW CODES	X	N(3.5;0.5)	N(7.5; 0.833) + N(15; 1.66)	N(1560;440)	-	?	-	-
GREEN CODES	X	N(7.5;0.833)	-	-	N(60;10)	-	N(15; 1.66)	?
BLUE CODES	X	N(7.5;0.833)	-	-	-	-	N(12.5;0.833)	?
WHITE CODES	X	N(7.5;0.833)	-	-	-	-	N(7.5;0.833)	?

4.4.5.1 Model validation

The data used for the construction of the model are associated to a period of three months, from January to March 2012. These patient volumes are also used for the model validation, to ensure it maps the hospital operations. To calibrate and validate the model the simulation-generated outputs are verified with the actual data.

Some discrepancies may occur during the comparison due to the probability distribution used by the program, especially with respect to the patients' acceptance upon arrival. As far as the system measurements are concerned, one important measure is the time spent in the system; even more important are the data regarding the Waiting Time (WT) experienced by each patient. By comparing the simulation results with the actual data collected in a trimester (January-March 2012), differences in average waiting time are obtained for each group.

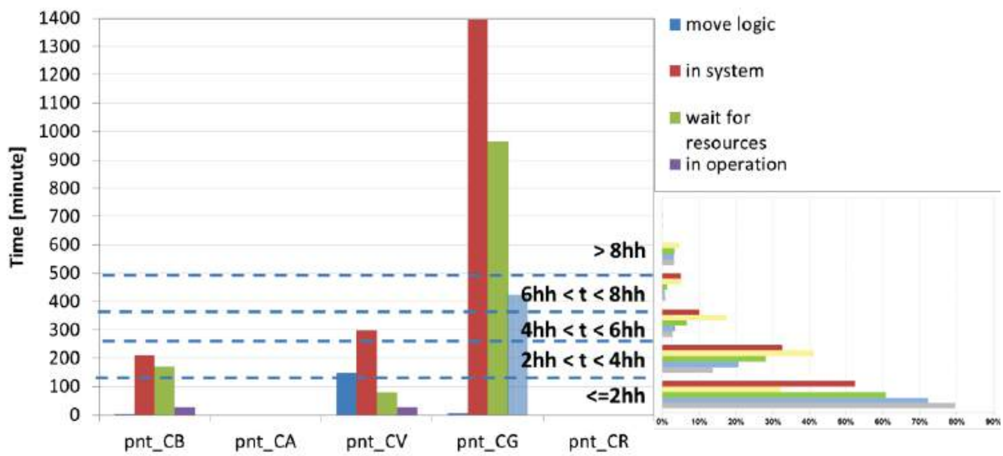


Figure 4. 50 Output data from the model and current data from the hospital database.

Considering the difficulties to capture the exact actual data (that refer to an entire semester) and the waiting time registered in the hospital for each patient group (sometimes given with the OBI rooms time, sometimes given without OBI and/or Recovery time), the variance in waiting time (WT) is compared with that of the actual data with a good result.

For certain patient groups the value displayed by the simulation result is found to be higher than the variance showed by actual data. Into Figure 4. 50 is compared the waiting time from the model's simulations (vertical bar-graph), with the data provided by the hospital database (horizontal-bar graph). All the data is divided by a range of time of 2 hours.

4.4.5.2 Simulation of scenarios

The functionality conditions of a normal scenario drastically change in case of emergency, when more resources, like operating rooms (ORs), are activated according to the procedures of maxi emergency (PEMAF plan). The ORs, in accordance with the emergency procedures, have to suspend all programmed surgeries in order to accommodate the emergency cases. At the same time, all patients whose health condition allows them to leave the hospital are to be discharged in order to increase the number of beds available for new admissions.

Figure 4. 51 sums up the transformation of the hospital system from the Normal Scenario to the Emergency Scenario and what concerns the striking of an earthquake.

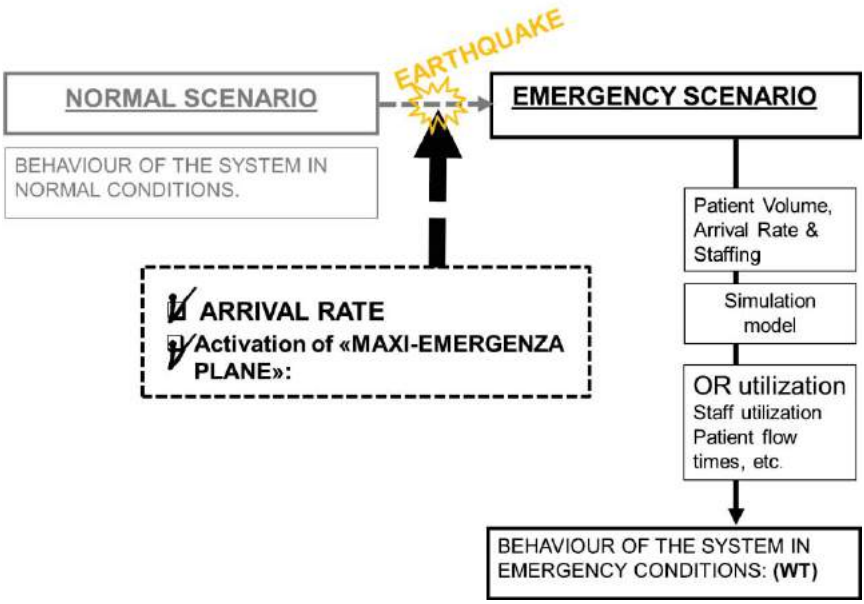


Figure 4. 51 From a Normal scenario to Emergency scenario general view.

As regards the model in an emergency scenario, all operating rooms have the same capacity; operating rooms are considered to be not damaged, and the emergency staff in the operating rooms is considered available. Also in the model relative to the state of emergency the only vertical connection between the ER and the operating rooms were taken into account and simulated by waiting a few minutes for the next step in the path traced to the operating room.

In order to evaluate the performance of the ED functioning, to identify areas for improvements or changes and to assess the impact of adding more surgical case, the following models were made and performed:

(1) Current patient volume and staff levels with the arrival pattern identified on the base of historical data (Model Name: Normal Condition ED);
(2) Seismic arrival volume and current staff levels with the arrival pattern derived from the Northridge Hospital during the 1994 earthquake (Model Name: Emergency Condition NO PEMAF);
(3) Seismic arrival volume and emergency staff levels following the emergency procedure (according to the PEMAF plan) with the arrival pattern derived from the Northridge Hospital during the 1994 earthquake (Model Name: Emergency Scenario PEMAF);
(4) Seismic arrival volume and emergency staff levels following the emergency procedures with seismic arrival rate scaled with a factor from 1.0 to 1.6 (Models Name: Emergency Scenario α=1.1, 1.2, …);
(5) Seismic arrival volume and emergency staff levels following the emergency procedures with seismic arrival rate and closure of locations from 0 to 3 (Models Name: Emergency Scenario n=0, 1,2,…).

Each of the above models is simulated under different scenarios to evaluate possible improvements. More details for each model and characteristics are described in Chapter 5.

4.4.5.2.1 Emergency planning of the hospital: the PEMAF plan

The hospital organization of the emergency assistance in case of a disaster (called maxi-emergency) is delegated to the "emergency plan for massive inflow of injured patients" (called PEMAF- Piano di Emergenza Massiccio Afflusso di Feriti in Italian). This document describes in advance the most adequate logistic and organizational solutions to face a possible massive and unexpected flow of injured patients, also identifying the types of measures to be taken, the terms and, as far as possible, the execution times and the leaders and executors of different procedures. To be effective, the plan must satisfy the following requirements:

- Compatibility with the ordinary activities of the hospital;
- Integration with the network of district rescue;
- Adaptability to the multiplicity of the types of emergency or higher event;
- Flexibility to best respond to a possible rapid evolution of the current situation;
- Reliability, tested by regular exercises.

The articulation of the PEMAF plan must also define:

- The needs of particular sector of the population (children, disabled, foreigners);
- Solutions to ensure immediate acceptance of victims and rapid reintegration of materials;
- The hospital reception capacity in relation to the ordinarily resources available and the additional resources needed for the emergency.

The first step in the PEMAF drafting is to consider hazards in the specific area of the hospital, and the importance of the healthcare facility in the network. In effect, since the PEMAF structure document is similar to every Italian hospital, each structure has its own characteristics related to the hazard areas, the hospital size, the number of resources and the type of service deliverable.

With respect to this research, this case study refers to one of the most dangerous areas in Tuscany among those affected by earthquakes. The Emergency Plan must be coordinated with the other hospital activities in order to guarantee a medical service to the population; this entails a service both during an emergency in the case study's zone, and in another district for which the facility zone needs help. In case of PEMAF activation, the Emergency Department must quickly change its setting: more resources are required and patients able to walk and whose health condition is not critical are moved to other locations. The normal setting of the emergency rooms, OBI rooms and ACM ambulatory change and three new "zones" are determined resulting in a new capability:

- A RED zone is identified within the Emergency Department location, regularly used by Red and Yellow Codes: in this area, where 2 patients can be simultaneously accommodated, operate 2 doctors, 2 nurses and 1 help operator (OSS);

- A YELLOW zone identified within the Emergency Department places, regularly used by Yellow Codes and by OBI: in these areas, depending to the needs, operate from a minimum of 1 doctor to a maximum of 3 doctors, 3 nurses and 2 OSS operators.; four patients can be accommodated in this area at the same time;

- A GREEN zone is situated in the rehabilitation-gymnasium area. This area is designated for injured patients without alterations of vital parameters. Patients are accommodated in 12 beds within the near ambulatories. The necessary staff consists of 2 doctors, 3 nurses and 1 OSS operator.

These data are resumed in Table 4.12, while the architectural zoomed layout of the Emergency Department in Figure 4. 52 shows the new setting with the new resource disposition of the ED.

Table 4.12 Resources activated in the different zone, following the emergency procedures.

AREA	DOCTORS N°	NURSES N°	OSSs N°	PATIENTS MAXIMUM N°
TRIAGE	1	1	-	-
RED ZONE	2	2	1	2
YELLOW ZONE	2	3	2	4
GREEN ZONE	2	3	1	12

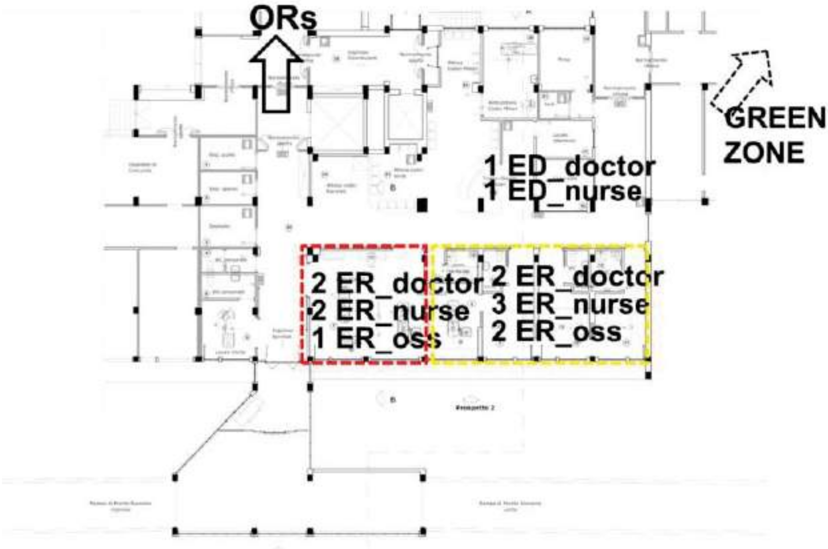


Figure 4. 52 Emergency Department changes in different zones following the Emergency procedures established by the PEMAF plan.

In addition to the changed set of the Emergency Department, other locations are activated. The operating rooms immediately suspend the scheduled surgeries, in order to operate the grave patients coming from the disaster area. Therefore the path from-to the Operating Rooms (ORs) is included into the ED distance matrix. Table 4.13 and Figure 4. 53 show the distances and a general overview of the main locations during the Emergency phase. It is worth to note that the ORs are located on the second floor of another building, not so close to the Emergency

Department. Moreover, the only vertical connection between the two floors is an elevator, reserved to the hospital personnel.

Table 4.13 From-to distance matrix of the locations activated following the Emergency procedures.

	ENTRY	RED ZONE	YELLOW ZONE	GREEN ZONE	OR
ENTRY	0	7,5	30	\	60
RED ZONE	-	0	10	\	60
YELLOW ZONE	-	-	0	\	70
GREEN ZONE	-	-	-	\	\
OR	-	-	-	-	0

* All distances are in meters, measured from layout drawing.

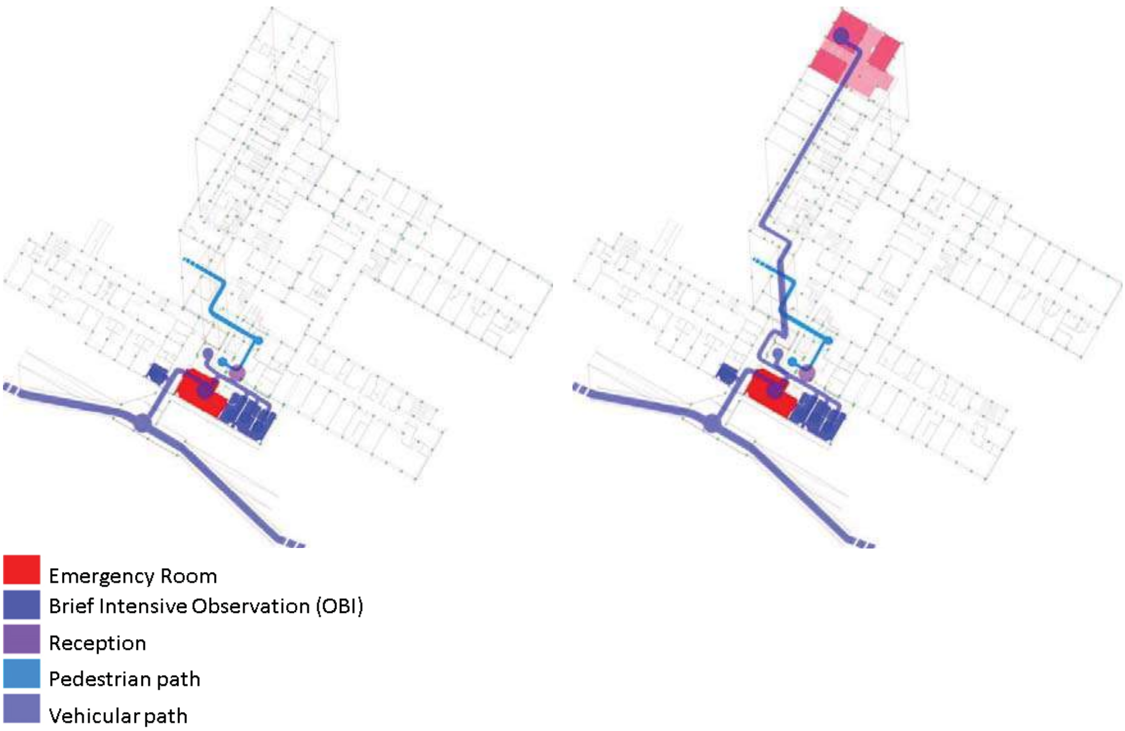


Figure 4. 53 Changed path (for pedestrians and vehicles) from the Normal Condition Model (on the left) to the Emergency Condition Model (on the right).

Patient paths and locations to accommodate them are modified following the emergency procedures. As described in the flow charts in Figure 4. 54, Figure 4. 55 and Figure 4. 56, patients skip the triage inside the emergency department since they are assigned a colour code before reaching the facility so that the emergency measures can proceed more rapidly than in a normal scenario.

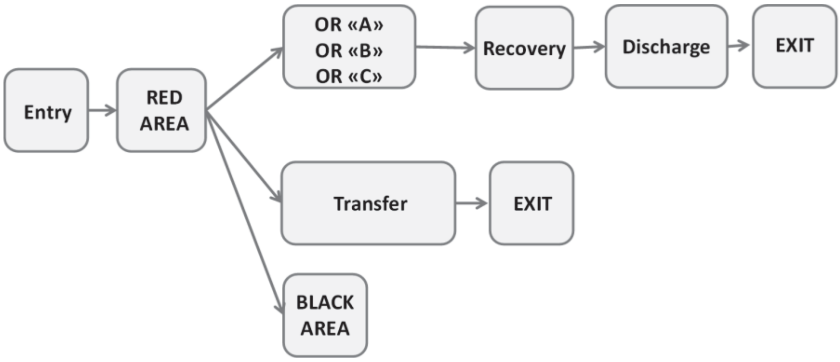


Figure 4. 54 Flow chart of Red Codes during an emergency scenario.

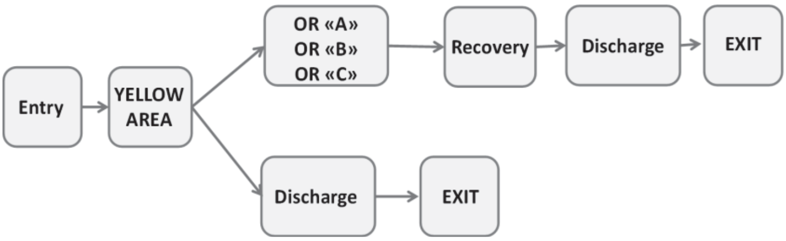


Figure 4. 55 Flow chart of Yellow Codes during an emergency scenario.

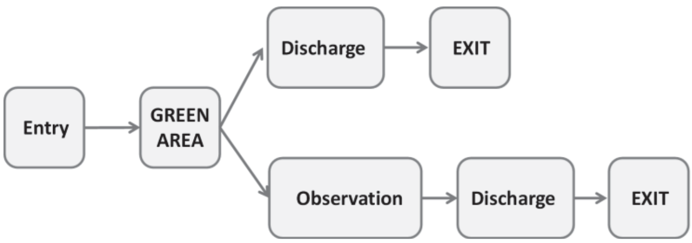


Figure 4. 56 Flow chart of Green Codes during an emergency scenario.

A new model (see Figure 4. 57) is built for the emergency scenario, adding resources and locations, modifying the patient flow charts and extending the layout until the ORs. The elevator is simulated to have the capacity of 1 patient location: the patient and the personnel wait some minutes to reach the upper floor. On the second floor, where the operating rooms are allocated, there are doctors and nurses dedicated to the surgeries. Therefore the medical staff that accompanies the patient delivers him to the staff operating on the second floor. This means that the hospital personnel of the emergency department must take care of patients until they are accommodated on the second floor.

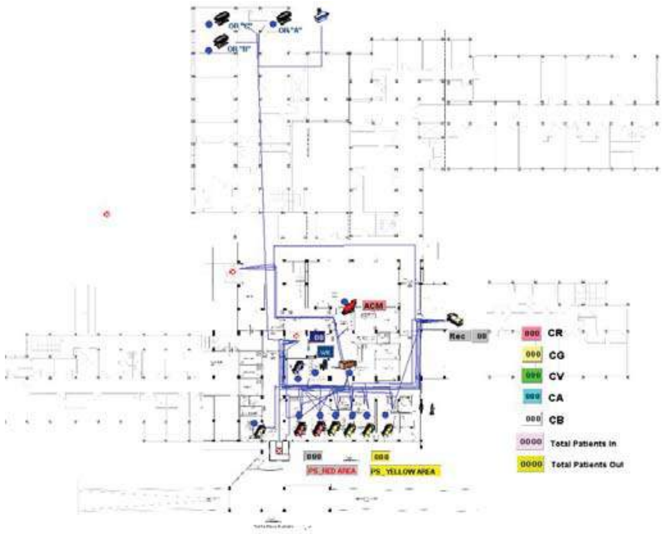


Figure 4. 57 Screenshot of the Model during an Emergency Scenario

4.4.5.2.2 The seismic arrival rate

The arrival rate was determined by scaling the patient inflow of the Northridge hospital in Los Angeles, California, calculated during the earthquake which occurred in 1994 (Cimellaro et al. 2011). First, the peak ground acceleration (PGA) at the site of the hospital was determined using the Italian seismic standard (for a Probability of Exceedance -P_{VR}- of 10% in 50 years), and the arrival rate at the Northridge hospital following the 1994 earthquake was scaled to the PGA value measured in the site of the hospital.

The peak ground acceleration is evaluated according to the Italian Code (NTC- § 3.2); for those data is necessary to know other details regarding the structure and its location. The first one is the return Period, evaluated as a function of the reference period V_R (NTC08 - § 2.4.3) and according to the corresponding probability P_{VR} of exceeding of prearranged limit state during the reference period. The reference period (VR) is calculated as a function of the nominal life V_N (NTC08 - § 2.4.1) and the coefficient of use C_U (NTC08 - § 2.4.3):

$$V_R = V_N * C_U \quad \text{(Eq.4. 5)}$$

The nominal life of a building is defined as the number of years in which the structure, as long as it has undergone routine maintenance, must be able to be used according to the purpose it is intended for (see Table 4.14)

Table 4.14 V_N index for different buildings (NTC08table 2.4.I)

TYPE OF BUILDING	V_N
Provisional building – Structures in building	≤ 10
Ordinary buildings, bridges, infrastructural constructions and dams of restrained dimensions or normal importance	≥ 50
Big structures, bridges, infrastructural constructions and dams of big dimensions or strategic importance	≥ 100

The *coefficient of use* which depends on the building *class of use* (see Table 4.15). This class is assigned to the buildings based on their potential consequences as a result of a seismic event, such as interruption of operations or the eventual collapse (NTC - § 2.4.2). For buildings having public functions or being strategic, as hospitals are, the class of use is equal to IV.

Table 4.15 Class of use and coefficient CU (NTC08table 2.4.II)

Class of use	I	II	III	IV
Coefficient C_U	0.7	1.0	1.5	2.0

The probability PVR of exceeding the reporting period, , is displayed in Table 4.16.

Table 4.16 Probability of exceedance in the referred period VR, for different limit states

Limit States	**P_{VR} : Probability of exceedance in the referred Period V_R**	
SLE	SLO	81%
	SLD	63%
SLU	**SLV**	**10%**
	SLC	5%

The "Consiglio dei Lavori Pubblici" developed a program that allows to calculate the design spectra for different reference periods, simply entering the town or the geographical coordinates of the building site. For the case study, the definition of the peak ground acceleration is calculated on the base of the following data:

- Definition of *nominal life* and *class of use* of the building leading to the definition of the Reference Period of the seismic action. In this case, VN=50, CU=2 and VR=100.

Assumption, as a function of the Latitude and Longitude (Table 4.17), of the basic seismic parameters a_g, F_0 and T_C for the Limit State SLV. The peak ground acceleration for the site of the case study is calculated on bold calculated in
Table *4.18*.

Table 4.17 Geographic coordinates.

LONGITUDE	**LATITUDE**
12.15389907	43.57111808

Table 4.18: Seismic parameters for every return period associated with the different limit states.

LIMIT STATE	T_R [years]	a_g [g]	F_o	T_c [sec]
SLO	60	0.098	2.343	0.271
SLD	101	0.124	2.339	0.277
SLV	949	**0.287**	2.397	0.310
SLC	1950	0.361	2.403	0.324

Considering the PGA for the 1994 earthquake in San Francisco, equal to 0.568 g, the scaling procedure is produced. However, this method presents some limitations; for instance, it does not take into account the real level of damage related to the area in which the earthquake happens. As matter of fact the case study inflow shows too low values compared to those of the Northridge 1994 earthquake (see Figure 4. 58).

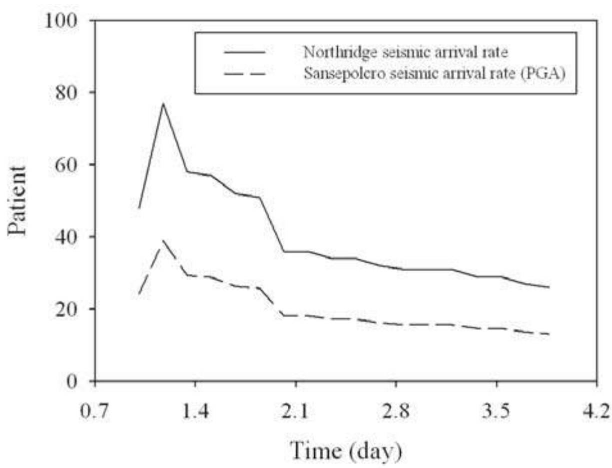


Figure 4. 58 Seismic arrival rate calculated on the base of the inflow at the Northridge hospital during the 1994 earthquake and scaled for the case study with the PGA scale factor.

In order to get more significant results from the model, even putting the system under great pressure (in terms of patients number), another scaling has been used

The Modified Mercalli Intensity (MMI) scale, which takes in account all the above features, has been applied as a second scaling procedure.

To compare seismic hazards in terms of PGA and certain intensities, it is necessary to have an empirical relation between intensity and acceleration, which allows to transform the macro-seismic data into usable parameters (as it is here the case of the peak ground acceleration).

Over the last 50 years many reports have been published about these correlations. This literature mainly differs with respect to the data under investigation and the addition of any extra parameter. On the base of such choices, a certain range of values within the formulation itself can be considered valid. İn order to use these relations, the PGA of this case study must be assumed as follows:

$$PGA_{case\ study} = 0.287g = 281.45\ cm/s^2 = 281.45\ m/s^2 \quad \text{(Eq.4. 6)}$$

The PGA corresponds to the MMI intensity value which can be used in the formulations. The MMI scale has been determined using the relationships available in the literature (see Table 4.19) between the MMI values and the horizontal average and maximum PGA values at the site.

Table 4.19 Formula available in the literature to compare PGA and MMI values.

Author	Relation	Unit PGA	Intensity range (validity)	PGA range (cm/s^2)
Faccioli e Cauzzi (2006)	I_{MCS}=1,96LogPGA+6,54	m/s^2	4/5≤I_{MCS}≤9	18-600
Marin et al. (2004)	I=10+2,3LogPGA	g	-	-
Wald et al. (1999)	I_{MM}=3,66LogPGA-1,66	cm/s^2	5≤I_{MM}≤8	4-1000
Decanini et al. (1995)	LogPGA=0,594+0,237I_{MM}	cm/s^2	4≤I_{MM}≤11	-
Theodulis and Papazachos (1992)	LnPGA=0,28+0,67I_{MM}+0,42S S=0 at alluvium site S=1 at rock site	cm/s^2	4≤I_{MM}≤8	8,8-530
Chiaruttini e Siro (1981)	LogPGA(g*100)=-0,19+0,17I	g	-	-
Murphy & O'Brien (1977)	LogPGA=0,25+0,25I_{MM}	cm/s^2	4≤I_{MM}≤8	10-700
Ambraseys (1975)	LogPGA=-0,16+0,36I_{MM}	cm/s^2	4≤I_{MM}≤10	2-600
Medvedev and Sponheuer (1969)	LogPGA=-0,408+0,301I_{MM}	cm/s^2	5≤I_{MM}≤10	12-800
Neumann (1954)	Average distance of 25km LogPGA=-0,429+0,308 I_{MM} Average distance of 160km LogPGA=-0,041+0,308 I_{MM}	cm/s^2	5≤I_{MM}≤8	40-300

The average values obtained by applying the above mentioned relations display an intensity equal to 8.26 IMM for the site of the case study, while the value was 9 in the Northridge case. Therefore a new scaling is obtained, as shown in Figure 4. 59.

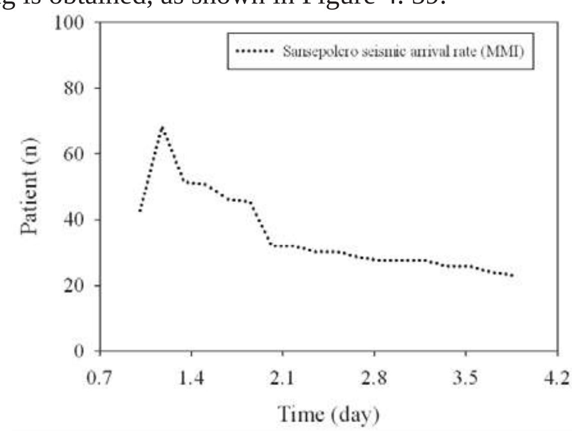


Figure 4. 59 Seismic arrival rate calculated for the inflow at the Northridge hospital during the 1994 earthquake and scaled for the case study with the Modified Mercalli Intensity (MMI) scale factor.

Figure 4. 60 shows the trend of the seismic patient inflow of the Northridge hospital and the patient seismic inflow modified according to the PGA (small dotted line) and the MMI (dotted line) for the hospital. The latter scaling procedure is used in the organizational model in order to simulate the inflow during an emergency.

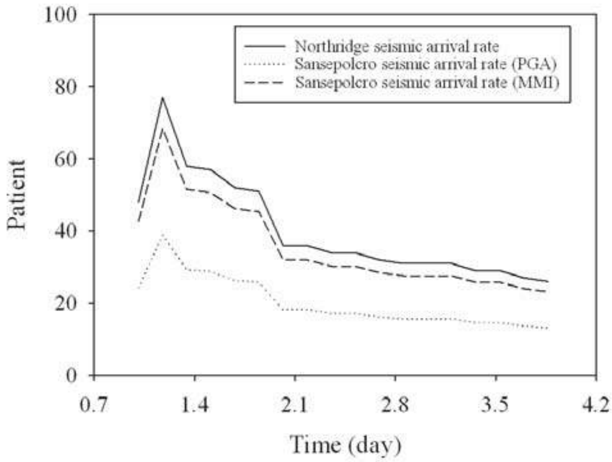


Figure 4. 60 Arrival rate in case of an Emergency scenario, following the Northridge data trend and scaling with PGA and MMI values.

The inflow of the patient in terms of patient/minute during the emergency days (three days in the case of the Northridge earthquake) does not represent the only essential data. As matter of fact different disasters may result in different type of injuries. In this research, the disaster under consideration is an earthquake. In an emergency situation such as an earthquake, keeping track of patient/treatment is usually considered as a low priority activity (Pengfei 2005). As can be imagined, the pathological effects or injuries consequential to events of such significant magnitude can be varied, although in most cases they can be attributed to the following categories:

a) harmful effects of traumatic injuries/burns;
b) harmful effects of toxic nature/radiations;
c) infections;
d) diseases of the cardiovascular, respiratory and systemic organs.

The proper distribution of cases within the hospital, the extent and the nature of the resources mobilized will depend, of course, on the main type of detrimental or pathological manifestations.

Unfortunately, few injury data are available for analysis. Only two earthquakes are well documented (Aroni & Durkin 1987; Cheu 1994; Durkin 1995; Mahue 1996; Olson & Alexander 1996; Salinas et al. 1998): the Northridge, CA earthquake in January 1994 and the Loma Prieta, CA earthquake in October 1989.

It is difficult analyse the injuries; for this reason, according to the past researches, some data need to be taken into consideration, as well as the fact that physical injuries contribute to a large extent to the total ER examinations, and medical injuries also occupy ED resources.

Durkin (1995) reports the distribution of general types of injuries and medical problems in four hospitals' emergency rooms for the first 24 hours after the Northridge earthquake. Since these data referring to different earthquakes are not consistent, an additional adjustment is made to achieve a safe estimation; patients with similar medical needs and undergoing the same treatment procedure are grouped in six categories. These six categories are further divided according to the five Italian colour codes, in order to apply the patient/treatment distribution during an earthquake to the categories of the Italian hospital procedures.

The results are shown in Table 4.20, where the percentages of patients in normal and emergency conditions as well as the number of entries are reported.

Table 4.20 Arrivals at the Emergency Department in the normal scenario and in the emergency scenario.

PATIENT TYPE	NORMAL SCENARIO	EMERGENCY SCENARIO	
	%	%	number of people
RED COLOR	0.5	3.7	37
YELLOW COLOR	10.6	40	396
GREEN COLOR	45.11	48.4	476
BLUE COLOR	1.72	7.8	77
WHITE COLOR	41.88	0	5

During the emergency scenario, the emergency department of the case study treats only the major codes (red and yellow ones), while the minor codes are addressed to other parts of the hospital in order to facilitate the access to the emergency rooms. Since waiting times differ significantly for surgical and non-surgical patients, these categories are further classified in OR and non-OR patients as shown in Table 4.21.

Table 4.21 OR and non-OR patients division.

PATIENT TYPE	OR patients	Non-OR patients
	%	%
RED COLOR	0.215	0.785
YELLOW COLOR	0.19	0.81

In order to sketch a good comparison and to better comprehension the differences regarding the massive inflow of patients in an emergency scenario, Figure 4. 61 shows the normal arrival rate calculated in 31 days, and the derived seismic arrival rate for the first 3 days of emergency after the shock. On the right a zoomed 3-days comparison between the two arrival rates is shown: the peak around the end of the first day is more than two times the trend of the normal arrival rate expected for the same hospital. Both the inflows represent the total patients categories; into the model the distinction among the colour codes refers to the previously calculated percentages.

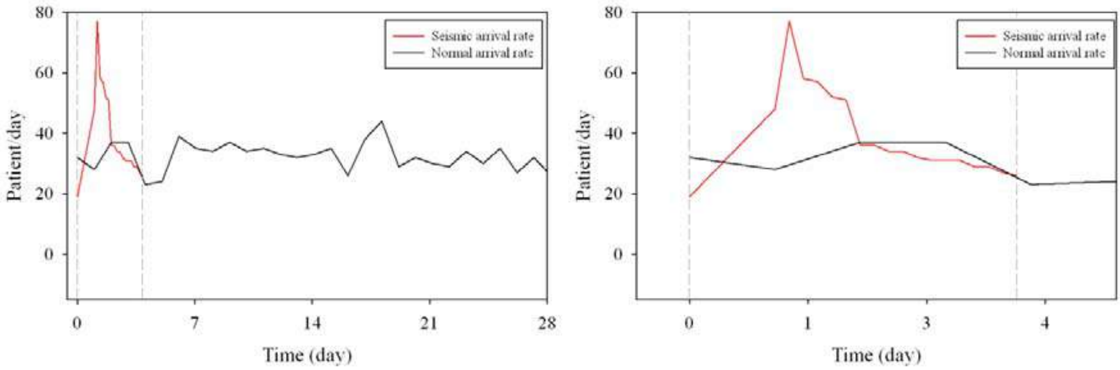


Figure 4. 61 Comparison between the arrival rate of Normal Scenario and the Seismic arrival rate defined for the Emergency Scenario.

In both models (normal and emergency scenarios), the output data under consideration are represented by the Waiting Time (WT) for each category of patient.

It is possible to determine the effect of a "seismic" arrival rate on the organization and function ability of the ED personnel. The effects on patients WT, however, change drastically depending on the different applied models. In this research the WT considered as the unique value is the WT of Yellow Codes. This choice is due to two main facts: first, the impossibility to quantify WT for the Minor Codes (because of their movements during the Emergency phase) and second, the high priority reserved to Red Codes that, in most cases, are transferred to other structures. Accordingly the Yellow Codes appears to be the best category to be analysed and the easier to compare in different models. Since the simulation model does not apply to the first few hours immediately after a shock (an earthquake in this case), two factors have been left out of consideration: the issue of supplementary medical staff and the impossibility to reach the hospital. Their analysis, however, may constitute a future development of this research.

Chapter 5

Meta-models and resilience

5.1 Tools and data

The performance of organizational models is analysed and evaluated considering a unique variable: the waiting time. As matter of fact this variable (see Ch. 3.1.1 for a detailed description) seems to be the most important to assess since it is the unique one being relevant for applying the methodology at different stages and therefore for describing the behaviour of the system under different conditions. The waiting time is calculated for each yellow-code patient entering the emergency department. The waiting time is calculated considering the patient's movements upon his/her arrival until he/she receives the first medical treatment, both in normal (red asterisk in Figure 5. 1) and emergency scenarios (red asterisk in Figure 5. 2).

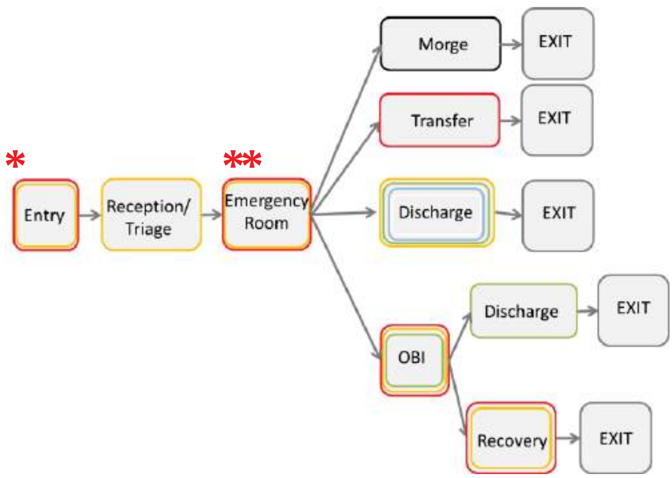


Figure 5. 1 Yellow patients' flowchart in a normal scenario.

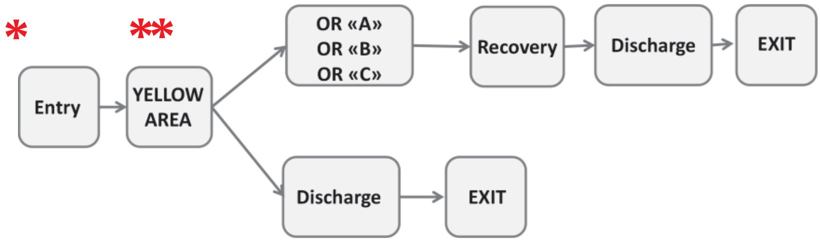


Figure 5. 2 Yellow patients' flowchart in an emergency scenario.

The Figures above show the beginning of the waiting time (indicated by a red asterisk) and its ending (signalled by a double red asterisk). The WT is measured inside the emergency room immediately after the first care is provided: in effect measuring the WT at the very entrance of the emergency room does not guarantee the medical assistance, say the patients getting the emergency room are not necessarily provided medical treatments. Monte Carlo methods of the organizational model are performed one hundred times: the resulting file lists the waiting time experienced by each patient. Such evidence must be filtered according to the colour code of the patients, then it is necessary to set the data clouds (black dots in Figure 5. 3), in order to calculate a median curve of these points (red dots in Figure 5. 3).

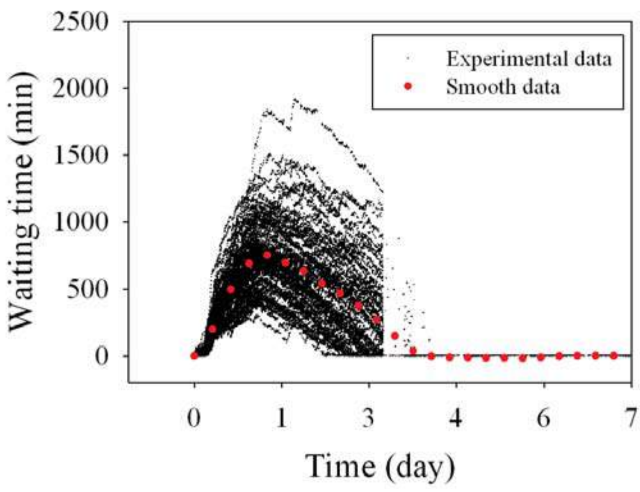


Figure 5. 3 Yellow patients' flowchart in a normal scenario.

Generally the curves follow the same trend, well represented by a bell-curve. After a series of fittings, the Lognormal equation with three parameters results the best for fitting for all the curves, being a shifted Lognormal with two parameters. Indeed, some simulations are performed with normal-condition-days before the shock (normal scenario), and some other are performed starting with the seismic arrival rate (emergency scenario). Three parameters are finally found, and they can be used to compare a series of models with variable parameters. This is illustrated in the following chapters.

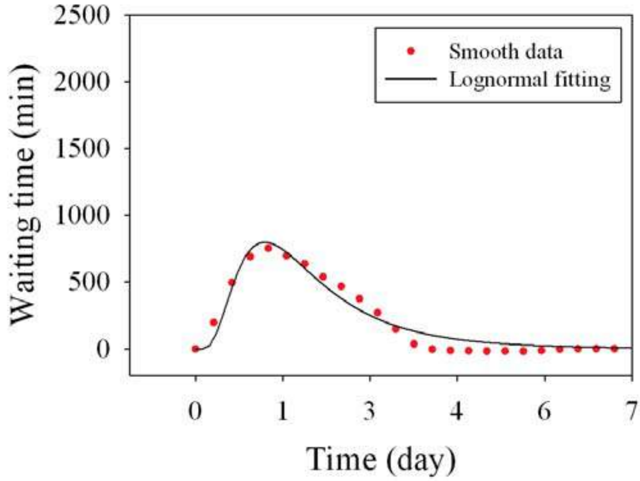


Figure 5. 4 Yellow patients' flowchart in a normal scenario.

These analytical manipulations permit to mathematically assess the waiting time experienced by patients under specific conditions: such evaluation can be used as a final tool by the medical personnel and the hospital manage to predict and prevent a loss of functionality inside the hospital.

This curve is well represented as a Gaussian-curve, for which the best fitting has been found. All the waiting time curves have approximatively the same shape, and therefore the same fitting is used.

After several approximations, the equation Lognormal with three parameters has been chosen. Such a choice depends on the possibility, in the future, to perform other simulations that take into account also the days before the shock event: the Lognormal distribution with three parameters is shifted to the right, which permits to compare different simulations at the same time. It is worth to keep in mind that the simulation that permitted to calibrate the model was performed on the base of two days in the normal scenario before the three days in the emergency scenario and some more days under normal conditions for re-establishing the normality of the system.

This study exclusively refers to the waiting time experienced by yellow code patients: this is due to the fact that these patients are subject to a great variety of medical procedures, both under normal conditions and in case of emergency. Besides, according to the statistics provided by the hospital database, yellow code patients are those whose colour code more often changes after the first medical treatment. Moreover, in an emergency, the majority of patients entering the emergency department are yellow-coded and the treatments they undergo are statistically the most probable during an earthquake (see par. 4.4.4).

Even though red-code patients have a higher priority than yellow-code patients, the latter are subject to a greater number of clinical pathologies that this specific case-study is able to treat. As matter of fact, red-code patients are mostly transferred to other healthcare structures.

The DES model is able to register the waiting time at all stages of the simulation and, once conveniently set, the occurrence of different needs.

5.2 Organizational models performed

The organizational models performed in this work have a fundamental role inasmuch they are predictive of specific emergency situations in which the system can be tested. After the calibration of the model in normal conditions, it is possible to assume that the response to the seismic input, whit the activation of the general emergency procedures, is representative of a real situation, in which the system has to face a critical phase.

Accordingly several organizational models have been performed after having introduced some dissimilarities. Three groups of models are identified, with multiple variable cases. For each group, assumptions are made in order to adapt the model to the main aim of the work, that is: to determine the behaviour of the hospital system under different critical conditions.

In addition, other typologies of models are developed in order to validate the methodology presented in Ch.3, and to pinpoint the peculiarities of the healthcare facility.

The performed simulations can be grouped as follows:

- CASE 1: group of organizational models with permanent room closures and emergency procedures activated for all length of the simulation;
- CASE 2: group of organizational models with permanent room closures;
- CASE 3: group of organizational models with temporary room closures.

Within each group, several variations are introduced, depending on the variables involved. In the paragraphs concerning each group of simulations the peculiarity and the characteristics of these groups are specifically presented. From a general point of view, the following assumptions are considered for all the groups:

- the emergency phase lasts 3 days (72 hours): this parameter is due to the nature of the only available data, i.e. the Northridge patients' inflow;
- the room closures are considered "permanent" if they are caused by damages which persist for 72 hours or more;
- the rooms can accommodate one patient at a time, if the rooms are occupied, patients must wait until the first room is available;
- the totality of closed rooms does not constitute a possible case (such a case would be nonsensical for the present investigation);
- the access to the rooms by lined up patients is determined by the FIFO (first-in-first-out) law, for patients sharing the same code;
- resources in terms of hospital personnel are fully available (which also implies that no member of the medical staff is injured);
- no damages to the infrastructures network are considered: people arriving to the hospital gain access through the ambulance entry (if they are classified as "major codes"), or through the pedestrian entry (if they are classified as "minor codes");
- during the emergency phase the arrival of "minor codes" arrivals is interrupted, due to the emergency procedures;

- the major codes have the priority on the minor codes and, in particular, red codes have the priority on the yellow one; however, if a medical operator is treating a patient with lower priority, before taking care of an entering major-code-patient, he/she must conclude the treatment to the first patient;
- the seismic arrival rate is drastically increased, even if the general standard is not provided for a massive patients inflow (this choice is imposed by the necessity to mathematically analyse the healthcare system);
- only the emergency department is taken into account because the emergency procedures involve this specific area of the hospital and impose to the rest of the building only a greater availability of recovery beds;
- the results depend on a unique variable, i.e. the waiting time experienced by yellow-code patients.

100 Monte Carlo simulations have been performed for each type of model described, in accordance with the arrival rate both under normal conditions and in emergency conditions. The number of the Monte Carlo methods has been reduced to 100 for simplifying the resulting file, since the results with a higher number of simulations is similar to these adopted. The statistical results are considered and manipulated as outputs data of simulations. For each group of models, presented in the following paragraphs, a Metamodel is built to predict the waiting time experienced by a single patient at a certain time, and to consider other variables depending on the models analysed. The analytical construction of the waiting time predictive equation is singularly illustrated for each group of different organizational models.

5.2.1 CASE 1: permanent closures of rooms

With respect to the other models, for this group of simulations the efficiency of the system is investigated by introducing three days of emergency scenario.
For this reason, after two normal-days the shock is introduced, i.e. it is represented by the seismic arrival rate, in terms of increased patients' inflow.
In order to represent an hypothesized scenario in which to investigate the best performance of the system and the variation of the waiting time experienced by patients exclusively as a consequence of room closures and the seismic arrival rate, a model with the following characteristics is performed:

- the emergency phase lasts 3 days, following the (properly scaled) Northridge patients' inflow;
- for room closure (n value) it is intended the total number of rooms available, from the beginning to the end of the simulation; human resources, i.e. the hospital personnel, are fully available and no member of the staff is injured;
- no damages to the infrastructures network are considered: people arriving to the hospital gain access through the ambulance entry (if they are classified as "major codes"), or through the pedestrian entry (if they are classified as "minor codes");during the emergency phase the arrival of "minor codes" arrivals is interrupted, due to the emergency procedures; the seismic arrival rate is drastically increased, in order to mathematically analyse the healthcare system (α values);

only the emergency department is taken into account since the emergency procedures involve this specific area of the hospital and impose to the rest of the building only a greater availability of recovery beds;

This model is performed for 29 days (648 hours). The performance begins in normal conditions (2 days), after the seismic event the increased arrival rate lasts for the entire emergency phase (3 days) and thereafter 24 days of normal arrival rate are considered (cf. Figure 5. 5). With respect to this it is important to keep in mind that the emergency staff is available for the whole simulation period.

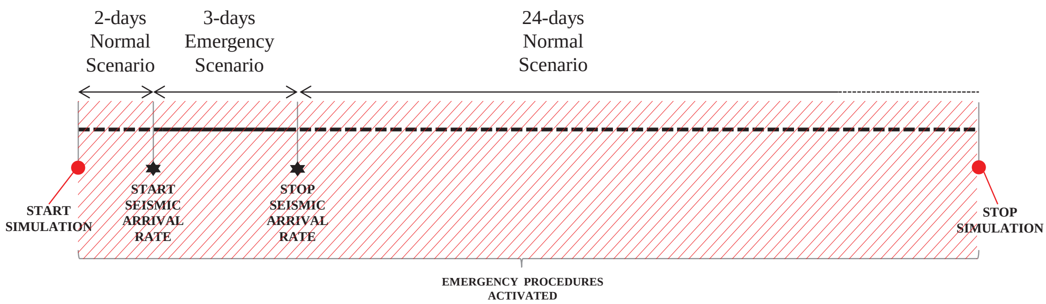


Figure 5. 5 Diagram of the simulation characteristics (CASE 1).

As described above, each simulation consists of 100 Monte Carlo replications. The goal is to investigate the behaviour of the system, under critical condition, with the variation of the number of available rooms for treating patients. Two parameters vary in the simulations:

- the number of closed rooms, *n*;
- the seismic arrival rate, α.

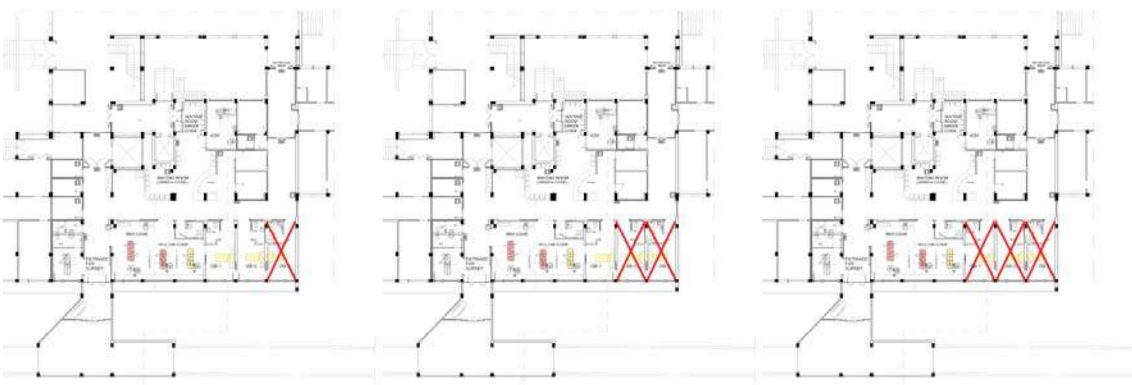


Figure 5. 6 Permanent room closure: representation of the n *coefficient, varying from 1 to 3.*

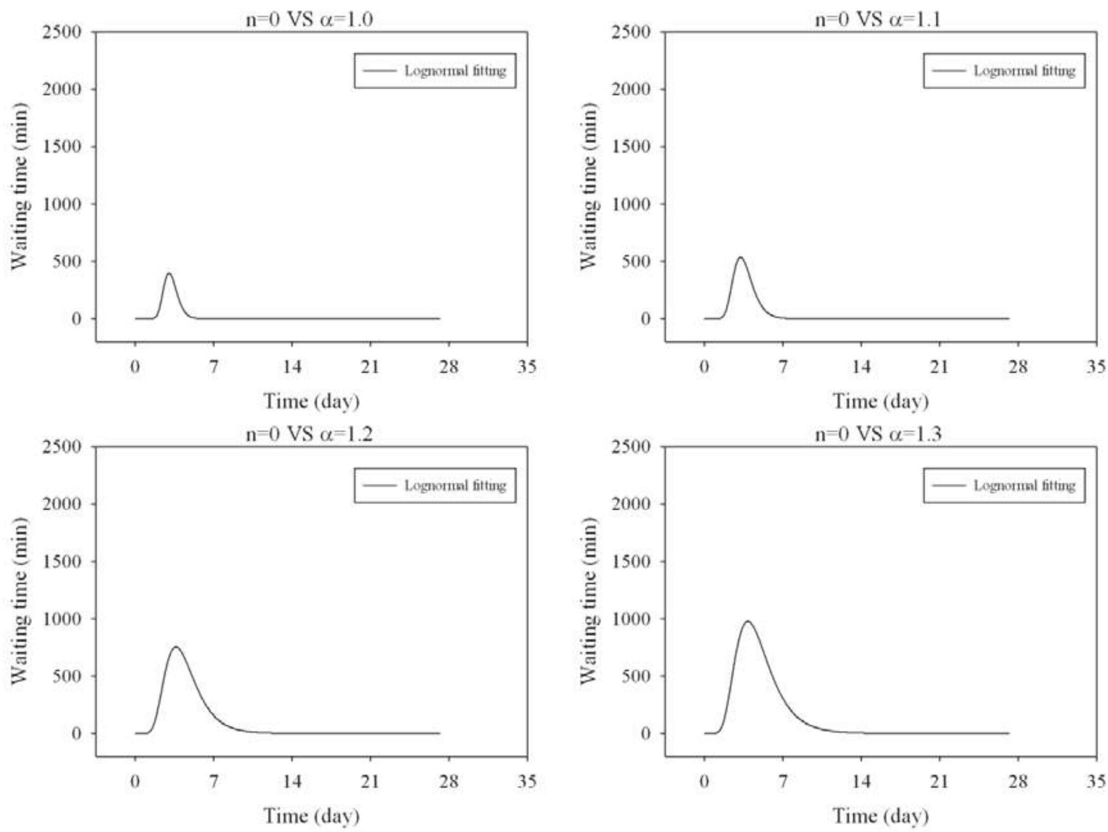
The number of closed rooms varies from 0 (no closure) to 3: the latter value represents the worst case of damage (Figure 5. 6 shows three cases when rooms are closed, with *n* variation from 1 to

3). The increasing of the seismic arrival rate is calculated with a scale factor, from α=1 to a α=1.6, as described in Ch. 4. All the cases in which these two factors combine are analysed.
At first seven models (depending on the variation of the parameter α) are performed by varying the seismic arrival rate with no room closure involved. This is shown in Table 5.1:

Table 5.1 Models developed with several arrival rates and no room closure involved.

Model (name)	**Closure of rooms**	**Closure time**
Model_n0E_ α=1.0	NO	-
Model_n0E_ α=1.1	NO	-
Model_n0E_ α=1.2	NO	-
Model_n0E_ α=1.3	NO	-
Model_n0E_ α=1.4	NO	-
Model_n0E_ α=1.5	NO	-
Model_n0E_ α=1.6	NO	-

The waiting times resulted and estimated thanks to the model are manipulated as previously described and the final WT bell-curves are assessed. The following plots represent the results of the models listed in Table 5.1, without room closures (n=0) and varying the α parameter.



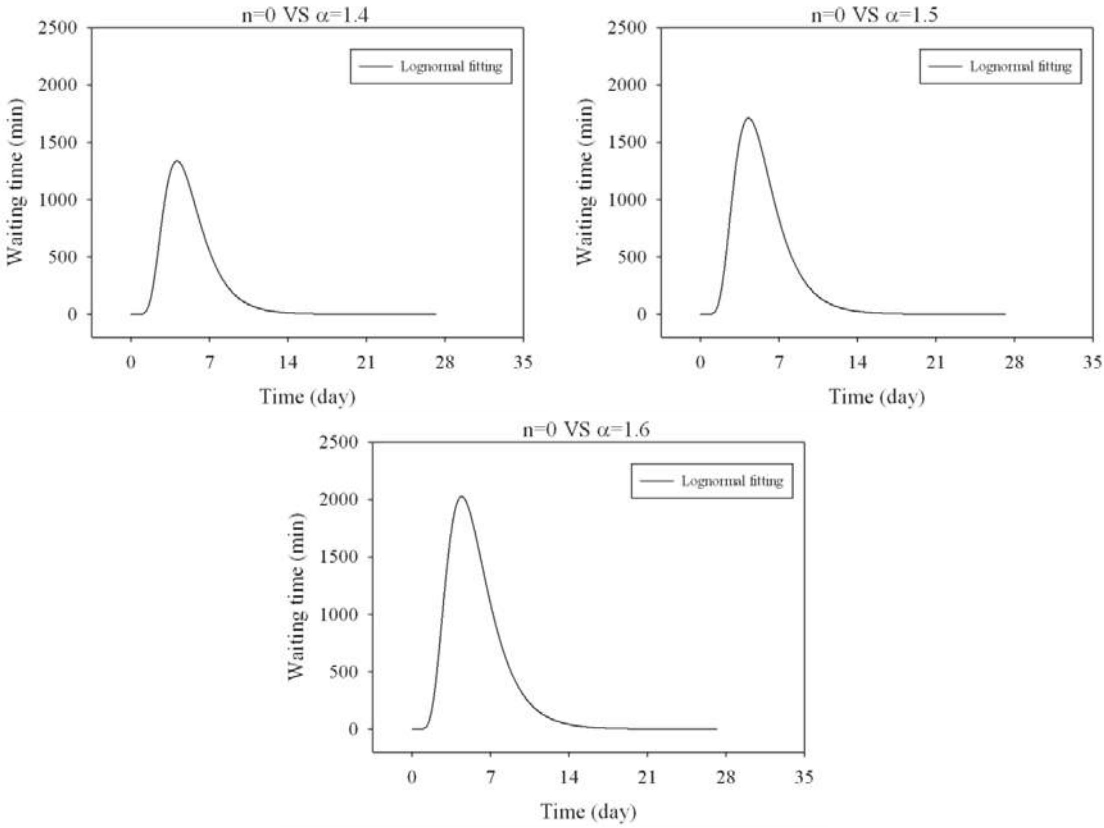


Figure 5. 7 Waiting time curves for n=0 and α varying between 1.0 and 1.6 (see the attachments for all the other cases).

The same procedure is followed for the models with an increasing number of closed rooms (*n* parameter). These models are listed in Table 5.2, Table 5.3 and Table 5.4. The waiting time curves for each model are estimated with the same technique (for all the graphs, see the attachments).

Table 5.2 Models developed with varying arrival rates and one closed room (the room closure is maintained for the entire simulation period – MESP -).

Model (name)	**Closure of rooms**	**Closure time**
Model_n1E_ α=1.0	1	All run length
Model_n1E_ α=1.1	1	All run length
Model_n1E_ α=1.2	1	All run length
Model_n1E_ α=1.3	1	All run length
Model_n1E_ α=1.4	1	All run length
Model_n1E_ α=1.5	1	All run length
Model_n1E_ α=1.6	1	All run length

Table 5.3 Models developed with varying arrival rates and two closed room (the room closure is MESP).

Model (name)	Closure of rooms	Closure time
Model_n2E_ α=1.0	2	All run length
Model_n2E_ α=1.1	2	All run length
Model_n2E_ α=1.2	2	All run length
Model_n2E_ α=1.3	2	All run length
Model_n2E_ α=1.4	2	All run length
Model_n2E_ α=1.5	2	All run length
Model_n2E_ α=1.6	2	All run length

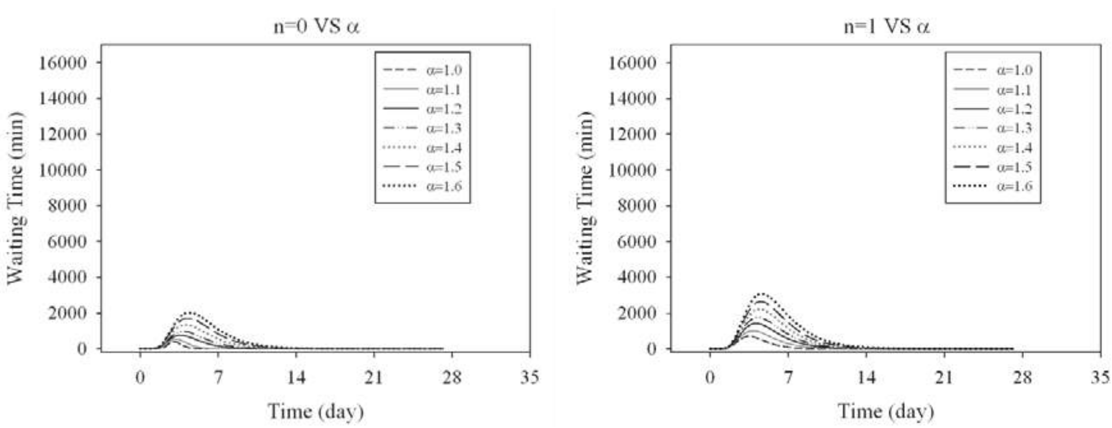
Table 5.4 Models developed with varying arrival rates and three closed room (the room closure is MESP).

Model (name)	Closure of rooms	Closure time
Model_n3E_ α=1.0	3	All run length
Model_n3E_ α=1.1	3	All run length
Model_n3E_ α=1.2	3	All run length
Model_n3E_ α=1.3	3	All run length
Model_n3E_ α=1.4	3	All run length
Model_n3E_ α=1.5	3	All run length
Model_n3E_ α=1.6	3	All run length

5.2.1.1 **The construction of the meta-model**

In order to create the meta-model for the yellow-code patients, the drastic increase in waiting time is considered as a consequence of two parameters, i.e. α and n. A good illustration of this variation is provided by the following pictures, where the n parameter is constant, while the α parameter varies:

- n = constant
- α = variable



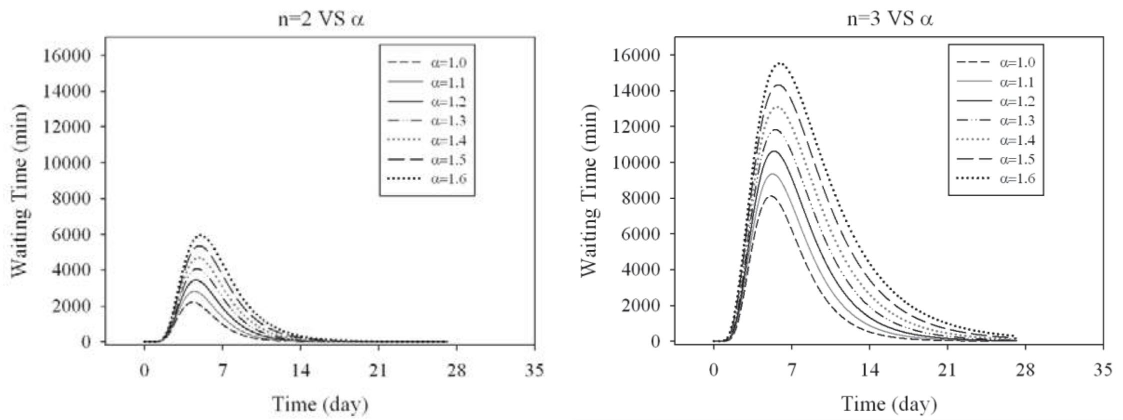
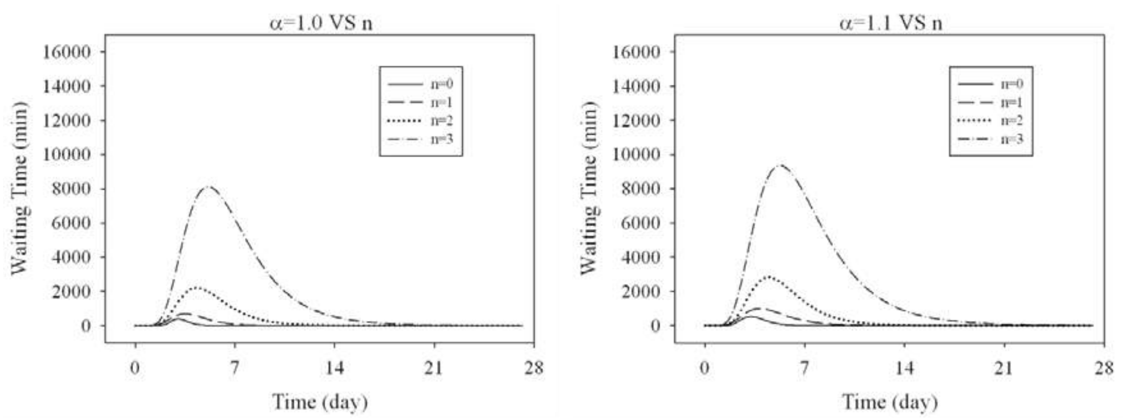


Figure 5. 8 Waiting time curves with n=constant and α= variable (for all the cases described).

By analysing the α variation it is clear that the model is mainly subject to the variation of the peaks values, which rise with the increment of α values: the changes displayed by the bell-curve on the high dimension is the main characteristic. By the contrary, considering the variation regarding the room closures and plotting the waiting time curves with:

- *n*= variable, and
- α= constant.

It is evident that the waiting time increases considerably. The following graphs show this behaviour, for each scale factor α (from 1.0 to 1.6 values). The main difference on these graphs is represented by the width of the bell-curve, rather than by the peak values (that for n=3 are extensively high).



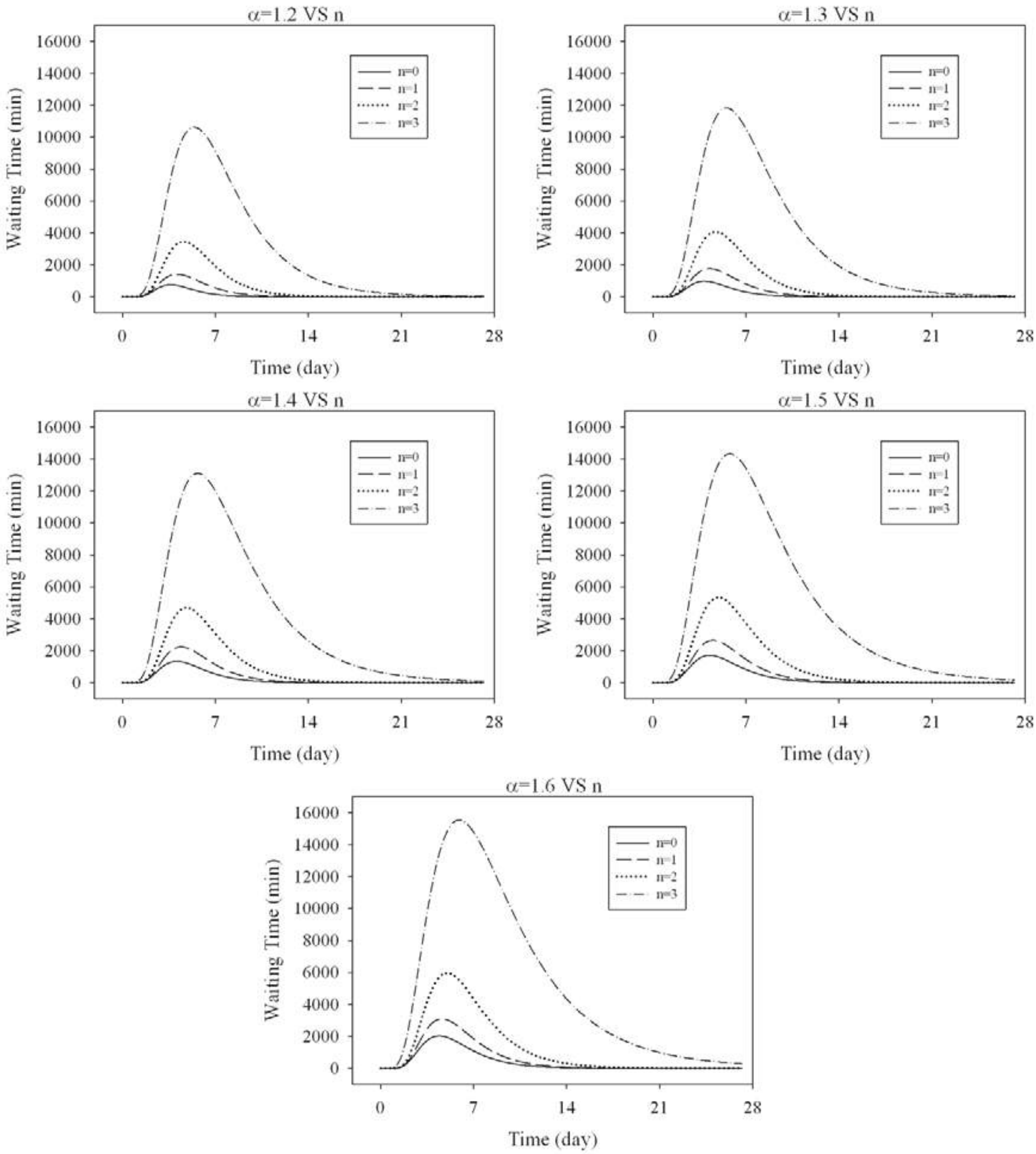


Figure 5. 9 Waiting time curves with n=variable and α= constant (for all the cases described).

After having considered the variation of these two parameters, the main goal is the construction of a mathematical model able to describe the trend of the waiting times, as a function of time, number of closed rooms and seismic arrival rate.

The equation in (5.1) generally indicate how to express the waiting time as a function of the chosen variables:

$$WT = f(t, n, \alpha) \qquad \text{(Eq.5. 1)}$$

where t stands for the time of the simulation, n for the number of closed rooms and α for the seismic arrival rate.

The first consideration to make is that, for any n or α, the curve which describes the waiting time in function of the time is always a bell-curve. Accordingly it is possible to approximate this curve with a Lognormal curve able to fit each variation of the parameters n and α.
As described in the introduction of this chapter, the equation that better approximates the curve is the following:

$$WT(t) = a * \exp(-0{,}5 * \left(\frac{\ln\left(\frac{t}{c}\right)}{b}\right)^2)/t \qquad \text{(Eq.5. 2)}$$

where a, b, and c are the coefficients assuming different values for each variation of the two parameters n and α.

The coefficients are evaluated by a dynamic-nonlinear regression: different sets of these three coefficients (a, b, and c) are calculated, as shown in Table 5.5 (for all the parameter values, see Appendix b).

Table 5.5 Coefficients deriving from the dynamic fit-nonlinear regression analysis of the models with n=0.

Model (name)	**Parameters**		
	a	***b***	***c***
Model_n0E_ α=1.0	1744236	0.1957	4470.938
Model_n0E_ α=1.1	2547769	0.2583	4907.4
Model_n0E_ α=1.2	4175566	0.3698	5940.189
Model_n0E_ α=1.3	5808548	0.3887	6418.565
Model_n0E_ α=1.4	8479162	0.4009	6865.804
Model_n0E_ α=1.5	11353831	0.41	7214.502
Model_n0E_ α=1.6	13917735	0.4135	7482.819

At this point it is worthwhile to find an equation able to express the behaviour of the three parameters as a function of the coefficient α, maintaining the n parameter fixed. The following graphs, for instance, represent only the variation of the parameters for $n=0$ (all the parameters can be found in Appendix b).

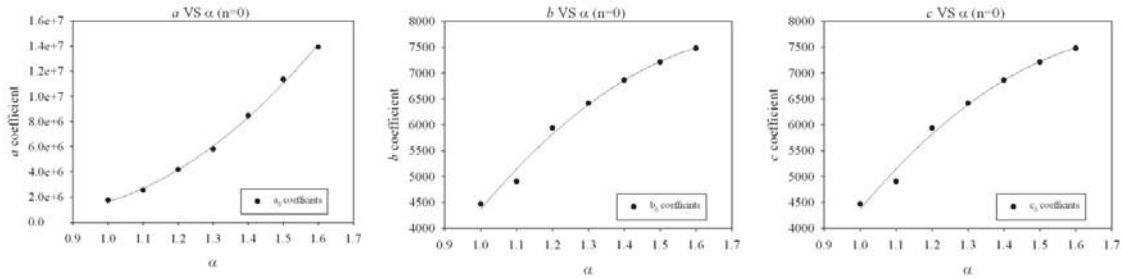


Figure 5. 10 Varying parameters for n=0.

Then, thanks to an additional dynamic-nonlinear regression analysis, it is possible to express the variation of the parameters *a*, *b*, and *c* through a general form of a quadratic polynomial equation, as follows:

$$a(\alpha) = a_0 + a_1\alpha + a_2\alpha^2 \qquad \text{(Eq.5. 3)}$$

$$b(\alpha) = b_0 + b_1\alpha + b_2\alpha^2 \qquad \text{(Eq.5. 4)}$$

$$c(\alpha) = c_0 + c_1\alpha + c_2\alpha^2 \qquad \text{(Eq.5. 5)}$$

These equations are valid for all sets of the three parameters, for *n* coefficient varying from 0 to 3. For each parameter other three sub-parameters are identified. These sub-parameters (a_0, a_1, a_2, b_0, b_1, b_2, c_0, c_1, and c_2) permit to express the general three-parameter-set in function of *α*. Therefore it is possible to write the equation representing the waiting time as a function of both the time *t* and the coefficient *α*.

$$WT(t,\alpha) = a(\alpha) * \exp(-0{,}5 * \left(\frac{\ln\left(\frac{t}{c(\alpha)}\right)}{b(\alpha)}\right)^2)/t \qquad \text{(Eq.5. 6)}$$

Even the sub-coefficients can be correlated as a function of *n*, as the following graphs show, and be represented by an equation. The procedure is the same as the previous one: the graph in Figure 5. 11, for instance, represent only the variation of a_0, a_1, a_2 (first sub-parameter group) for varying *n* (all the sub-parameter sets can be found in Appendix b).

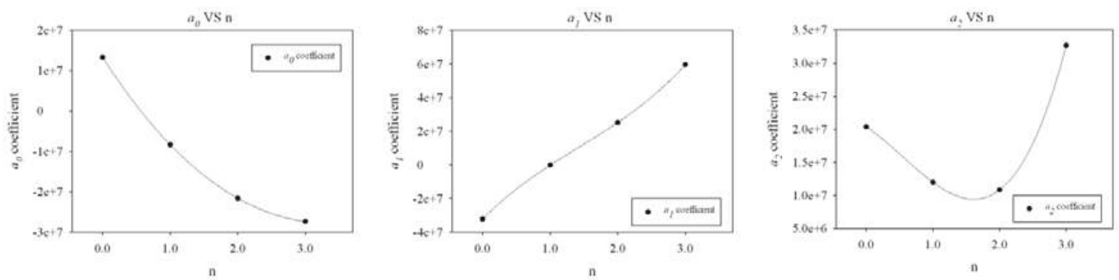


Figure 5. 11 Varying parameters for a_0, a_1, a_2 in function of the n *coefficient.*

After having estimated the other sub-parameters, i.e. b_0, b_1, b_2, c_0, c_1, and c_2, it is possible to find another correlation by means of equations able to describe their trend as a function of *n*, in order to estimate the values for setting the global meta-model (Eq.5. 2). The best fitting estimated is represented, for this case, by the cubic polynomial equation, whose general form is:

$$a(n) = \begin{cases} a_0(n) = a_{00} + a_{01}n + a_{02}n^2 + a_{03}n^3 \\ a_1(n) = a_{10} + a_{11}n + a_{12}n^2 + a_{13}n^3 \\ a_2(n) = a_{20} + a_{21}n + a_{22}n^2 + a_{23}n^3 \end{cases} \qquad \text{(Eq.5. 7)}$$

$$b(n) = \begin{cases} b_0(n) = b_{00} + b_{01}n + b_{02}n^2 + b_{03}n^3 \\ b_1(n) = b_{10} + b_{11}n + b_{12}n^2 + b_{13}n^3 \\ b_2(n) = b_{20} + b_{21}n + b_{22}n^2 + b_{23}n^3 \end{cases} \qquad \text{(Eq.5. 8)}$$

$$c(n) = \begin{cases} c_0(n) = c_{00} + c_{01}n + c_{02}n^2 + c_{03}n^3 \\ c_1(n) = c_{10} + c_{11}n + c_{12}n^2 + c_{13}n^3 \\ c_2(n) = c_{20} + c_{21}n + c_{22}n^2 + c_{23}n^3 \end{cases} \qquad \text{(Eq.5. 9)}$$

Substituting the values determined with the dynamic fitting, the equations become the followings:

$$(n) = \begin{cases} a_0(n) = 13341705.11 - 26110938.14n + 4612817.19n^2 - 143283.98n^3 \\ a_1(n) = -32094014.42 + 40324759.95n - 10944142.247n^2 + 2566340.53n^3 \\ a_2(n) = 20370804.46 - 6705753.61n - 4304009.46n^2 + 2636023.41n^3 \end{cases} \qquad \text{(Eq.5. 10)}$$

$$b(n) = \begin{cases} b_0(n) = -1.72 + 2.52\,n - 1.0\,n^2 + 0.12\,n^3 \\ b_1(n) = 2.8937 - 3.3693\,n + 1.2473\,n^2 - 0.1402\,n^3 \\ b_2(n) = -0.9773 + 1.1281\,n - 0.4031\,n^2 + 0.0446\,n^3 \end{cases} \qquad \text{(Eq.5. 11)}$$

$$c(n) = \begin{cases} c_0(n) = -9073.9362 - 3327.9221\,n + 9075.0383\,n^2 - 2127.5277\,n^3 \\ c_1(n) = 18587.6473 + 8417.0521\,n - 14398.3454\,n^2 + 3296.4067\,n^3 \\ c_2(n) = -5146.9712 - 3776.9696\,n + 5281.2951\,n^2 - 1136.9422\,n^3 \end{cases} \qquad \text{(Eq.5. 12)}$$

In the end, the global meta-model (Eq.5. 13) depending on these three parameters is estimated. It has the following general form:

$$WT(t, \alpha, n) = a(\alpha, \mathrm{n}) * \exp(-0{,}5 * \left(\frac{\ln\left(\frac{t}{c(\alpha, \mathrm{n})}\right)}{b(\alpha, \mathrm{n})} \right)^2)/t \qquad \text{(Eq.5. 13)}$$

This meta-model assesses the waiting time experienced by yellow-code patients, when a damage occurs which determines the permanent closure of the dedicated rooms (from 1 to 3, up to a total of 4). Thanks to an Excel file and to the values found for the parameters, it is possible to estimate the waiting time value for the patients, for a determined number of closed room (*n*), depending on the seismic arrival rate (*α*), for a specific instant of time *t*. An example extrapolated from the Excel file is shown in Figure 5. 12.

n	3
alpha	1.6
t	1000
%	0.7
WT	**5.82**

Figure 5. 12 Estimation of the waiting time for a determined n, α, and t.

The validation of the meta-model can be easily achieved by plotting the estimated WT curve on the top of the drawn WT-curves associated with the group of simulations. The curve calculated with the meta-model equation is drawn with the black line in the graph, while the waiting time for a specific instant of time (*t*) is shown in the red block; the desired values for the parameters are displayed in the red blocks (Figure 5. 13, on the left) with an arrow-shape object. The parameters used in the boxes, which correspond to those which have been previously calculated, are inserted as a coefficient of the analytical equation of WT.

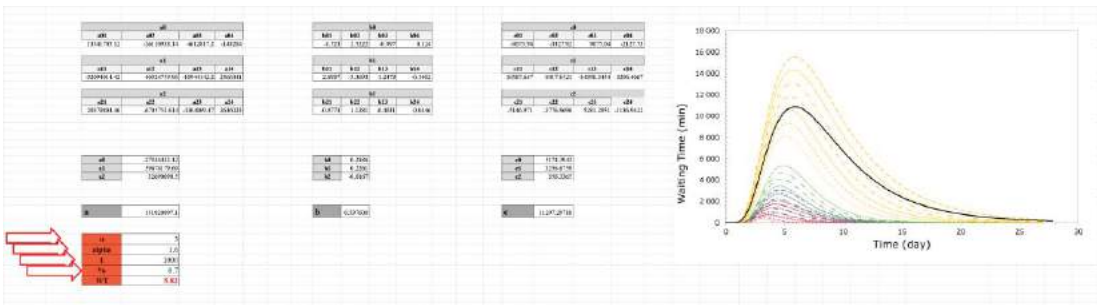


Figure 5. 13 Metamodel graph and validation (extracted from the Excel file).

Moreover, another coefficient is included in the formulation, that is: a percentage (%) which represents the percentage of damaged structure as it is assumed by the methodology in case of structural fragility curves associated with the damage limit state. Accordingly, such a procedure also allows to approximate the damaged area.

5.2.2 CASE 2: permanent room closure

Unlike the previous case, this model starts with the shock due to the earthquake, and the seismic arrival rate begins at time 0 and lasts three days (72 hours). After this critical 72 hours, other 26 days of normal arrival rate are considered for a total amount of 29 days (648 hours). In the normal scenario, resources in terms of medical staff and beds available are re-activated; all-code patients are treated into the emergency department. The diagram corresponding to the simulation properties of this model is represented in Figure 5. 14:

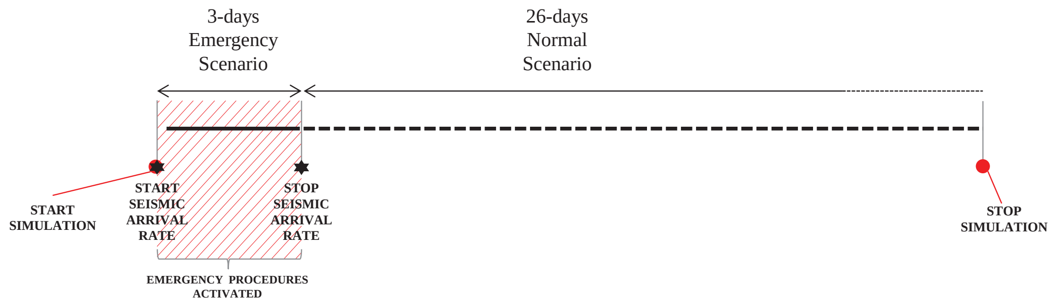


Figure 5. 14 Diagram of the simulation properties (CASE 2).

The peculiarity of this model depends on the presence of the emergency staff only during the emergency phase: after three days (72 hours), the medical staff reverts to the normal setting and the treatments to minor-codes patients are performed again. The general setting of dedicated beds is restored and the ORs do not execute any longer emergency surgeries.

As for CASE1, the goal is to investigate the behaviour of the system under critical condition: in this model real procedures are set into the organizational planning in order to evaluate the system under several conditions. Therefore two varying parameters are taken into account:

- the number of closed rooms, n;
- the seismic arrival rate, α.

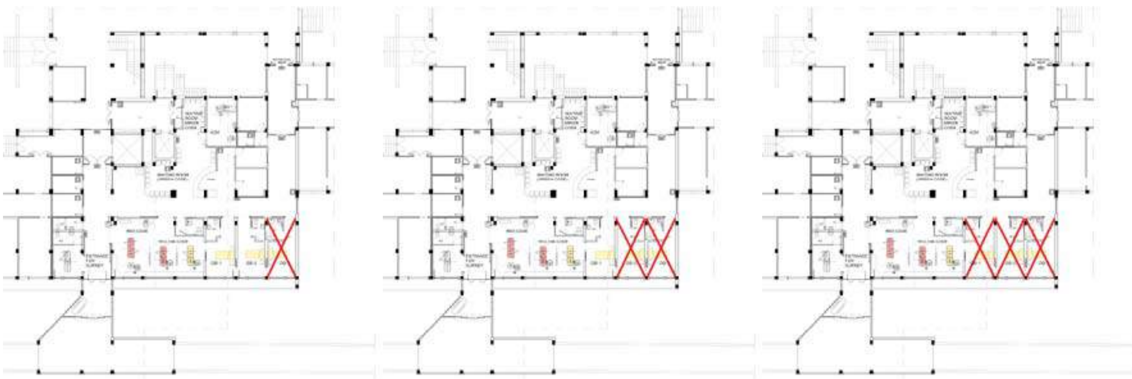


Figure 5. 15 Permanent room closure: representation of the n *coefficient, varying from 1 to 3.*

The number of closed rooms varies from 0 (no closure) to 3, which represents the worst case of damage (Figure 5. 15 shows three cases when rooms are closed, with n values variation from 1 to 3). The totality of closed rooms is not taken into account. The increasing seismic arrival rate is calculated with a scale factor, from α=1 to a α=1.6, as described in the Ch. 4. All the cases in which these two factors combine are analysed. At first seven models (depending on the variation of the parameter α) are performed by varying the seismic arrival rate with no room closure involved. This is shown in Table 5.6:

Table 5.6 Models run with several arrival rates and no closed rooms.

Model (name)	Closure of rooms	Closure time
Model_n0_ α=1.0	NO	-
Model_n0_ α=1.1	NO	-
Model_n0_ α=1.2	NO	-
Model_n0_ α=1.3	NO	-
Model_n0_ α=1.4	NO	-
Model_n0_ α=1.5	NO	-
Model_n0_ α=1.6	NO	-

The waiting times resulted and estimated thanks to the model are manipulated as previously described and the final WT bell-curves are assessed. The following plots represent The results of the models listed in Table 5.6, in terms of waiting time curves for yellow-code patients, are graphically represented in Appendix c.

The same procedure is followed for the models with an increasing number of closed rooms (*n* parameter). These models are listed in Table 5.7, Table 5.8 and Table 5.9. The waiting time curves for each model are estimated with the same technique (for all the graphs, see Appendix c).

Table 5.7 Models developed with varying arrival rates and one closed room (the room closure is maintained for the entire simulation period).

Model (name)	Closure of rooms	Closure time
Model_n1_ α=1.0	1	All run length
Model_n1_ α=1.1	1	All run length
Model_n1_ α=1.2	1	All run length
Model_n1_ α=1.3	1	All run length
Model_n1_ α=1.4	1	All run length
Model_n1_ α=1.5	1	All run length
Model_n1_ α=1.6	1	All run length

Table 5.8 Models developed with varying arrival rates and one closed room (the room closure is maintained for the entire simulation period).

Model (name)	Closure of rooms	Closure time
Model_n2_ α=1.0	2	All run length
Model_n2_ α=1.1	2	All run length
Model_n2_ α=1.2	2	All run length
Model_n2_ α=1.3	2	All run length
Model_n2_ α=1.4	2	All run length
Model_n2_ α=1.5	2	All run length
Model_n2_ α=1.6	2	All run length

Table 5.9 Models developed with varying arrival rates and one closed room (the room closure is maintained for the entire simulation period).

Model (name)	Closure of rooms	Closure time
Model_n3_ α=1.0	3	All run length
Model_n3_ α=1.1	3	All run length
Model_n3_ α=1.2	3	All run length
Model_n3_ α=1.3	3	All run length
Model_n3_ α=1.4	3	All run length
Model_n3_ α=1.5	3	All run length
Model_n3_ α=1.6	3	All run length

The procedure for the construction of the meta-model is similar to that described for case1, and the increasing waiting time is considered as the main variation depending on the two parameters, α and n. The following plots well illustrate the dissimilarities displayed by different simulations, where the n parameter is constant, while the α parameter varies:

- n = constant
- α = variable

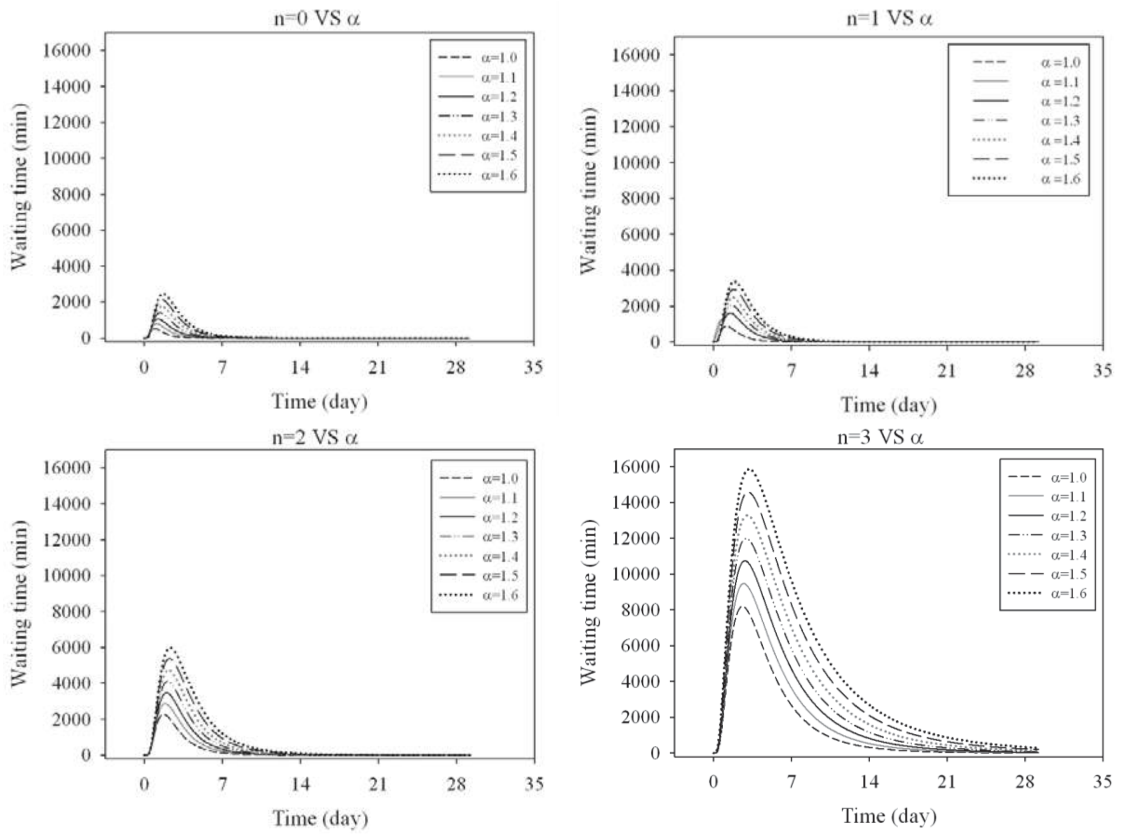
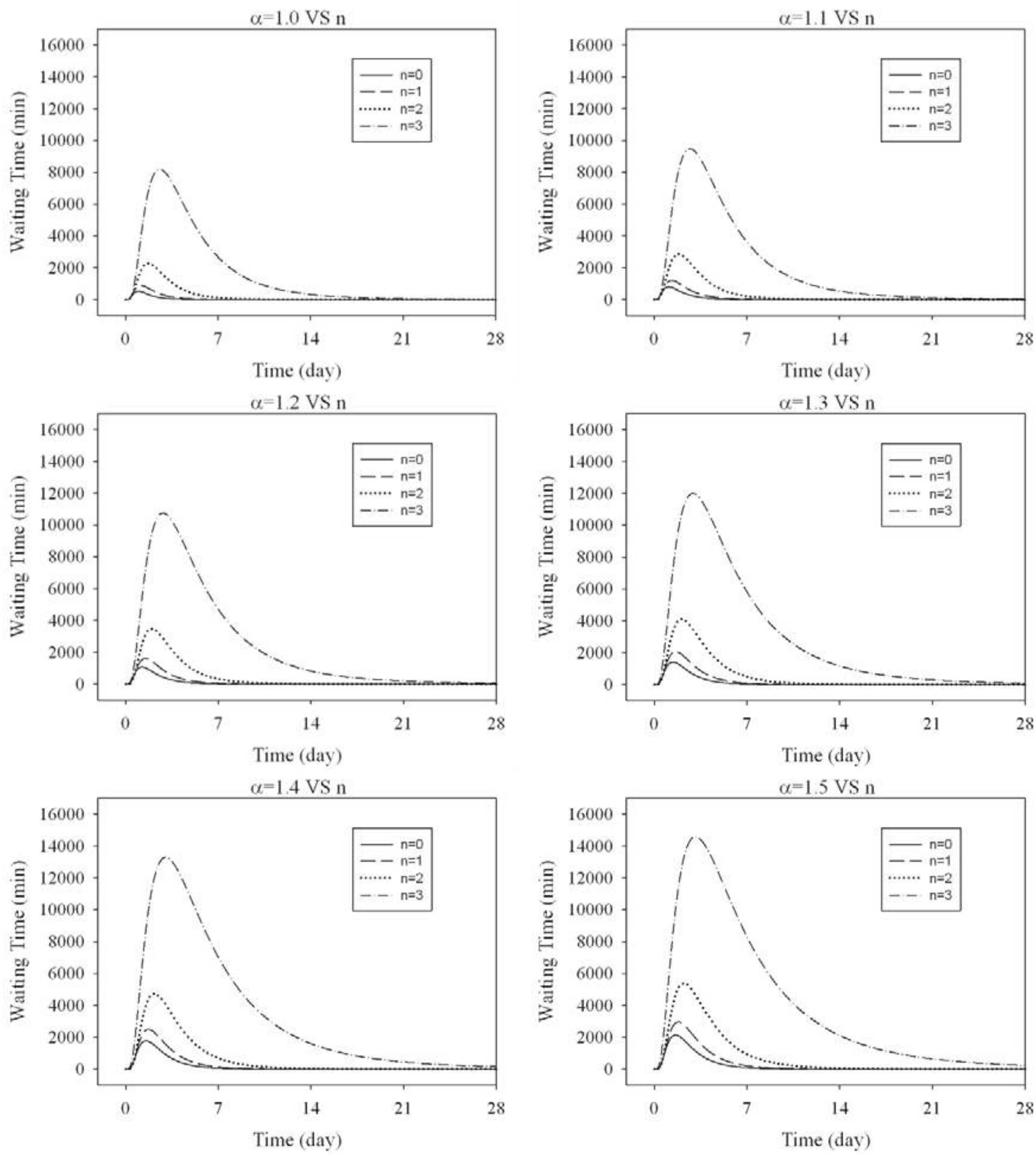


Figure 5. 16 Waiting time curves with n=constant and α= variable (for all the cases described).

The analysis of the α parameter indicate that the most significant change regards the waiting time peaks : accordingly, the dimension which is mostly affected by such variation is the height of the curve. However, considering the variation regarding the room closures and plotting the waiting time curves with:

- n = variable, and
- α = constant

it is evident that the waiting time increases considerably. The following graphs show this behaviour, for each scale factor α (from 1.0 to 1.6 values). The main difference on these graphs is represented by the width of the bell-curve, rather than by the peak values (that for n=3 are extensively high).


α=1.0 VS n
α=1.1 VS n
α=1.2 VS n
α=1.3 VS n
α=1.4 VS n
α=1.5 VS n
Waiting Time (min)
Time (day)
n=0
n=1
n=2
n=3
0
2000
4000
6000
8000
10000
12000
14000
16000
0
7
14
21
28

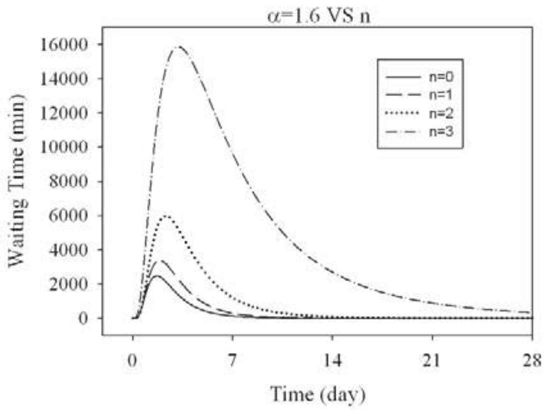


Figure 5. 17 Waiting time curves with n=variable and α= constant (for all the cases described).

To construct a mathematical model able to describe the trend of the waiting times, as a function of the time (*t*), the number of closed rooms (*n*), and the seismic arrival rate (*α*), the equation in (Eq.5. **1** must be considered inasmuch it describes the general form to express the waiting time.

The first consideration to make is that, for any *n* or *α*, the curve which describes the waiting time in function of the time is always a bell-curve. Accordingly it is possible to approximate this curve with a Lognormal curve able to fit each variation of the parameters *n* and *α*.

The coefficients are evaluated by a dynamic-nonlinear regression: different sets of these three coefficients (*a*, *b*, and *c*) are calculated, as shown in Table 5.10 (for all the parameter values, see Appendix c).

Table 5.10 Coefficients deriving from the dynamic fit-nonlinear regression analysis of the models with n=0.

Model (name)	Parameters		
	a	***b***	***c***
Model_n0_ α=1.0	858222.3	0.5791	1949.654
Model_n0_ α=1.1	1525402	0.6076	2292.202
Model_n0_ α=1.2	2283117	0.619	2567.834
Model_n0_ α=1.3	3387885	0.5903	2855.197
Model_n0_ α=1.4	4610620	0.5877	3096.354
Model_n0_ α=1.5	5801531	0.5879	3238.725
Model_n0_ α=1.6	7075789	0.5867	3405.085

At this point it is worthwhile to find an equation able to express the behaviour of the three parameters as a function of the coefficient *α*, maintaining the *n* parameter fixed. The following graphs, for instance, represent only the variation of the parameters for *n=0* (all the parameters can be found in Appendix c).

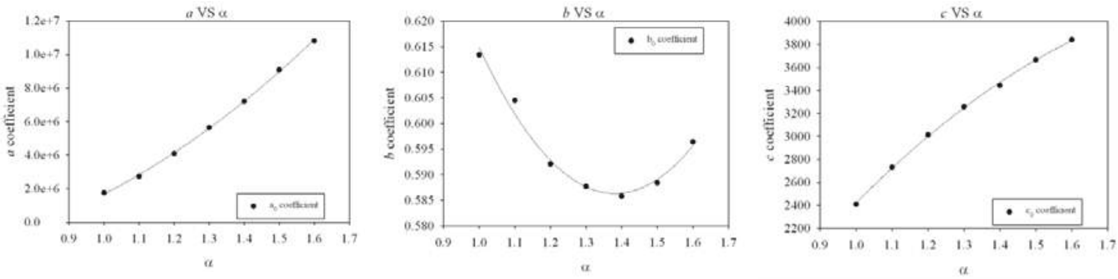


Figure 5. 18 Varying parameters for n=0.

Then, thanks to an additional dynamic-nonlinear regression analysis, it is possible to express the variation of the parameters *a*, *b*, and *c* through a general form of a quadratic polynomial equation, such as in CASE 1; the equations are valid for all sets of the three parameters, for *n* coefficient varying from 0 to 3. For each parameter other three sub-parameters are identified. These sub-parameters (a_0, a_1, a_2, b_0, b_1, b_2, c_0, c_1, and c_2) permit to express the general three-parameter-set in function of *α*. Even the sub-coefficients can be correlated as a function of *n*, as the following graphs show, and be represented by an equation. The procedure is the same as the previous one: the graph in Figure 11, for instance, represent only the variation of a_0, a_1, a_2 (first sub-parameter group) for varying *n* (all the sub-parameter sets can be found in Appendix c).

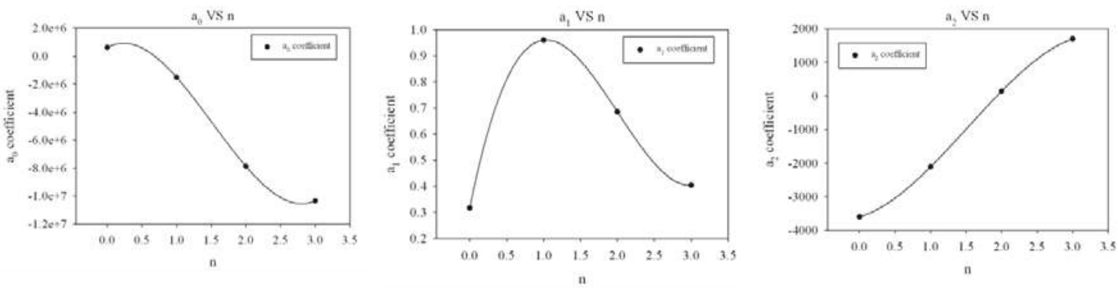


Figure 5. 19 Varying parameters for a_0, a_1, a_2 in function of the n *coefficient.*

It is possible to find another correlation by means of equations able to describe the trend of the sub-parameters (b_0, b_1, b_2, c_0, c_1, and c_2) as a function of *n*, in order to estimate the values for setting the global meta-model (Eq.5. 1). The best fitting estimated is represented, for this case, by the cubic polynomial equation. Substituting the values found through the dynamic fitting into (Eq.5. 13, the meta-model in function of *t*, *α* and *n* is determined.

This Metamodel assesses the waiting time experienced by yellow-code patients, when a damage occurs which determines the permanent closure of the dedicated rooms (from 1 to 3, up to a total of 4).

The validation of the metamodel can be easily achieved by plotting the estimated WT curve on the top of the drawn WT-curves associated with the group of simulations. The curve calculated with the metamodel equation is drawn with the black line in the graph, while the waiting time for a specific instant of time (*t*) is shown in the red block; the desired values for the parameters are displayed in the red blocks (Figure 5. 20, on the left) with an arrow-shape object.

The parameters used in the boxes, which correspond to those which have been previously calculated, are inserted as a coefficient of the analytical equation of WT.

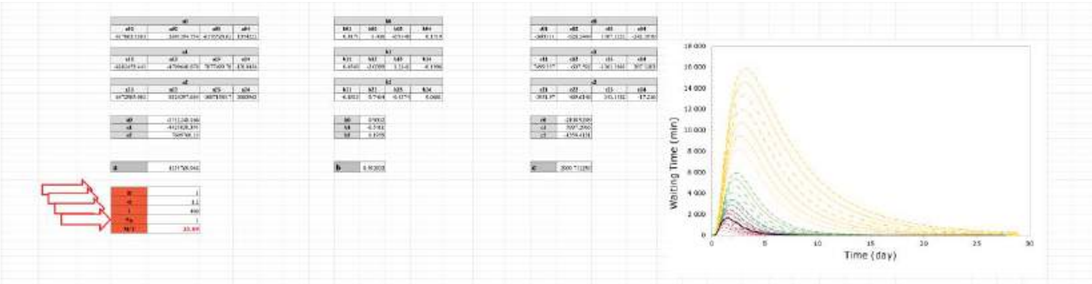


Figure 5. 20 Metamodel graph and validation (extracted from the Excel file).

Moreover, another coefficient is included in the formulation, that is: a percentage (%) which represents the percentage of damaged structure as it is assumed by the methodology in case of structural fragility curves associated with the damage limit state. Accordingly, such a procedure also allows to approximate the damaged area.

5.2.3 CASE 3: temporary room closure

In order to obtain results for damages caused by non-structural failures, a series of hypotheses involving the temporary closure of the OBI rooms have been performed. The simulations for this type of organizational model relies on a total amount of 29 days (648 hours). The simulation starts with the shock due to the earthquake (which is represented by the seismic arrival rate, lasting 72 hours): after the emergency phase (3 days), other 26 days of normal arrival rate are taken into account. During the normal phase, resources in terms of medical staff and number and beds available are re-activated; all-code patients are treated into the emergency department. The diagram corresponding to the simulation properties of this model is represented in Figure 5. 21:

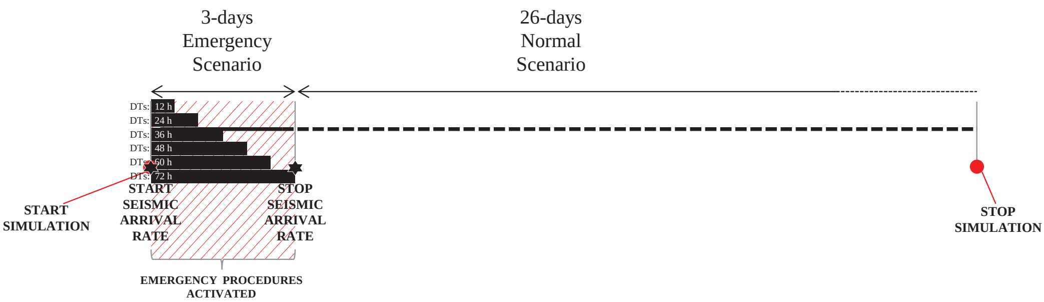


Figure 5. 21 Diagram of the simulation properties (CASE 3).

In this case, room closure affects the OBI rooms but, unlike permanent closures, after a pre-set amount of time, these rooms become available again. As for permanent closures, during the simulation two variables are taken into account:

- the number of closed rooms, *n*;
- the downtime, *DTs*.

Figure 5. 21 shows the different downtimes (DTs) during the emergency phase, while Figure 5. 22 shows the variation of the *n* parameter, from 1 to 3. The yellow-cross indicates that the closure is not permanent. Table 5.11 lists the downtimes of the rooms that, thereafter, return to be operative, i.e. patients' accommodation is again available. During the downtime, a restoration is supposed in order to reopen the room.

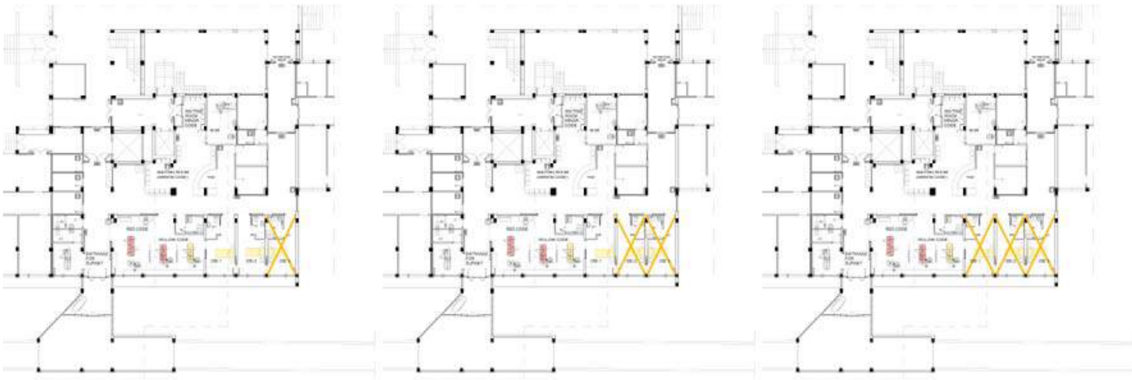


Figure 5. 22 Temporary room closures: representation of the n *coefficient, varying from 1 to 3.*

The different downtimes indicate the time needed to restore the room, conditioned by the failures of non-structural components, the effects on other non-structural elements and the extension of the damage; furthermore, it is worth to consider the difficulties encountered by operators to reach the hospital and to work during the emergency. For these reasons six time intervals (*DTs*) are supposed which cover the entire emergency phase (3 days, 72 hours) and correspond to the last downtime: this assumption matches the first hypothesis of permanent closure.

Table 5.11 Models developed with several downtimes (DTs) for one OBI room.

Model (name)	Closure of rooms	Downtime (hour)
Model_OBI1_DT12	YES	12
Model_OBI1_DT24	YES	24
Model_OBI1_DT36	YES	36
Model_OBI1_DT48	YES	48
Model_OBI1_DT60	YES	60
Model_OBI1_DT72	YES	72

The waiting times estimated by the model are manipulated as described in par. 5.1 and the final bell-curves are assessed.

The same procedure is followed for the models having a higher number of closed rooms (*n* parameter), as shown in Table 5.12 and Table 5.13. The waiting time curves for each model are estimated with the same technique (for all the plots, see Appendix d).

Table 5.12 Table 1 Models developed with several downtimes (DTs) for two OBI rooms.

Model (name)	Closure of rooms	Downtime (hour)
Model_OBI2_DT12	YES	12
Model_OBI2_DT24	YES	24
Model_OBI2_DT36	YES	36
Model_OBI2_DT48	YES	48
Model_OBI2_DT60	YES	60
Model_OBI2_DT72	YES	72

Table 5.13 Table 2 Models developed with several downtimes (DTs) for three OBI rooms.

Model (name)	Closure of rooms	Downtime (hour)
Model_OBI3_DT12	YES	12
Model_OBI3_DT24	YES	24
Model_OBI3_DT36	YES	36
Model_OBI3_DT48	YES	48
Model_OBI3_DT60	YES	60
Model_OBI3_DT72	YES	72

The procedure for constructing the meta-model is similar to the others (see par. 5.2.1.1), however, since the number of simulations is different, several dynamic-nonlinear regressions are applied. By varying the two coefficients, the waiting time curves change noticeably; therefore it is possible to build the analytical Metamodel also for temporary closures, using the two parameters, *DTs* and *n*. Figure 5. 23 describes the variation of the waiting time curves, applying the different downtimes (*DTs*), for a fixed number of closed rooms *n*:

- *n* = constant
- *DTs* = variable

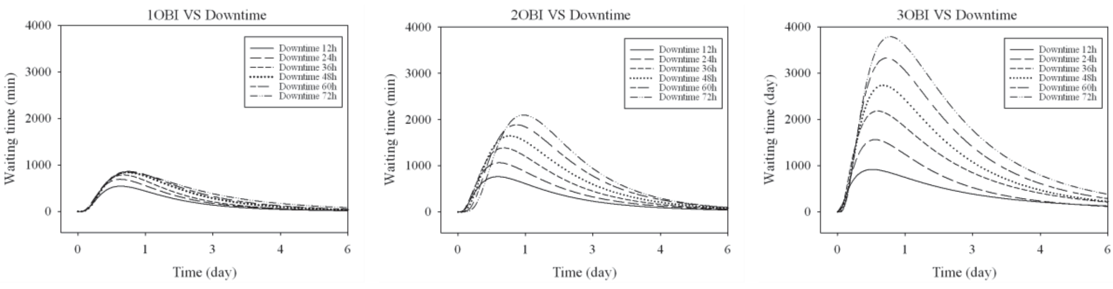


Figure 5. 23 Waiting time curves with n=constant and DTs=variable.

Then, plotting the waiting time curves considering the *n* parameter (closured rooms) and a fixed downtime:

- *n* = variable, and
- *DTs* = constant

a considerable increase in waiting time is evident. The following graphs show this behaviour, for each time-range performed *Dts* (with values from 12 to 72 hours). The main dimension subject to variation is the width of the bell-curve, while the height dimension is more susceptible to the change of the downtime.

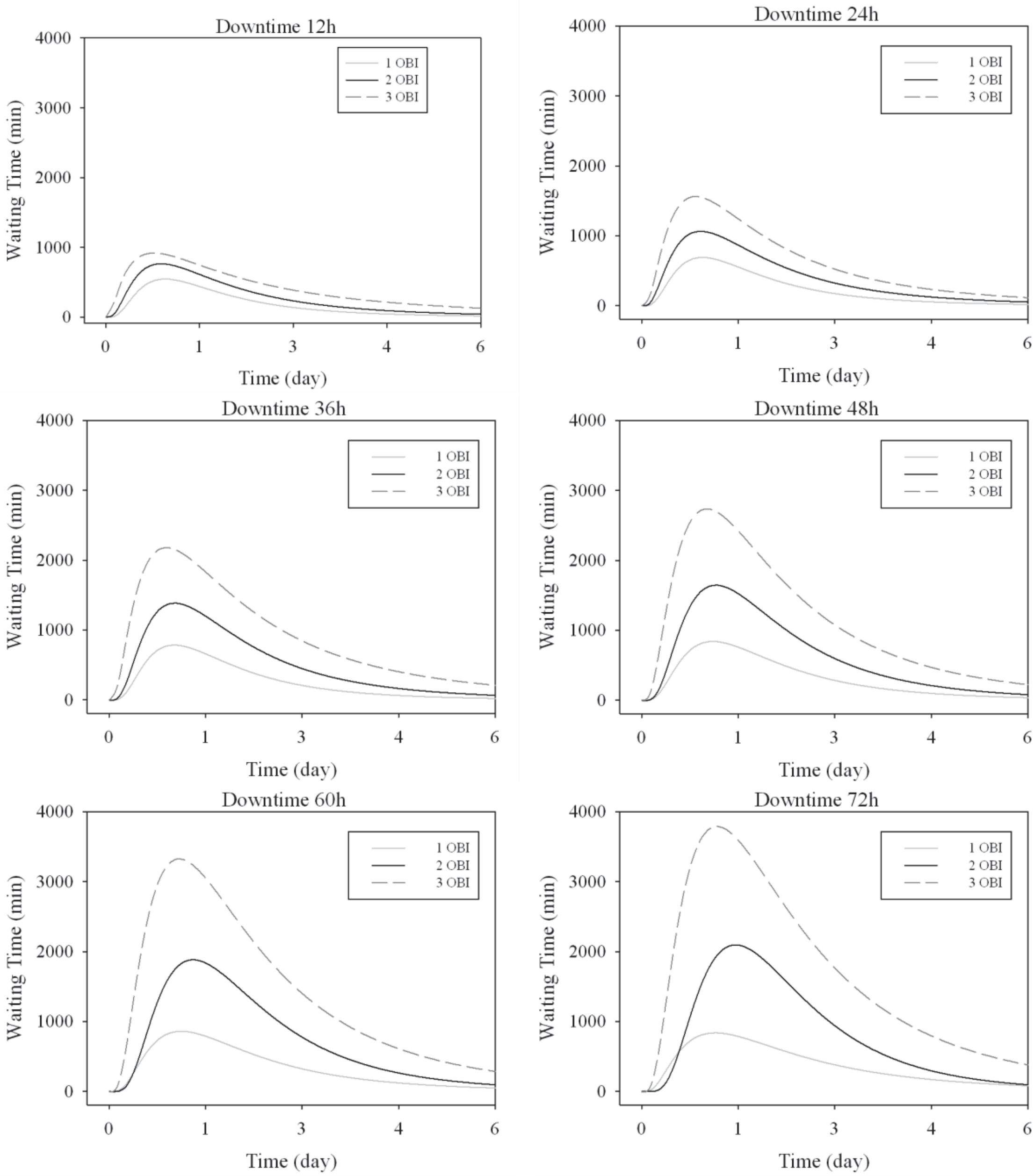


Figure 5. 24 Waiting time curves with DTs=constant and n=variable.

To construct the mathematical model able to describe the trend of the waiting times, in function of the time (*t*), the number of closed rooms (*n*), and the downtime (*DTs*), the equation in (Eq.5. 14 must be considered, that describes the general form to express the waiting time, in function of the variables presented:

$$WT = f(t, n, DT) \qquad \text{(Eq.5. 14)}$$

where *t* is the time of the simulation, *n* is the number of closed rooms and *DTs* is the downtime.

The first consideration to make is that, for any *n* or *DTs*, the curve which describes the waiting time in function of the time is always a bell-curve. Accordingly it is possible to approximate this curve with a Lognormal curve able to fit each variation of the parameters *n* and *DTs*.
As described in the introduction of this chapter, the equation that better approximates the curve is the following:

$$WT(t) = a * \exp(-0{,}5 * \left(\frac{\ln\left(\frac{t}{c}\right)}{b}\right)^2)/t \qquad \text{(Eq.5. 15)}$$

where *a*, *b*, and *c* are the coefficients assuming different values for variable *n* and *DTs*.

The coefficients are evaluated by a dynamic-nonlinear regression: different sets of these three coefficients (*a*, *b*, and *c*) are calculated, as shown in Table 5.14 (for all the parameter values, see Appendix d).

Table 5.14 Coefficients deriving from the dynamic fit-nonlinear regression analysis of the models with n=1.

Model (name)	**Parameters**		
	a	***b***	***c***
Model_OBI1_DT12	877764	0.6954	2049.951
Model_OBI1_DT24	1110638	0.6989	2047.238
Model_OBI1_DT36	1324832	0.6664	2104.993
Model_OBI1_DT48	1560612	0.679	2335.281
Model_OBI1_DT60	1652308	0.7038	2456.303
Model_OBI1_DT72	1719602	0.7704	2759.523

At this point it is worthwhile to find an equation able to express the behaviour of the three parameters as a function of the coefficient *DTs*, maintaining the *n* parameter fixed. The following graphs, for instance, represent only the variation of the parameters for *n=0* (all the parameters can be found in Appendix d).

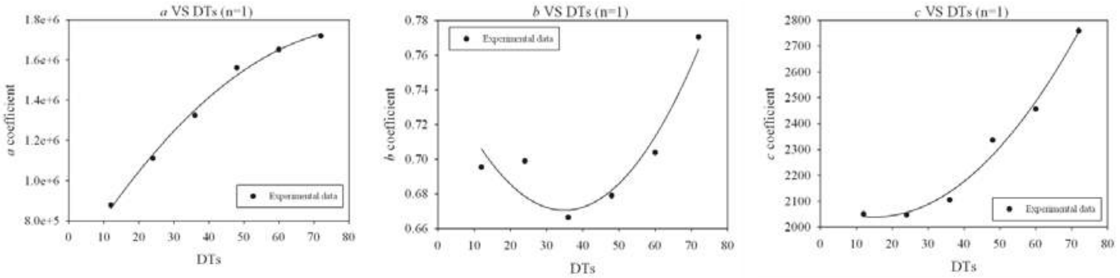


Figure 5. 25 Varying a, b, c parameters for n=1.

Parameters a, b, and c are expressed through a quadratic polynomial equation. Then, each parameter other three sub-parameters are identified (a_0, a_1, a_2, b_0, b_1, b_2, c_0, c_1, and c_2).

Therefore it is possible to write the equation representing the waiting time as a function of both the time *t* and the coefficient *DTs.*

$$WT(t, DTs) = a(DTs) * \exp(-0{,}5 * \left(\frac{\ln\left(\frac{t}{c(DTs)}\right)}{b(DTs)}\right)^2)/t \qquad \text{(Eq.5. 16)}$$

Even the sub-coefficients can be correlated as a function of *n*, as the following graphs show, and be represented by an equation. The procedure is the same as the previous one: the following graphs, for instance, represent only the variation of a_0, a_1, a_2 (first sub-parameter group) for varying *n* (all the sub-parameter sets can be found in Appendix d).

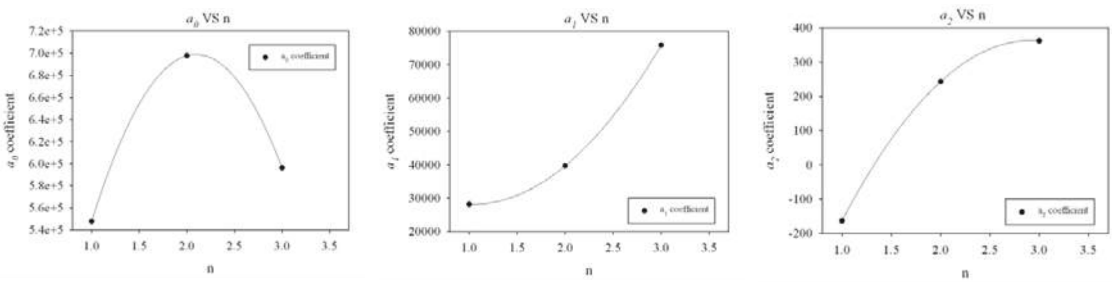


Figure 5. 26 Varying parameters of a_0, a_1, a_2 in function of n coefficient.

Such as in the cases previously described, the global meta-model (Eq.5. 17) depending on these three parameters is estimated. It has the following general form:

$$WT(t, DTs, n) = a(DTs, n) * \exp(-0{,}5 * \left(\frac{\ln\left(\frac{t}{c(DTs, n)}\right)}{b(DTs, n)}\right)^2)/t \qquad \text{(Eq.5. 17)}$$

This meta-model assesses the waiting time experienced by yellow-code patients, when a downtime from 0 to 60 hours occurs which determines the permanent closure of the dedicated rooms (from 1 to 3). The meta-model is not valid for values over the 60 hours, therefore if the downtime exceeds the 80% of the emergency phase, i.e. its total duration, such a case is not considered as a temporary closure. The Metamodel is able to estimate the waiting time experienced by the patients for a determined number of closed rooms c *n*, depending on the downtime occurred (*DTs*), for a specific instant of time *t*.

The validation of the meta-model can be easily achieved by plotting the estimated WT curve on the top of the drawn WT-curves associated with the group of simulations. The curve calculated with the metamodel equation is drawn with the black line in the graph, while the waiting time for a specific instant of time (*t*) is shown in the red block; the desired values for the parameters are displayed in the red blocks (Figure 5. 27, on the left) with an arrow-shape object. The parameters used in the boxes, which correspond to those which have been previously calculated, are inserted as a coefficient of the analytical equation of WT.

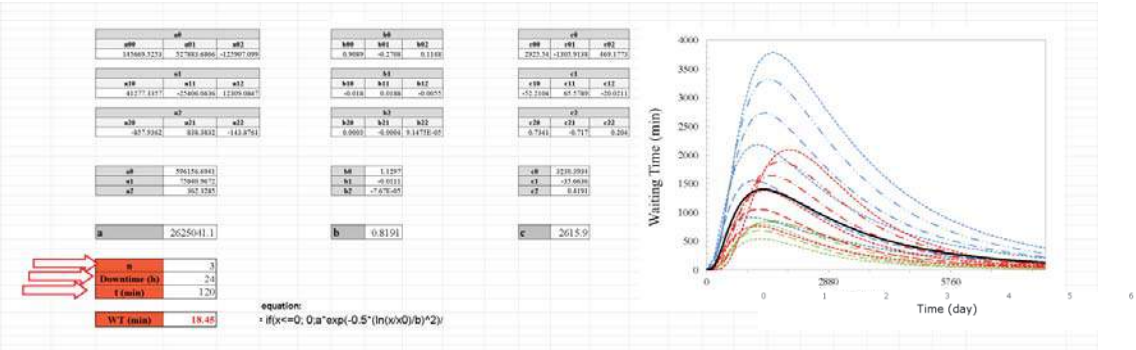


Figure 5. 27 Metamodel graph and validation through the Excel file.

5.2.4 Analysis of the peaks of waiting time

The waiting time peaks are worth to be analysed for each model. This analysis permits to evaluate the variation regarding the maximum waiting time experienced and, in particular, the extent to which such variation depends on the two parameters used for the simulations.

Figure 5. 28 shows that the values displayed by the two parameters follow different trends: in this particular case, for a model subject to permanent closures during the emergency phase, the increase of the peaks is linear if associated with α variation, and exponential if associated with a varying number of closed rooms. In effect, by increasing the seismic arrival rate the maximum time increases proportionally to the variation of α. The values in Figure 5. 28 resulted from the analyses are high, but it depends on the extreme α increment. The unrealistic input (seismic arrival rate) is used for the mathematical assessing of the Meta-model and for the evaluation of the organizational system. Moreover the analysis on the “sensitive parameters” (see Chapter 6) show the importance of the proportion between inflow of patients and resources, that in this case is not take into account.

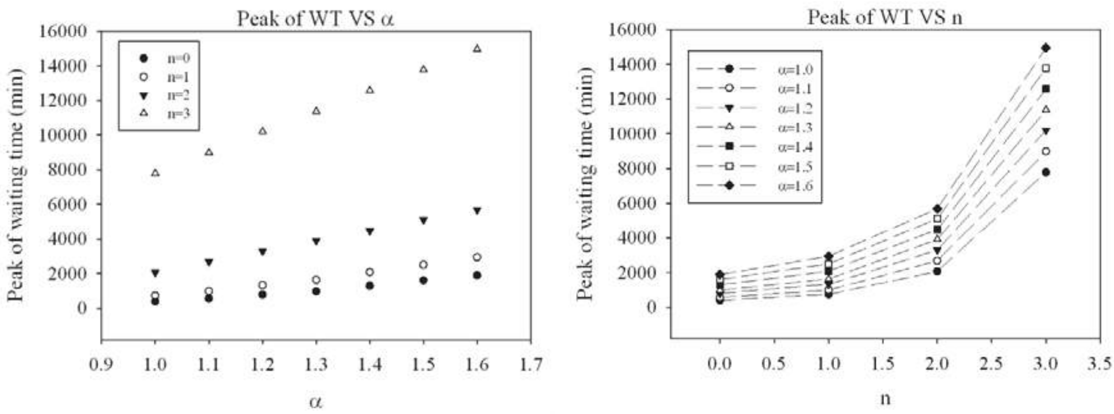


Figure 5. 28 Waiting time peaks in function of the α parameter (on the left), and the n parameter (on the right) for CASE 1-MODEL.

It is worth to note that for case 1 and case2 the peaks have the same trend, which is related to the variation regarding the seismic arrival rate and the number of closed rooms; however, the peaks vary in values since in case 1 there are more resources available and, even if the *n* parameter does not change (it varies from 1 to 3, on a total amount of 4 rooms), the higher availability of medical staff affects the system.
Since the values are so high, it is possible to conclude that, globally, the responses of the two system are not so different. Therefore an analysis on the "sensitive parameters" needs to be performed in order to investigate which parameters mostly affect the system response (see Chapter 6).

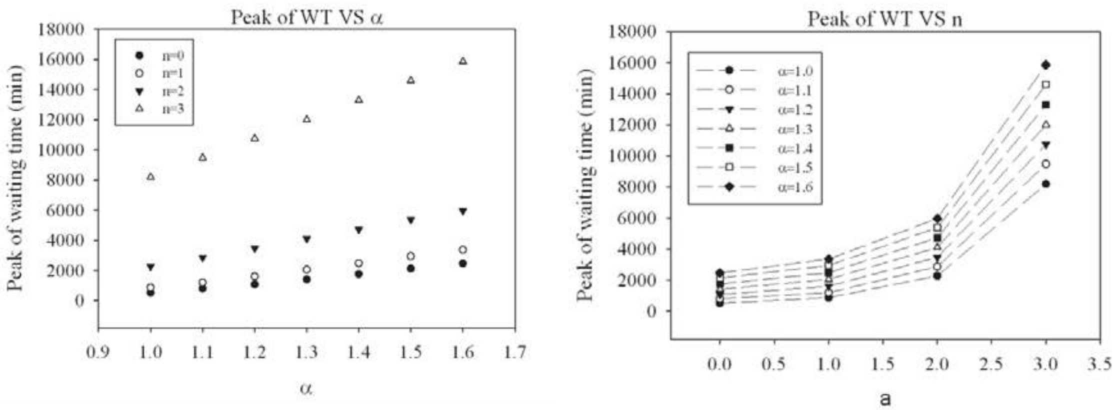


Figure 5. 29 Waiting time peaks in function of the α *parameter (on the left), and the* n *parameter (on the right) for CASE 2-MODEL.*

Case 1 displays the same behaviour: here the differences are related to the availability of additional resources during the simulations. If the model suffers from temporary downtimes of the rooms, the trend of WT peaks related to the number of the closed rooms is less evident. This result is associated with the time of the closures that, on the base of the whole simulation-length, is less incisive.

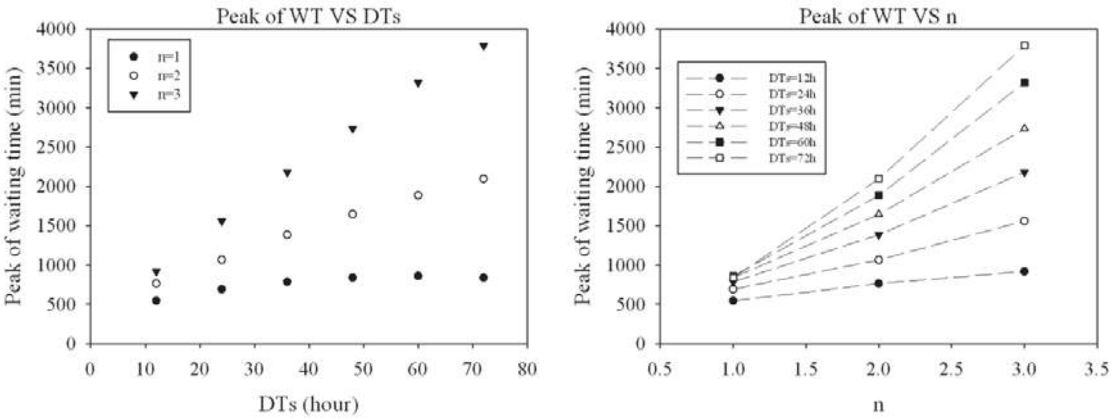


Figure 5. 30 Waiting time peaks for different downtimes (on the left) and for different closed rooms (on the right) for CASE 3-MODEL.

5.3 Resilience

In order to estimate the total resilience of the system, the maximum waiting time value displayed during the simulation needs to be identified. Such a value corresponds to the worst occurrence for a system after an earthquake shock. It is quite improbable for hospital system to offer continuous medical treatments when more than half rooms are unavailable; however, it is convenient to hypothesize even extreme circumstances in order to prevent detrimental actions due to the unawareness of the system performance.

5.3.1 Estimation of the total loss of functionality

The meta-model data clearly indicate that the worst occurrence for the system verifies when the number of down rooms corresponds to the number of feasible rooms. This state of affairs is due to the reality of the hospital situation in an emergency, when the contribution of the system is still sufficient to take care of the injured population.
Generally speaking, in healthcare systems the maximum number of down rooms is determined by:

$$n_{max} = n_{tot} - 1 \quad \text{(Eq.5. 18)}$$

where n_{max} is the maximum value of closed/down rooms and n_{tot} corresponds to the total number of rooms for a specific category of patients, thanks to which the hospital is still considered to be functional.
In order to calculate the n_{max}, it would be useful work with the hospital staff and in collaboration with the hospital network leader.
The number of maximum rooms that can be closed is an indispensable factor to estimate the strategic points for both the waiting time curve and the associated resilience curve.

5.3.2 Equivalence between curves and representative points

The main issue is represented by the correspondence between the waiting time curve and the related resilience curve. For this procedure it is possible to assume that the increase in waiting time during an emergency corresponds to a decrease in the functionality of the system (for more information, see par. 2.2.1). Given this assumption, it is possible to identify the strategic points for building the resilience curve on the base of the associated waiting time curve.

Accordingly, it is convenient to linearize the waiting time curve. To do this the maximum waiting time registered during the simulations must be taken into account: the maximum waiting time point registered during several simulations, despite different ordinate values, has different abscissa (x-coordinate) values depending on the characteristics of the models and the variation of its parameters.

As illustrated in Figure 5. 31, the maximum waiting time can be shifted along the x-axis, but also the y-coordinate values vary conditioned by the variation of the parameters; therefore to identify the maximum value it is possible to evaluate only the ordinates of the waiting time points.,

Maybe it is convenient to suppose that, even if the waiting time increases following a variable incline, a drastic increase in waiting time implies a drastic loss of functionality. Accordingly it is possible identify the loss of functionality at the time the shock occurs.

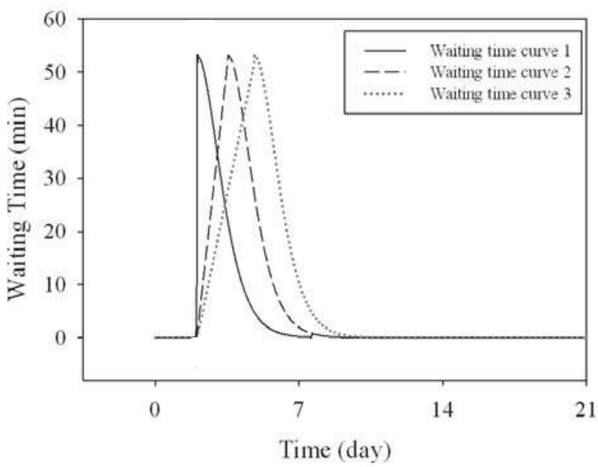


Figure 5. 31 Several possibilities of x-coordinates for the WT_{max} having the same y-coordinate.

As a consequence it becomes easier to compare different resilience curves corresponding to different scenarios in a system. After the setting of the maximum waiting time values, the equivalence of areas is adopted as a method to linearize the curves (cf. Figure 5. 32).

The equivalent area of the two curves is used to obtain the new linearized curve, for which specific points can be taken into account. The points represented within the graph and the table (cf. Figure 5. 33 and Table 5.15) are representative of the equivalent waiting time curve calculated by the equivalent area as a result of the organizational model of the system.

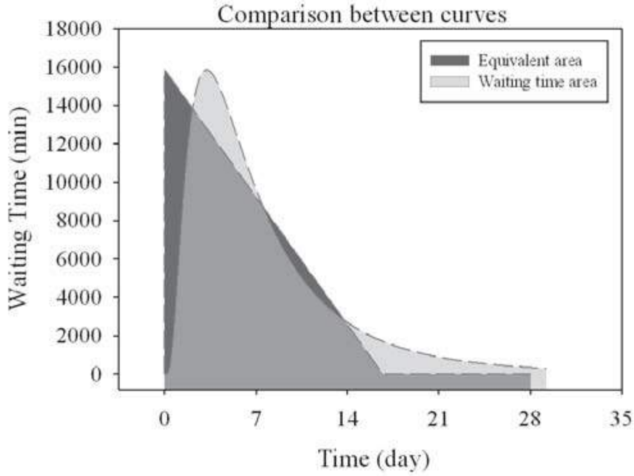


Figure 5. 32 Conversion between the equivalent areas.

The representative points illustrated in Figure 5. 33 and shown in the table below, are the main points used to build the associated resilience curve. Point A represents the starting point, while point B is the time at which the earthquake strikes; point C is the maximum waiting time value according to the experimental data and point D is the point representing the normalization of the waiting time.

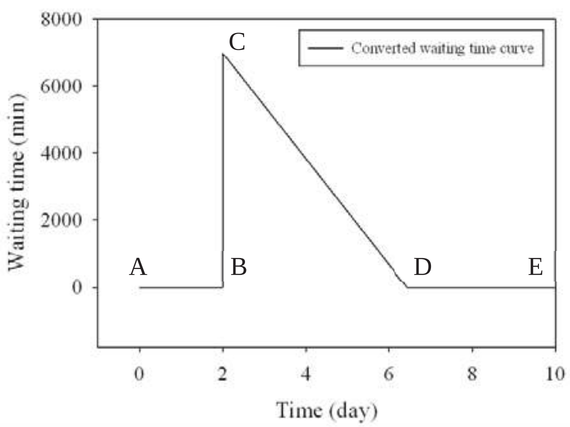


Figure 5. 33 Conversion between the equivalent areas.

Table 5.15 Points related to the conversion of the equivalent area

POINT	X-coordinate	Y-coordinate
A	0	0
B	Shock time	0
C	Shock time	max peak
D	shock time+ equivalent base	normalized WT
E	Simulation end	normalized WT

It is worth to note that the abscissa value of point C at the time the earthquake strikes. Finally, point E is the end of the simulation and also represents the restored waiting time in the system. These point acquire related meanings once translated into a resilience equivalent curve, as illustrated in Figure 5. 34 and Table 5.16. Accordingly point C becomes the representative point of the loss of functionality of the system, while point D represents the restoring point, i.e. the time the system reverts to its functionality.

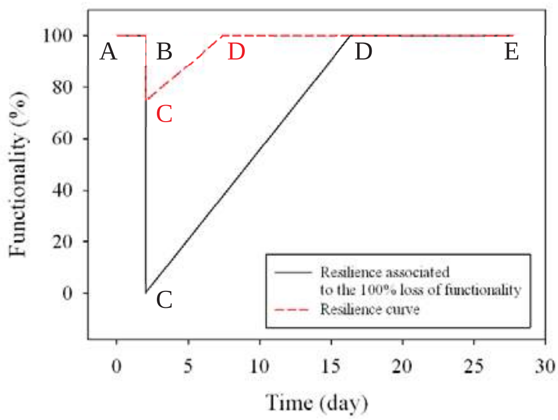


Figure 5. 34 Conversion through the equivalent areas.

Table 5.16 Points related to the conversion of the equivalent area

POINT	X-coordinate	Y-coordinate
A	0	Full functionality
B	shock time	Full functionality
C	shock time	Residual functionality
D	shock time+ equivalent base	Restored functionality
E	Simulation end	Restored functionality

The point C during several scenarios is calculated on the basis of the worst case acceptable for the hospital system. Once the point C in the worst case represents the total loss of functionality, associated with the highest value registered of the waiting time, all the other cases can be calculated. More specification are included into paragraph 5.3.2.2.

5.3.2.1 **Simplified recovery function model**

Once the representative points of the resilience curve are identified, bearing in mind the mathematical definition of resilience[6], it is essential to determine the function between point C and point D in the resilience curve. Indeed this is a complex operation: the recovery process – to be more precise the behaviour of the system in the time span between loss of functionality and recovery – depends on multiple factors affecting the system, like: time dimensions, spatial dimensions (e.g. different neighbourhoods may have different recovery paths), and interdependencies between different economic sectors involved (Cimellaro et al. 2009).

Currently few accurate recovery process models have been developed, in particular Miles and Chang (2006) have set out the foundations for building models of community recovery, presenting a comprehensive conceptual model, which indeed is too complicated for the purpose of this work.. However, the oversimplification provided by Cimellaro et al. (2009) permits to use recovery functions that can fit the more accurate results obtained with the model by Miles and Chang (2006)

Three possible recovery functions can be selected depending on the system and the social response: (i) a linear equation, (ii) an exponential equation (Kafali & Grigoriu 2005), and (iii) a trigonometric equation (Chang & Shinozuka 2004), as illustrated below:

[6] Resilience is defined graphically as the normalized shaded area underneath the functionality function of a system, defined as Q(t). Q(t) is a non-stationary stochastic process and each ensemble is a piecewise continuous function […] (Cimellaro et al. 2010, pag.2).

linear: $$f_{rec}(t, T_{RE}) = \left(1 - \frac{t - t_{0E}}{T_{RE}}\right) \quad \text{(Eq.5. 19)}$$

exponential: $$f_{rec}(t) = exp[-(t - t_{0E})\,(ln200)/T_{RE}] \quad \text{(Eq.5. 20)}$$

trigonometric: $$f_{rec}(t) = 0.5\{1 + cos[\pi\,(t - t_{0E})/T_{RE}]\} \quad \text{(Eq.5. 21)}$$

where t is the time, t_{0E} is the initial time of the extreme event E, and T_{RE} is the recovery time from event E.

The simplest form is the linear recovery function that is generally used when there is no information available about the organization of the community: however, as shown in Figure 5. 35, it is possible to associate the linear function (Eq.5. 19) with an average-prepared community, the exponential function (Eq.5. 20) with a not well-prepared community, and the trigonometric (Eq.5. 21 with a well-prepared community.

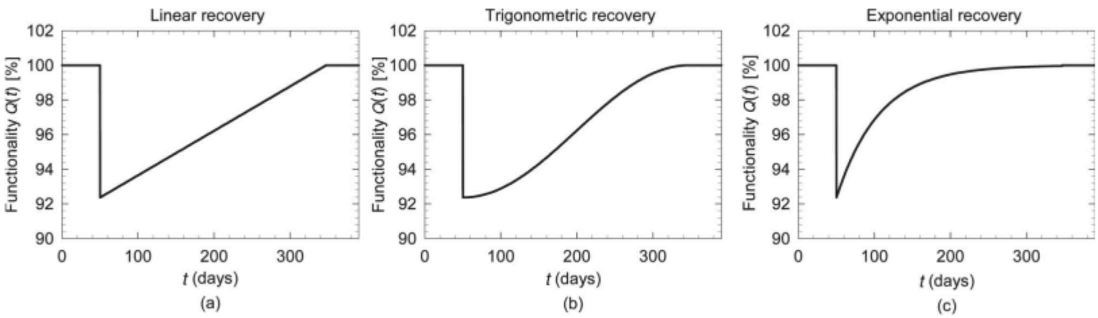


Figure 5. 35 (Cimellaro, Reinhorn and Bruneau, 2010) Functionality curves associated with the different equations: (a) average-prepared community (no information is provided regarding preparedness and available resources); (b) not well-prepared community (the social response is driven by some initial inflow resources, but then the rapidity of the recovery process slows down); (c) well-prepared community (the community displays an increasing organization and sometimes other communities offer their help so that the rapidity of the recovery process increases over time).

For the sake of simplicity this work uses the linear equation and the resilience curve obtained from the waiting time curve comparison is approximated with the equation in (Eq.5. 19): from point C in the resilience diagram the system improves its functionality in a linear way, until it reaches a new restored level of functionality (signalled by point D).
Indeed when the recovery process ends the system not necessarily reverts to its pre-disaster performance: depending on the performance of the system and on the characteristics of the organizational model, it can only be assumed *a priori* that some degree of functionality is restored.
To conclude, the resilience curve can be described as follows:

- the segment AB is the line joining the starting point of the simulation (A) with the starting time of the earthquake;

- the segment BC represents the loss of functionality of the system calculated on the base of the worst case as a percentage-base derivative;
- the segment CD is the linear segment adopted in this specific case, and better described in the following paragraph;
- the last segment, i.e. segment ED, represents the waiting time value of the restored organizational aspects into the hospital.

5.3.2.2 **Maximum value of point C**

The total loss of functionality in a system is determined on the base of the worst case calculated by the simulations for which a total loss of functionality (100%) is assumed. The maximum waiting time registered in that case is considered as the maximum loss of functionality due to the specific variation of the parameters used during the simulations.
By assuming a case of total loss of functionality it is possible to calculate/estimate the other resilience curves, following the general equation exemplified below:

$$full\ functionality - functionality\ loss_{(p_1=i,\, p_2=k)} = residual\ functionality_{(p_1=i,\, p_2=k)} \quad \text{(Eq.5. 22)}$$

where p_1 and p_2 respectively represents the condition 1 and the condition 2 which vary during the scenario, and the functionality loss is represented by the maximum waiting time, i.e. point C.

$$100 - Ycoordinate_{C\ point_{(p_1=i\ ,\, p_2=k)}} = residual\ functionality \quad \text{(Eq.5. 23)}$$

In order to assess the Y-coordinate of point C in the resilience curve, it is necessary to equalize the results to the maximum waiting time (by representing point C on the WT-curve and the 0% of functionality in the system) for each simulation, with a simple proportion:

$$MaxWT_{(p_1=max\ ,\, p_2=max)}: 100 = MaxWT_{(p_1=i\ ,\, p_2=k)}: x \quad \text{(Eq.5. 24)}$$

where $p_1 = max$ and $p_2 = max$ are the extreme conditions in which the maximum waiting time is registered.
By assuming the maximum waiting time to correspond to the maximum loss of functionality of the system (Eq.5. 25), all the other simulations due to the variation of the parameters involved are scaled on the base of the maximum case registered.

$$MaxWT_{(p_1=max\ ,\, p_2=max)} = MaxLOSS_{(p_1=max\ ,\, p_2=max)} = MinFUNCTIONALITY_{(p_1=max\ ,\, p_2=max)} \quad \text{(Eq.5. 25)}$$

Such a procedure permits to construct all resilience curves:

5.3.3 Evaluating global resilience in a post-earthquake period

For a global understanding of the hospital system, it may be useful to fix a limit time within which to assess the resilience of the hospital.

Considering the length of emergency phase (3 days), the drastic conditions assumed for the system and the amount of the seismic arrival rate, it is possible to fix the value of the limit time as five times the length of the emergency phase. This means that the global resilience of the hospital can be assessed 15 days after the shock, even though the system has not been completely restored yet. According to this methodology, the best possible case, say undamaged structure and patients' normal arrival rate, indicates a 100% resilience of the system: as a consequence, all other possible cases can be described by calibrating these opposite outcomes, i.e. worst case and best case. Considering the area under the curve, within the two limits defined, i.e. shock time and limit time (15 days after the shock), it is possible to estimate the resilience of the system with a percentage value, as shown in Figure 5. 36:

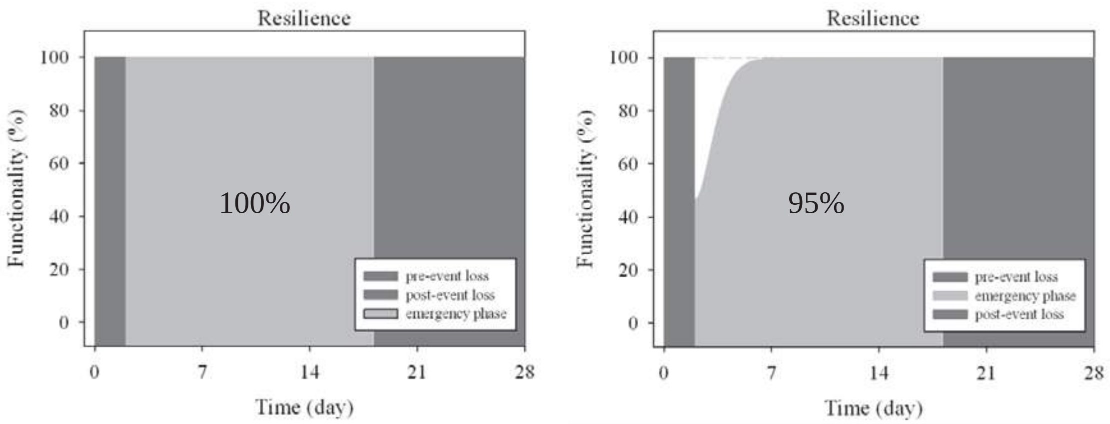


Figure 5. 36 Resilience evaluation by using the area method.

Chapter 6

Case study: application of the methodology

In this chapter the results obtained by applying the Methodology presented in Chapter 3 will be shown in terms of fragility curves. By comparing fragility curves referred to different scenarios it is possible to estimate the effects of the single examined properties regarding physical features and organizational aspects of the hospital system.

The first part of the chapter presents the structural fragility curves and then the fragility curves related to the assessment of structural and non-structural systems.

The second part of the chapter deals with some possible applicative outcomes of the illustrated procedure in order to show how the meta-model could be employed to improve the hospital functionality.

Finally a resilience assessment is provided, following the procedure sketched in par. 6.1.4.

6.1 Tool setting for the case study

The comparison between demand and capacity, estimated by considering the contribution of the non-structural components, has been performed by using a deterministic method, as a simpler alternative to probabilistic approaches.

Following this procedure, the probability of failure for non-structural components is estimated by considering different demands associated with various limit states. According to the Italian Code (Nuove Norme Tecniche per le Costruzioni, 2008), seismic demands corresponding to the Ultimate Limit State (called SLV in this work), and the Damage Limit State (associated with Serviceability Limit State, i.e. SLO, and Damage Limit State, i.e. SLD) are derived from the analyses of the building on the base of the 3D Ruaumouko model using an incremental dynamic analysis (IDA) for two ground motion record sets (FEMA and Site Specific).

6.1.1 Structural fragility curves

Structural fragility curves have been found for each ground level of the building: they have been calculated on the base of the displacement occurred at the storey after the assumed ground motion. Figure 6. 1 and Figure 6. 2 show the comparison between the obtained fragility curves. The comparison underlines the increasing acceleration from the ground level to the second floor. In effect, the highest value of acceleration is often registered on the top of the structure: this fact is very important for the current analysis, since the functionality of the system must be checked at each storey.

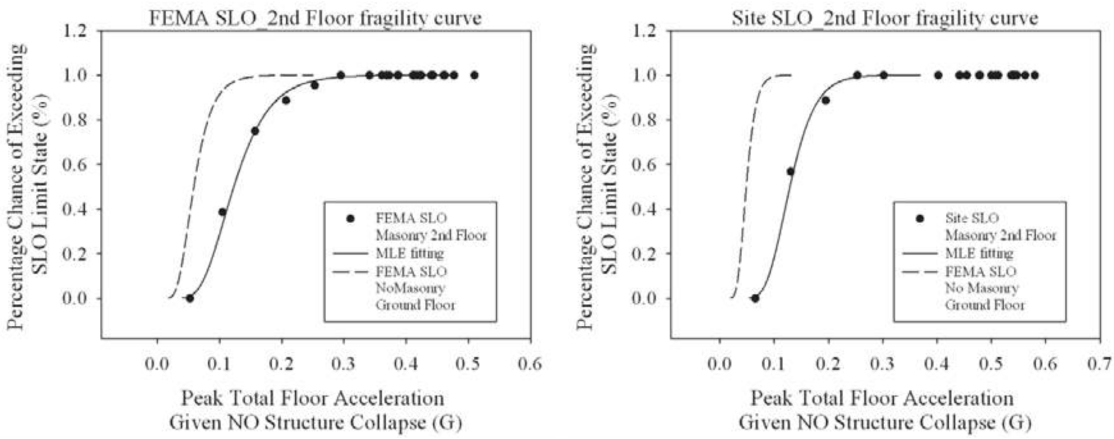


Figure 6. 1 Peak total first floor acceleration fragility curve for the serviceability limit state of the second floor(FEMA record set on the left and Site Specific record set on the right), compared with the fragility observed at the ground level.

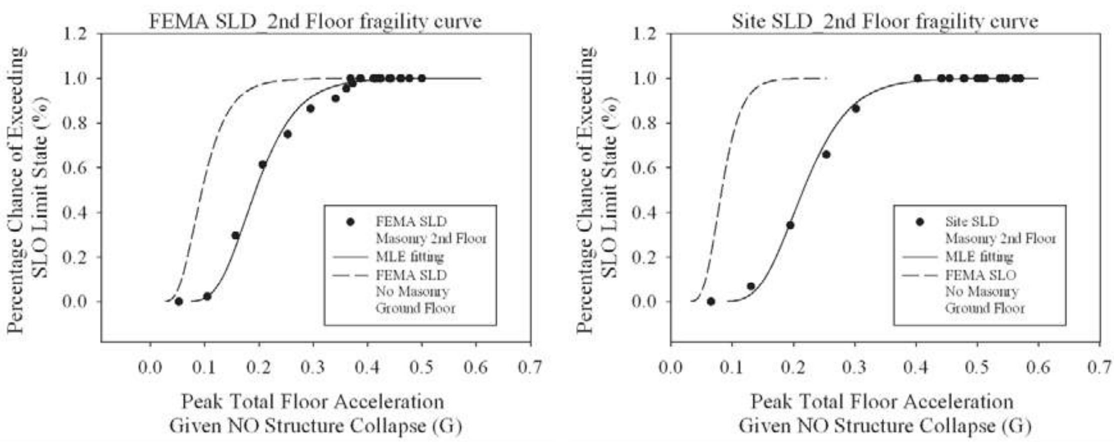


Figure 6. 2 Peak total first floor acceleration fragility curve for the damage limit state of the second floor(FEMA record set on the left and Site Specific record set on the right), compared with the fragility observed at the ground level.

The fragility curves at each storey have been calculated even for the serviceability and damage limit states and for the two record sets. In these two cases, all the non-structural components allocated inside the emergency department have been considered. Many examples of non-structural components can be made, for instance all the cabinets and their contents and all the "acceleration sensitive"[7] ones. By considering Figure 6. 1- Figure 6. 4 it is evident how the amount of acceleration at each storey can vary and, therefore, how different the required capacity of the non-structural components should be.

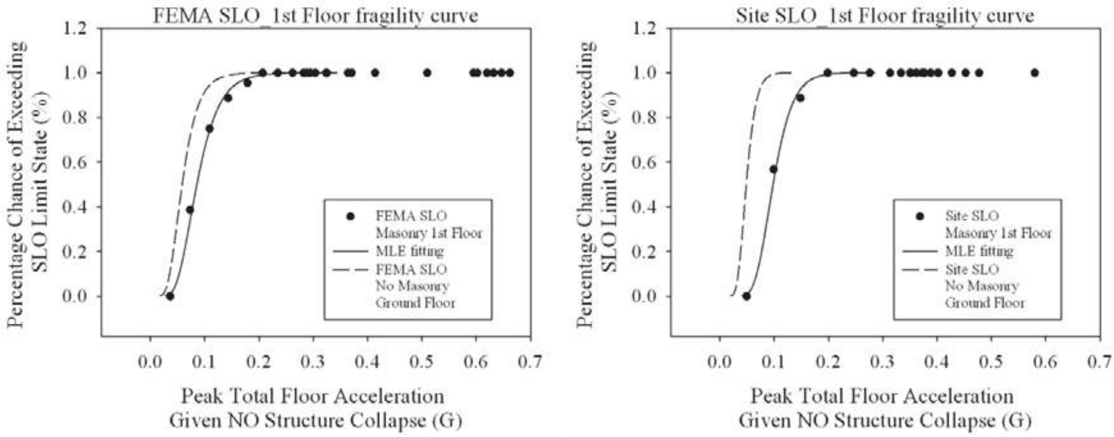


Figure 6. 3 Peak total first floor acceleration fragility curve for the serviceability limit state (FEMA record set on the left and Site Specific record set on the right).

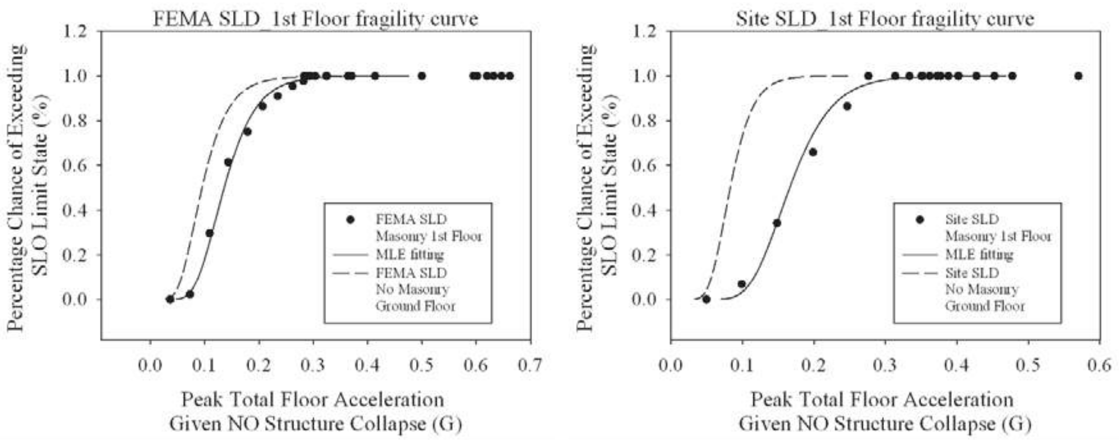


Figure 6. 4 Peak total first floor acceleration fragility curve for the damage limit state (FEMA record set on the left and Site Specific record set on the right).

6.1.2 Comprehensive (structural and non-structural) fragility curves

Suspending ceiling systems in two different types of room in the emergency unit have been assessed with reference to serviceability and damage limit states of the structure. The fragility of

[7] "Acceleration sensitive components" are elements subject to acceleration such as the Engineering Demand Parameter (EDP). By making a comparison between structural fragility curves and several non-structural fragility curves it is worth to note that non-structural elements must be susceptible to the same EDP. In this work the comparison is made between the structural fragility curves expressed by acceleration, and two non-structural components belonging to the class of the "acceleration sensitive components".

similar ceiling systems developed at the University of Canterbury, and based on experimental testing, has been adopted as the capacity curve for the case study. The envelope curve of the components' fragility curves has considered as the capacity. In addition, another non-structural component, i.e. the cabinet, has been taken into account thanks to the data provided by Cosenza et al. 2014. Accelerations for all the curves have been considered as the Engineering demand parameter (EDP).

6.1.2.1 Suspended ceiling system

For the Intensive Brief Observation (OBI) and the emergency rooms (ER) the fragility curves have been calculated both for the structure and for the comprehensive system, say the structure and the suspending ceiling system together. Figure 6. 5 - Figure 6. 8 show the comparison between these fragility curves. Since the suspended ceiling of the storey is related to the behaviour of its top floor, to find the fragility curves of the comprehensive system the fragility curves for the upper floor must have been calculated.

The comparison between these curves shows the effect of the non-structural components for the evaluation of the seismic reliability of the whole system, which is related to the type of closure (temporary or permanent) actualised. Figure 6. 5 and Figure 6. 6 indicate the assessments for the emergency room: it is clear that the suspending ceiling system is safe with reference to the serviceability and damage limit states. The same behaviour can be noted for the suspended ceiling system in the OBI room (Figure 6. 7 and Figure 6. 8), that is smaller in size and therefore is represented by a right-shifted curve in the graphs. Figure 6. 7 and Figure 6. 8 illustrate the big difference in safety between structural and non-structural fragility curves. In particular, it is possible to note how, choosing any referring peak floor acceleration (PFA), no simultaneous percentage of exceeding the associated limits (structural or non-structural) occurs.

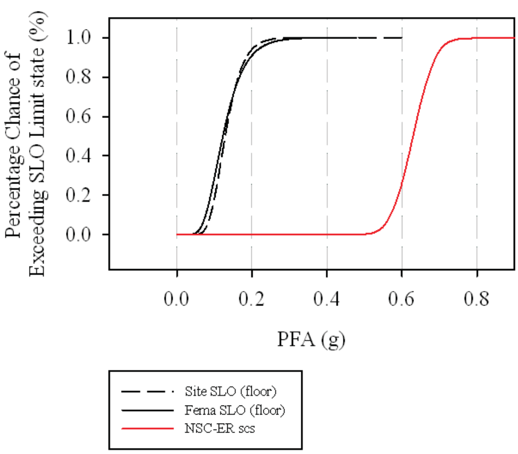


Figure 6. 5 Comparison between structural fragility curve associated to the serviceability limit state and the suspended ceiling system fragility curve for the emergency room.

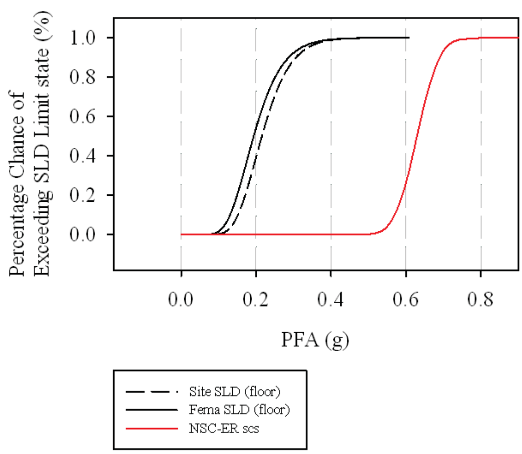


Figure 6. 6 Comparison between structural fragility curve associated to the damage limit state and suspended ceiling system fragility curve for the emergency room.

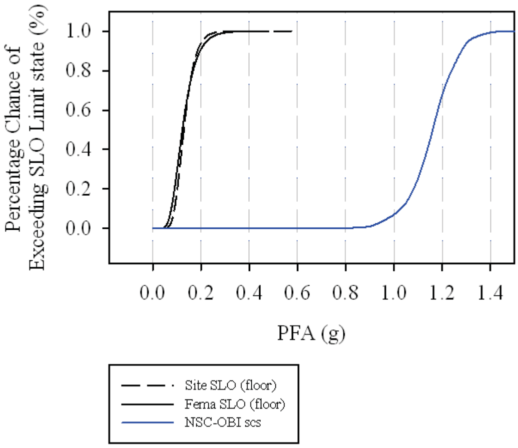


Figure 6. 7 Comparison between structural fragility curves associated to the serviceability limit state and suspended ceiling system fragility curve for the OBI room.

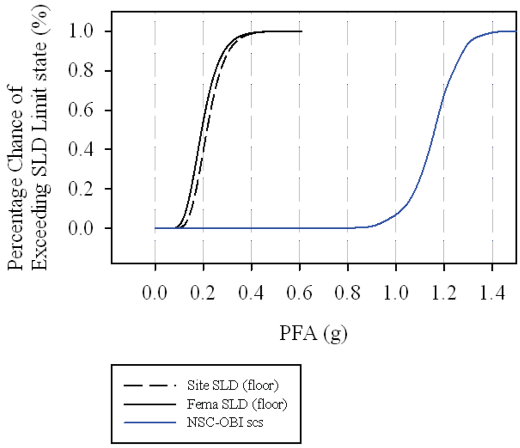


Figure 6. 8 Comparison between structural fragility curves associated to the damage limit state and suspended ceiling system fragility curve for the OBI room.

It is important to point out the significance of the curves representing the suspended ceiling system for both the rooms: in the case of the ER room, the representative fragility curve for the whole system is plotted, while for the OBI room the envelope curve is taken into account: both the curves are shifted on the left of the graph. To assess a safety condition for the entire system, the failure is assumed to occur as soon as one of its components fails. Such a failure does not necessarily imply the component to fail down: any loss of functionality depending on a certain component can result in a damage to other non-structural elements and may hinder the medical service. This strict assessing is precautionary for the service provided by this kind of facility and is closely related to the security of medical measures.

6.1.2.2 Cabinets

To assess the fragility curves associated with the cabinets the response parameters at the bottom level of the considered storey must be taken into account: this is due to the fact that cabinets are subject to the acceleration of their floor. The fragility curves of the structure, associated with the first floor, for both ground motion sets and limit states (serviceability and damage) are compared. *Figure 6. 9* and *Figure 6. 10* show that, for the considered limits states, no failure occurs to the cabinet. In this case, as it happens for other components (see par. 6.1.2.1), for a chosen referring acceleration no failure or damage can cause a permanent closure of the rooms (the term “permanent” conventionally refers to a time span of 3 days, i.e. the emergency phase).

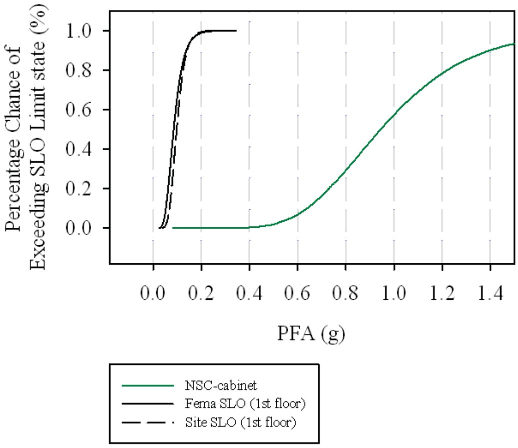


Figure 6. 9 Comparison between structural fragility curves associated to the serviceability limit state and the cabinet fragility curve.

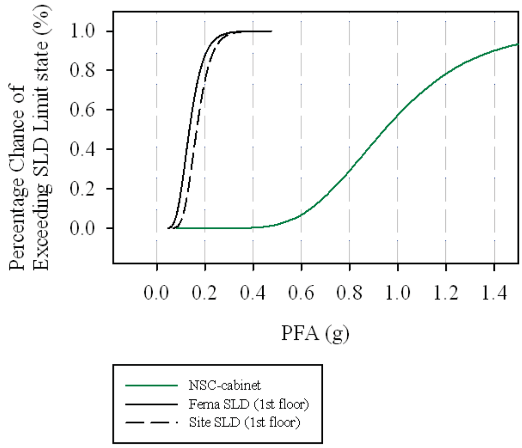


Figure 6. 10 Comparison between structural fragility curves associated to the damage limit state and the cabinet fragility curve.

As illustrated in par. 3.3.1.1, an emergency room is a complete and complex assembled combination of elements that must be operating and functional at the same time. This means that if a non-structural components fails, despite not being essential for the treatment of emergency patients, it can represent an obstacle for the functionality of the room. Therefore for assuming a room to be completely functional the contribution of all its non-structural components must be considered.

Despite the scarcity of data, a rough evaluation is possible that is representative of the proposed procedure: such an evaluation relies on the analysis of two non-structural elements inside the same room.

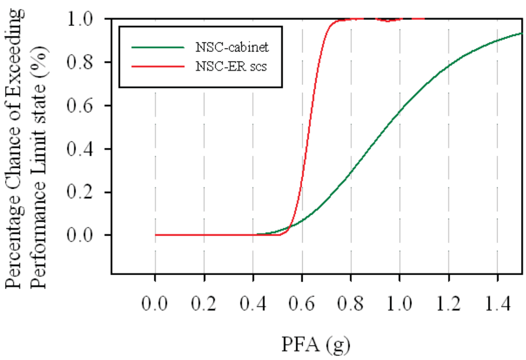


Figure 6. 11 Comparison between non-structural fragility curves of non-structural components in the ER room.

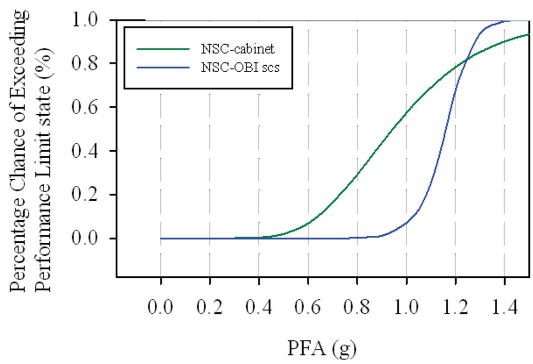


Figure 6. 12 Comparison between non-structural fragility curves of non-structural components in the OBI room

In Figure 6. 11 the two curves are assumed to refer to the ER room, while in Figure 6. 12 they are assumed to refer to the OBI room. In the ER room, the two curves cross each other in a little interval of PFA, and are associated with a low percentage chance of exceeding the performance limit state (PLS); by the contrary, in the OBI room the intersection appears for higher values of peak floor acceleration associated with a higher performance chance of exceeding the PLS.

Following the methodology, if the structural fragility curve crosses the two NSC fragility curves, an envelope curve for these latter should be assessed and compared. In this specific case the NSC fragility curves do not cross the structural fragility curves and no assessment is needed.

This technique follows the methodology introduced in Ch.3: it allows to evaluate the physical consequences for the health care facility after aseismic event, expressed in terms of room closures. The comparison between the fragility curves of non-structural components and the structural fragility curves associated with the different limit states indicates the role played by non-structural components in the global reliability of the system.

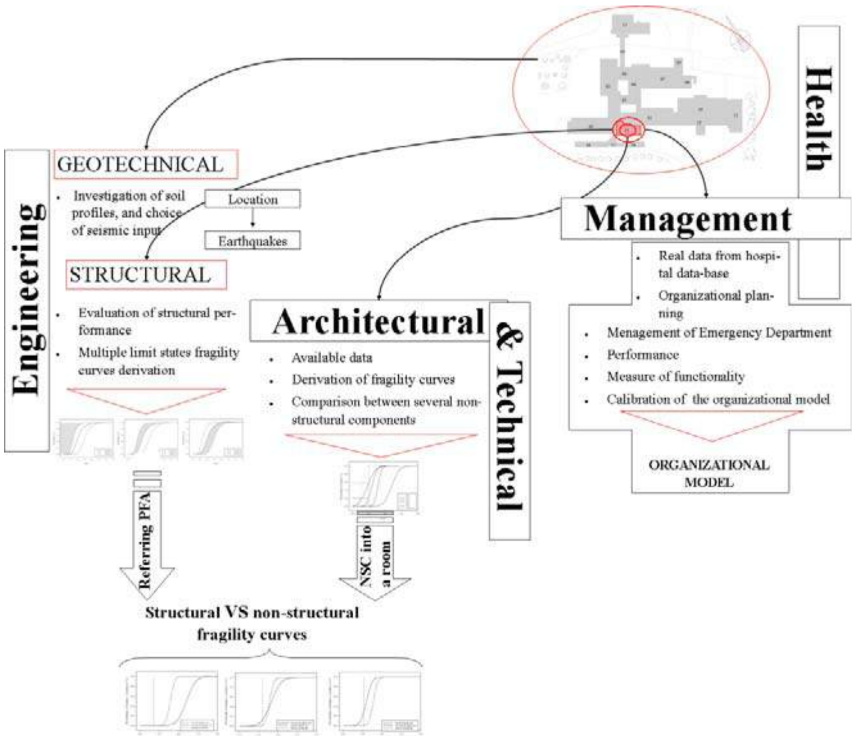


Figure 6. 13 Flowchart of the steps needed for assessing the physical characteristics of the hospital.

According to this study, the existing suspended ceilings and cabinets show a good performance at the serviceability and damage level demand for both the investigated rooms (ER room and OBI room). As matter of fact both the structural and non-structural fragility curves never cross each other: this means that no failures due to the chosen non-structural components occur that are related to the investigated limit state.

6.1.3 The organizational system

According to the methodology applied in this work (cf. Ch. 3), the assessment of the physical aspects concerning the case study must have consequences for the organizational setting of the hospital in case an earthquake occurs. The results permit to hypothesize the permanent closure of the rooms into the emergency department, adopting the case 2 organizational model. The assumptions for the setting of the emergency procedures are the same declared for the organizational model simulations.

In this section the meta-model calculated for the “case 2” (see par. 5.2.2) has been applied by varying the number of the closed rooms and the percentage of the damage extension, maintaining fixed the α parameter equal to 1.0. More specifically, a seismic arrival rate scaled with a MMI value, from the Northridge inflow and corresponding to the 0.27 g of the site, is applied to the DES model.

It is worth to note that, on the base of the “analysis of the picks”, a direct correspondence between α and the pick values is found; therefore it is possible to hypothesize that also for values less than 1.0, the metamodel well approximates the waiting time curve for the yellow-code patients during an emergency and with variable closed rooms.

The following equation (in the general form no.(5.13) is applied with sub-parameters of equations (5.10)-(5.11)-(5.12):

$$WT(t,\alpha,n) = a(\alpha,\mathrm{n}) * \exp(-0{,}5 * \left(\frac{\ln\left(\frac{t}{c(\alpha,\mathrm{n})}\right)}{b(\alpha,\mathrm{n})}\right)^2)/t \qquad \text{(Eq.5.13)}$$

Assuming that the shock occurs at:
t_0 = 0 min = 0 hour = 0 days
with a PGA= 0.27g
corresponding to a:
α =1.0;
it is possible to set the other parameters
n,
t,
and the percentage *(%)* of damaged area.

The waiting time curves are calculated and the waiting time values for a certain instant of time *t* can be assessed, as shown in Figure 6. 14:

Figure 6. 14 Metamodel for α =1 and the other varying parameters (extract of the Excel file).

The "physical" representation of the hospital system has been enriched by adding other information derived from the medical world and the healthcare management: this permitted to obtain the framework sketched in Figure 6. 15 that display the interaction between different fields, whose functionality is expressed in terms of WT.

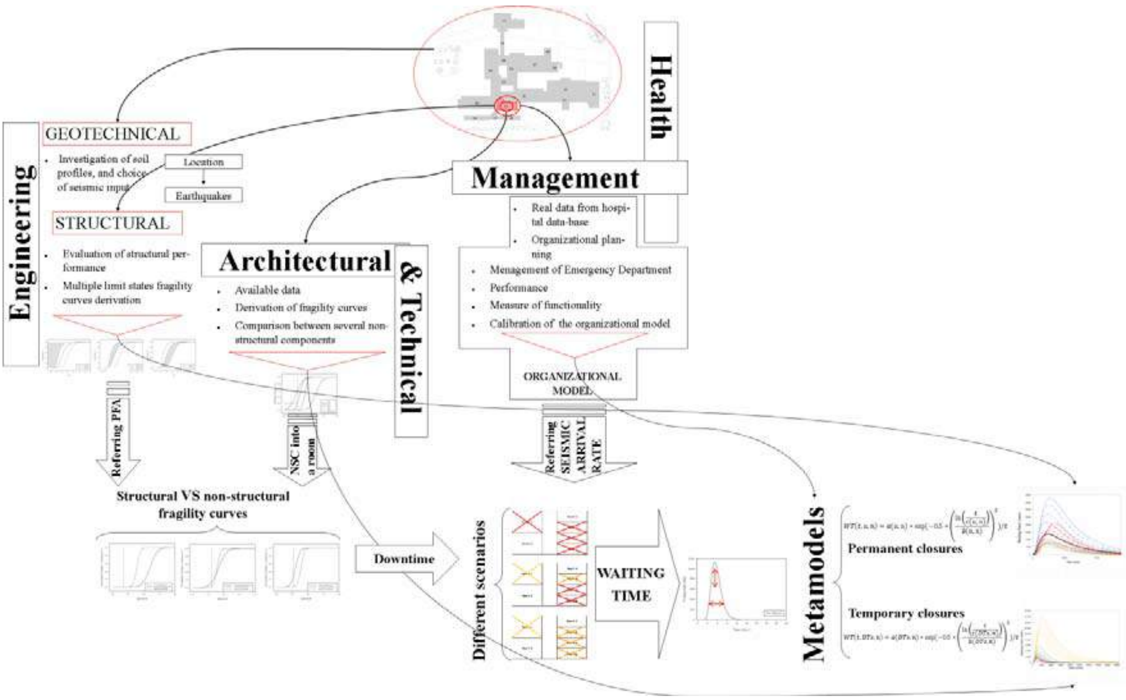


Figure 6. 15 Flowchart of the steps needed to include the organizational aspects of the hospital, and the assessment of meta-models associated with the case study

6.1.4 Resilience estimation

On the base of the waiting time curves of the meta-model corresponding to the case2-model, with α=1.0, it is possible to pinpoint the worst case and, consequently, to scale all other results. This further step is essential for evaluating the resilience depending on each possible occurrence, without overestimating the system.

Following the procedure illustrated in Ch. 5, the total loss of functionality (100%) is calculated thanks to the equivalence of the waiting time curve with the functionality curve. Table 6. 1 and Table 6. 2 show the coordinates for assessing the normalised waiting time curve and the associated functionality curve, as anticipated in par. 5.3.3.

Table 6. 1 Point coordinates of the normalized waiting time curve in the worst case for the Sansepolcro hospital.

POINT	X-coordinate	Y-coordinate
$A_{WTcurve}$	0	0
$B_{WTcurve}$	t_0	0
$C_{WTcurve}$	t_0	Max Peak of WT

$D_{WTcurve}$	t_0 + normalized equivalent base	0
$E_{WTcurve}$	Simulation end	0

Table 6. 2 Point coordinates of the associated functionality curve in the worst case for the Sansepolcro hospital.

POINT	X-coordinate	Y-coordinate
$A_{FUNCcurve}$	0	100
$B_{FUNCcurve}$	t_0	100
$C_{FUNCcurve}$	t_0	Residual functionality
$D_{FUNCcurve}$	t_0 + equivalent base	100
$E_{FUNCcurve}$	Simulation end	100

Referring to the data of this particular case, assuming that the shock occurs at:
t_0 = 2880 min = 48 hour = 2 days
with a PGA= 0.27g
corresponding to a seismic arrival rate with the amplifying factor
α =1.0,
the worst case is represented by a damage which affects three rooms
n =3
for the totality of their area = 100%.
The normalized waiting time curve associated with this case and the related functionality curve are described in the following Tables:

Table 6. 3 Point coordinates of the normalized waiting time curve in the worst case for the Sansepolcro hospital.

POINT	X-coordinate	Y-coordinate
$A_{WT(worst\ case)}$	0	0
$B_{WT(worst\ case)}$	2	0
$C_{WT(worst\ case)}$	2	8195.797
$D_{WT(worst\ case)}$	10.636	0
$E_{WT(worst\ case)}$	27.77	0

Table 6. 4 Point coordinates of the associated functionality curve in the worst case for the Sansepolcro hospital.

POINT	X-coordinate	Y-coordinate
$A_{FUNC(worst\ case)}$	0	100
$B_{FUNC(worst\ case)}$	2	100
$C_{FUNC(worst\ case)}$	2	0
$D_{FUNC(worst\ case)}$	10.636	100
$E_{FUNC(worst\ case)}$	27.77	100

Table 6. 4, is graphically represented in Figure 6. 16. The maximum peak of functionality loss is associated with the value 0%, while the time needed to restore the functionality is calculated

through the equivalence of the areas (cf. par. 5.3.2), using the simplified recovery function (cf. equation (5.19)), to represent the section between point C and point D.

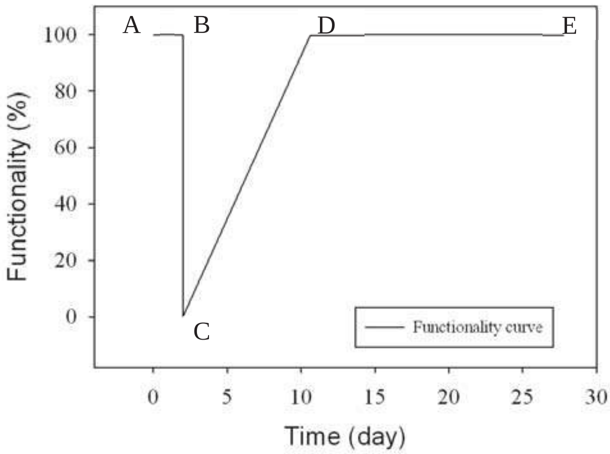


Figure 6. 16 Functionality curves related to the worst case, associated with α =1.0

The results in terms of functionality curves are showed in Figure 6. 17. The functionality curves, for variable *n* values, differ from each other and considerably increase both the BC segment and the X-coordinate-values of point D (corresponding to the time required to restore the functionality). The associated CD line, which corresponds to the recovery function, shows a changing slope, as a function of the *n* value.

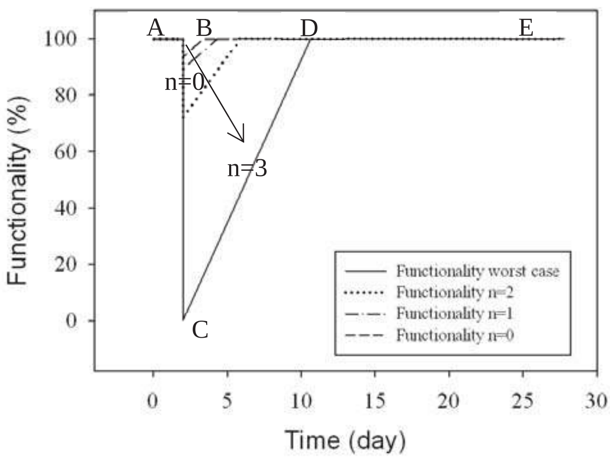


Figure 6. 17 Functionality curves related to α =1.0 and n variable.

The values obtained for the slope, as a function of the assumed *n* variable, is illustrated in Table 6. 5. From the analysis of the variation (see Figure 6. 18), an exponential function is taken into account as representative of the variation: this function is essential for a better understanding of the behaviour of the hospital system, subject to different room closures.

Table 6. 5 Values of the variation of the CD segment slope, in function of the n *variable.*

n	**Slope of the CD segment**
0	4.732364
1	4.719645
2	7.224772
3	11.57923

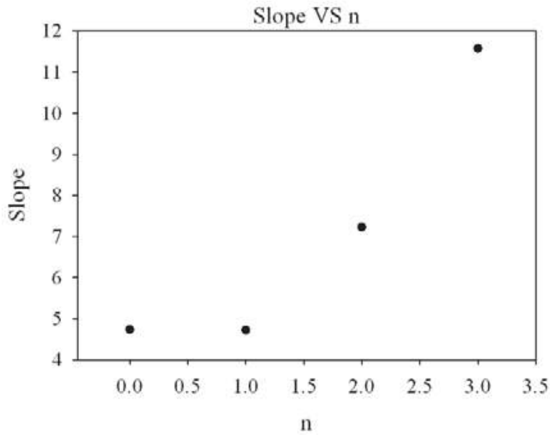


Figure 6. 18Variation of the CD segment slope, in function of the n variable..

In addition, the variation of the area under the curves is analysed, together with the peak values (Y-coordinates of point C). The values are shown in Table 6. 6 and Table 6. 7, and graphically represented in Figure 6. 19 and Figure 6. 20 respectively.

Table 6. 6 Values of the area under the linearized waiting time curve, as a function of the n *variable (with α=1.0).*

n	**area**
0	1245759.6
1	2689891.9
2	9610158.9
3	62763677

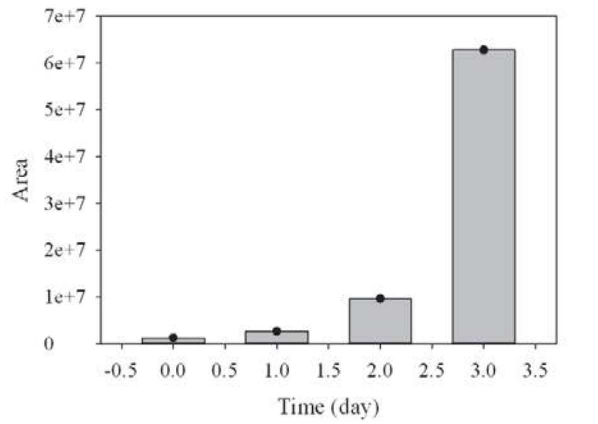


Figure 6. 19 Variation of the area under the linearized waiting time curve, as a function of the n *variable (with α=1.0).*

Table 6. 7 Values of the Y-coordinate of the C point, as a function of the n *variable (with α=1.0).*

n	**Y-coordinate of C point**
0	93.673
1	89.311
2	72.170
3	0

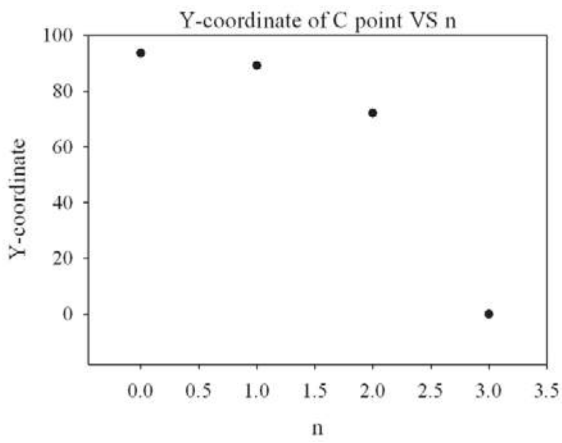


Figure 6. 20 Variation of the Y-coordinate of the C point, as a function of the n *variable (with α=1.0).*

The global behaviour of the hospital system is summarised in Figure 6. 21, where four percentages of damaged areas related to the corresponding *n* parameter are additionally plotted. The derivation of damages equal to 0%, 25%, 50%, 75% and 100% for the areas involved are calculated in order to understand the varying response of the system.

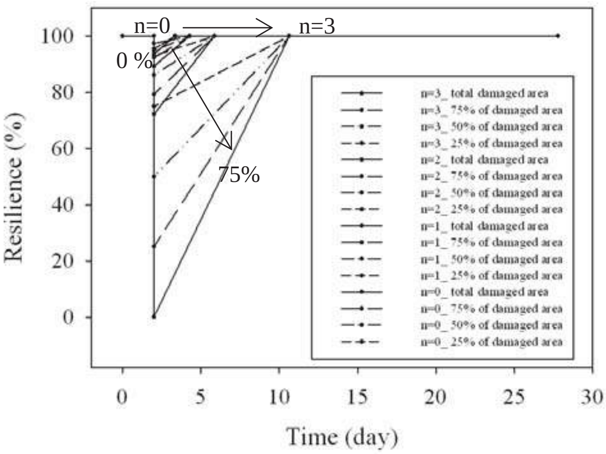


Figure 6. 21 Functionality curves related to different damaged areas, in function of n *variable (with α =1.0).*

Figure 6. 21 indicates that different percentages of damage and a variable number of rooms affect the variation of the resilience curves, which display a specific behaviour: point D of the resilience curves never changes. This happens because the variation of the damaged area percentage is applied within the same range (that in this case corresponds to the same *n* value), without affecting the BD segment of the resilience curve: therefore the latter is only subject to the variation of the *n* parameter. By the contrary, the area of the resilience curve and, consequently, the peaks and the recovery segment (respectively the segments BC and CD), are influenced by the extension of the damaged area.
By applying the equation in (5.3.2.2) all the all the points needed for the construction of the resilience curve are assessed, for the simplified cases of *n* variable, 100% of functionality of the rooms available, and α =1.0.

The following Figures illustrate the resilience curves assessed for *n* parameter ranging from 0 to 3; the resilience is calculated within the range of 18 days, which cover the emergency-phase (3 days) plus further 15 days after the shock, i.e. five times the emergency phase length.

This area is rudely scaled on the base of a "fully" operational curve, corresponding to resilience equal to 100%, and is associated with no occurred damages. If the rooms are partially damaged the difference in resilience will be within the range of each *n*-case, due to the linear variation of the functionality curve that have been previously analysed.

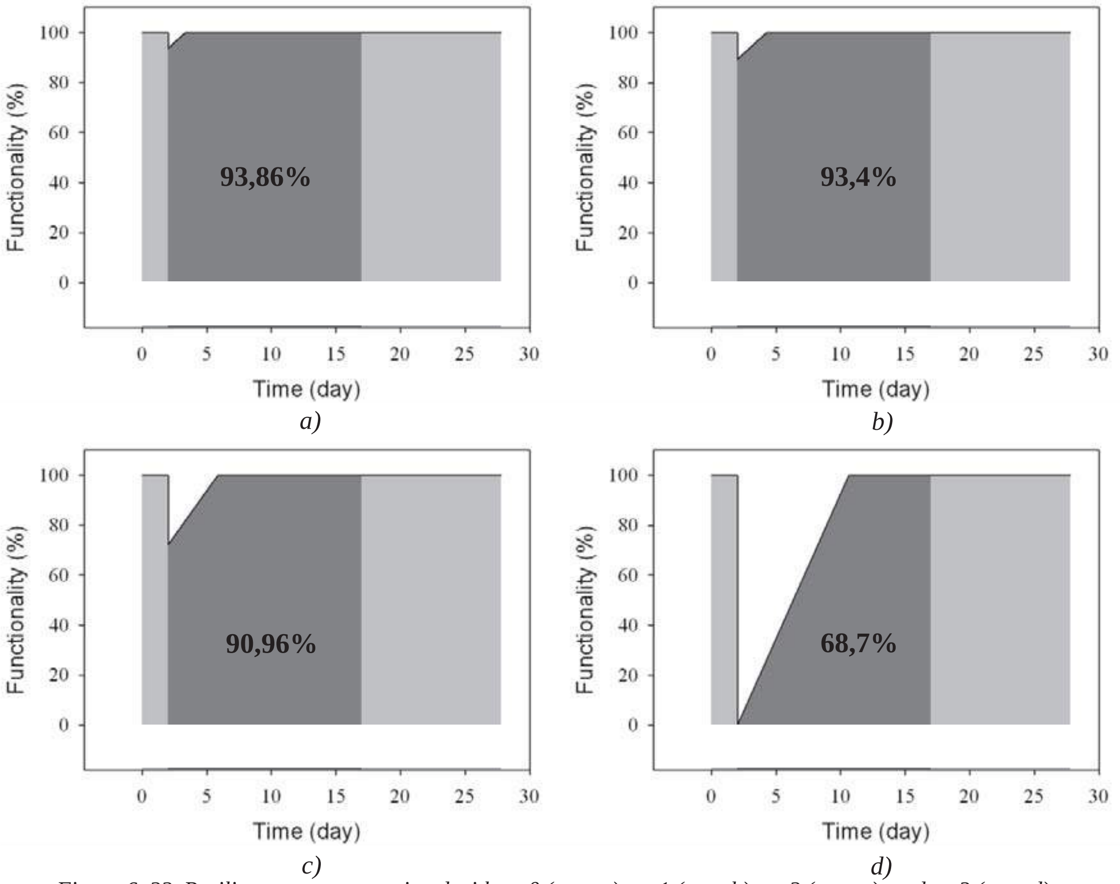


Figure 6. 22 Resilience curves associated with n=0 (case a), n=1 (case b), n=2 (case c), and n=3 (case d).

For instance, if n=2, (cf. case (c) in Figure 6. 22), the variation on resilience depending on the damage extension (%) do not exceed the 90,96%, probably varying between 93,4% and 90,96%. However, it is important to note that these results are closely related to the assumptions that, in turn, can be considered as valuable only for the case study. For other problems or buildings, different assumptions should be made that strictly depend on the specific system under consideration.

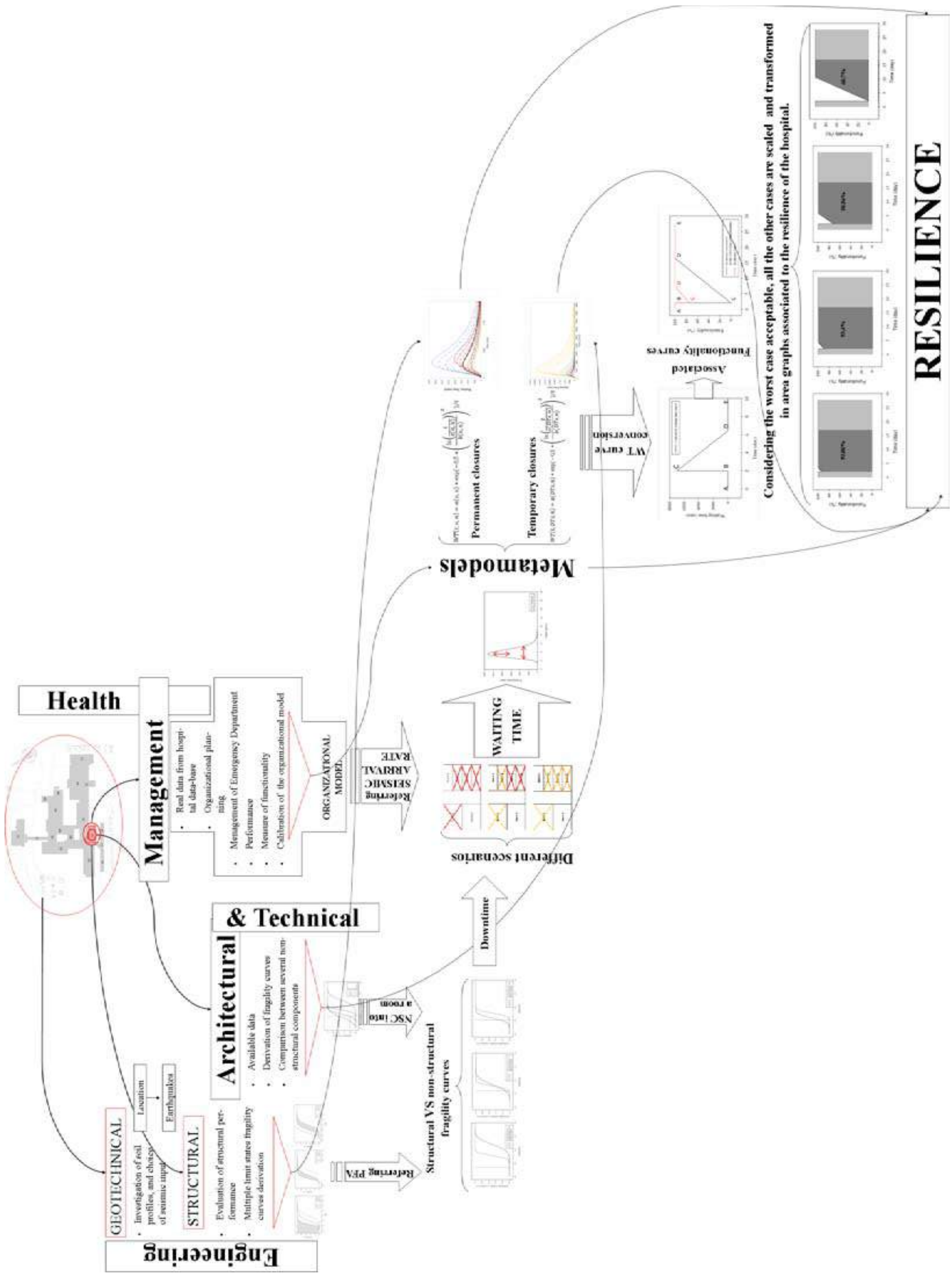


Figure 6. 23 Flowchart of the steps followed for assessing the resilience associated to the case study.

To conclude, Figure 6. 23 resumes the entire qualitative procedure which has been employed to assess the resilience of a healthcare facility, focusing on different fields. The arrows indicate the efforts made to channel all these competences in a unique direction. One of the more relevant applications of the presented methodology is the possibility to focus on the particular element that is responsible for the loss of functionality, as well as the possibility to modify the organizational setting of the emergency procedures in case low resilience depends on the organizational aspects.

Accordingly this procedure permits to identify the specific cause of a failure, be it of physical or organizational nature.

On the one hand, in case of damage due to one or more elements, the meta-model can be used to understand the possible interventions needed to improve the system functionality. As matter of fact, once the resilience of the system is known, it becomes feasible to identify the steps to be taken for ensuring the hospital's recovery: by fixing a certain value for the desired (expected) resilience, even the rime needed to achieve such result is known. On the other hand, if the performance is expressed in terms of time, it is also possible to quantify the resilience, together with all the related information. This tool can be very useful both in post-earthquake scenarios (for assessing the restoration time), and in pre-event scenarios (for improving the management involving all mentioned performances).

Even under normal conditions, i.e. normal scenarios where no emergency occurs, this approach constitutes a precious tool to calibrate the organizational aspects, minimizing the interruption of the service provided. It is important to mention that the real simulations performed by the medical staff, which are essential for the training of the hospital personnel, are expensive both in economic and human terms.

Illustrations of the procedures and relative interventions of the different aspects are shown in Figures 6.25-6.29, with reference to the following guide-outline: with the λ is represented the structural part, while the non-structural elements are symbolized with the β and the organizational aspects are described through the γ symbol (divided in γ_0 and γ_1 for no-earthquake and earthquake occurrence), with the ϕ symbol is represented the interrelation between the three aspects (completely shown in Figure 6.29).

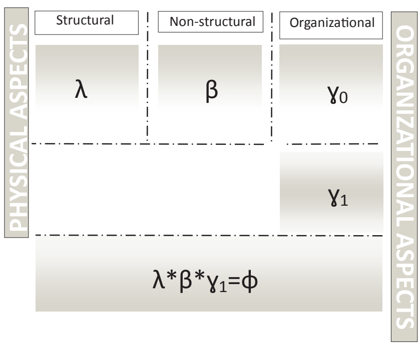
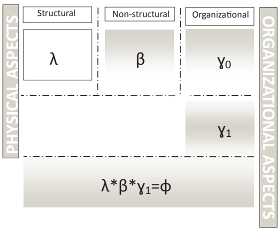


Figure 6. 24 Outline of the following flowchart taken into account in the study.



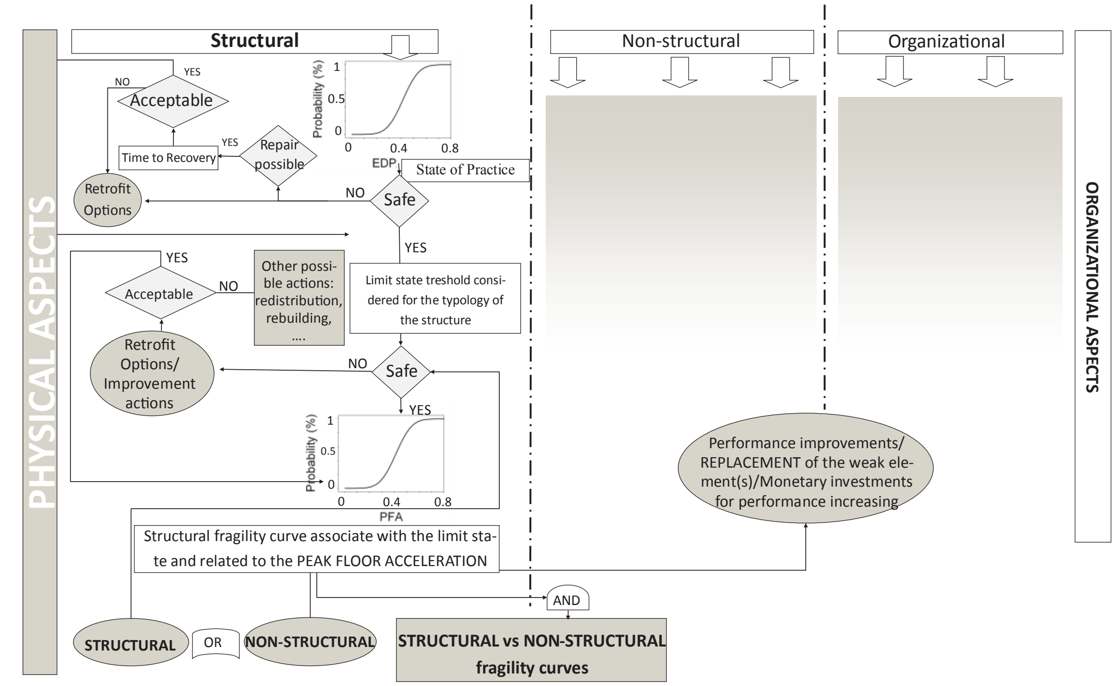
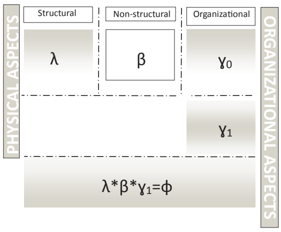


Figure 6. 25 Flowchart of the punctual steps into λ segment.



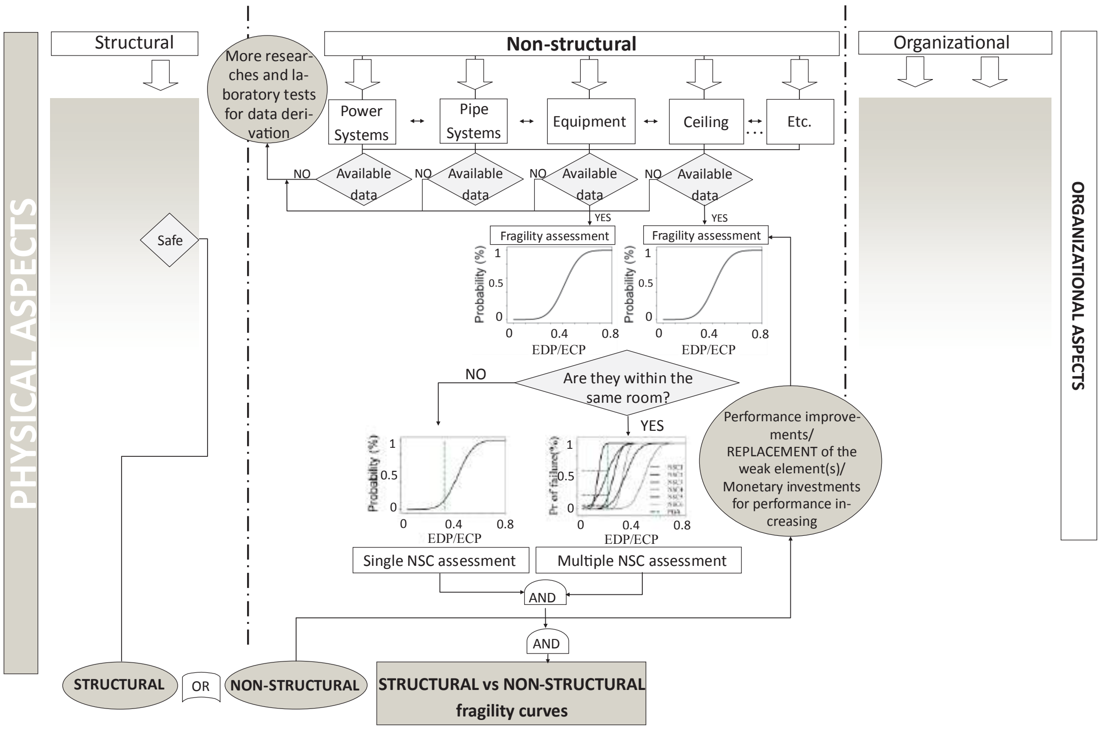
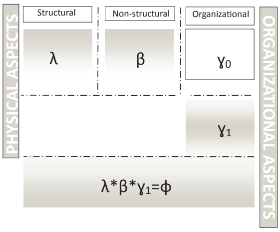


Figure 6. 26 Flowchart of the punctual steps into β segment.



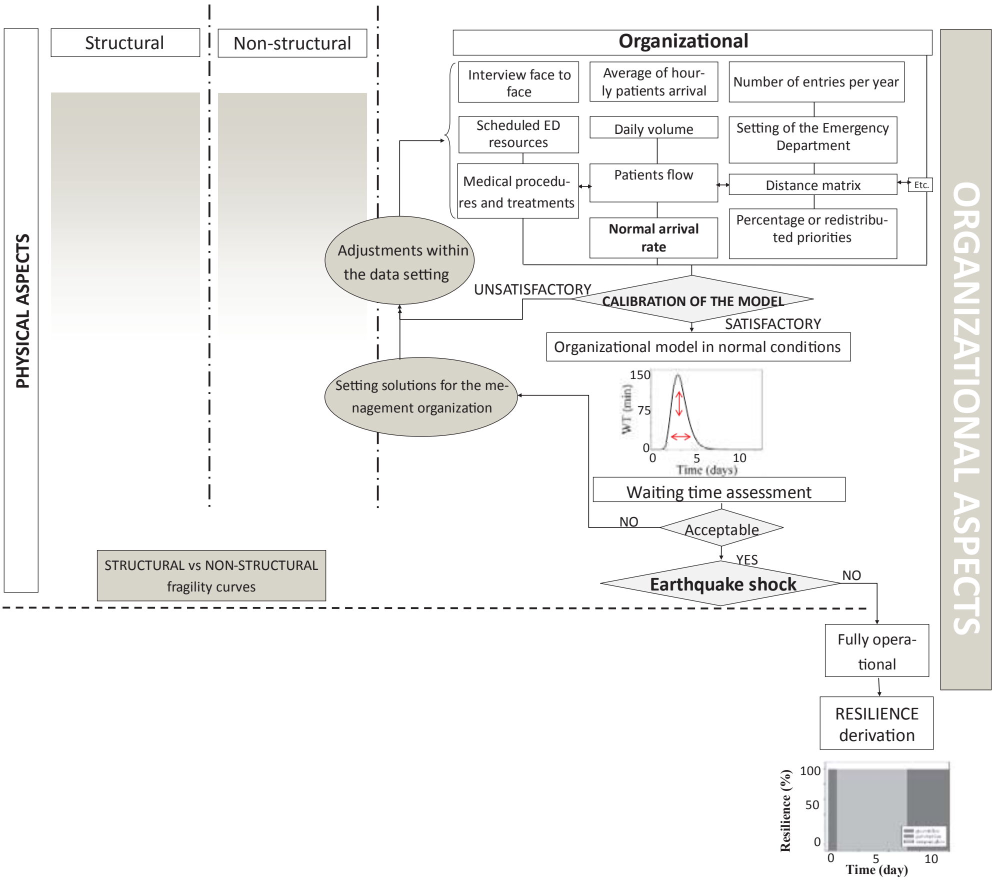
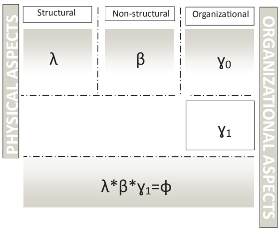


Figure 6. 27 Flowchart of the punctual steps into γ_0 segment.



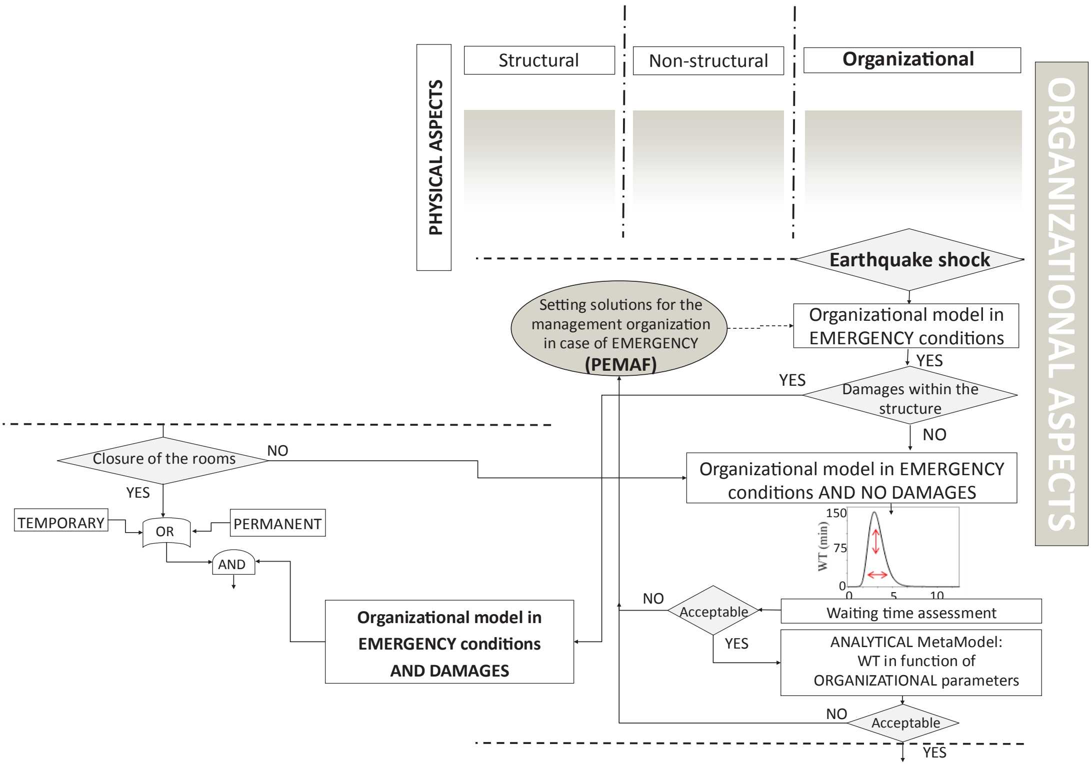


Figure 6. 28 Flowchart of the punctual steps into γ_1 segment.

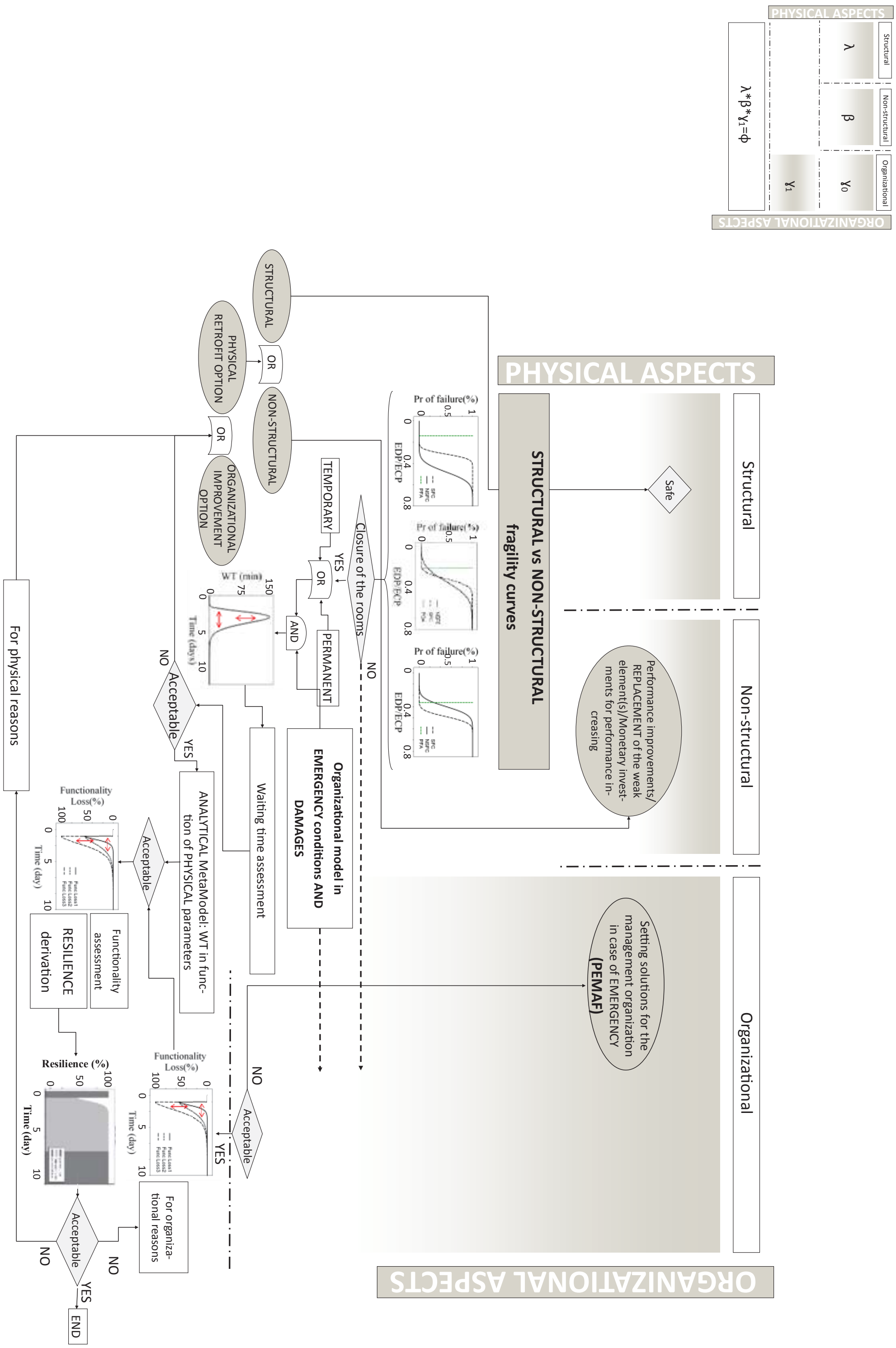


Figure 6. 29 Flowchart of the punctual steps into ϕ segment.

6.2 Application #1: how to evaluate the redundant elements

The results of this study may be applied to improve the current setting of the hospital system, or to figure out how a better functionality can be achieved in case of calamity. Figure 6.24 permits to define remarkable sub-flows focused on specific aspects, i.e. the role of non-structural components and of redundant sub-systems.

Figure 6. *30* shows the theoretical path followed to identify the weakest non-structural components into the current system as a result of its features, like: the location, the installation, the number and the capacity of the sub-systems. Once the weakest elements have been identified, possible solutions can be found, for instance how to replace them or how to by-pass their function by introducing new alternative sub-systems. With respect to this special attention has been paid to the “redundant” elements, by using the “redundancy factor” as introduced in par. 3.31.2. Even in this case, the referring waiting time curves are associated to the yellow code patients. The first applicative example presented here is the identification of the elevator as a weak element and a possible redundant improvement. This element is the only one which connects the emergency department (allocated on the first floor) with the emergency rooms on the second floor, that in case of emergency must be operative (following the emergency procedures of the hospital).

In case the elevator gets damaged there will be no possibility to reach the upper floor. As matter of fact the hospital plan has a complex structure and the ORs are not easy to be reached from other areas of the building; moreover the other elevators are too little in size to accommodate a stretcher. Figure 6. 31 shows the position of the elevator, located between two different structural units. It must be classified as a “strategic” device, since – despite its importance –it can easily undergo service interruption. Even for low-intensity ground motions, the seismic response of the structure can compromise the effectiveness of the elevator (Figure 6. 31b), with a consequent loss of connections between the two storeys.

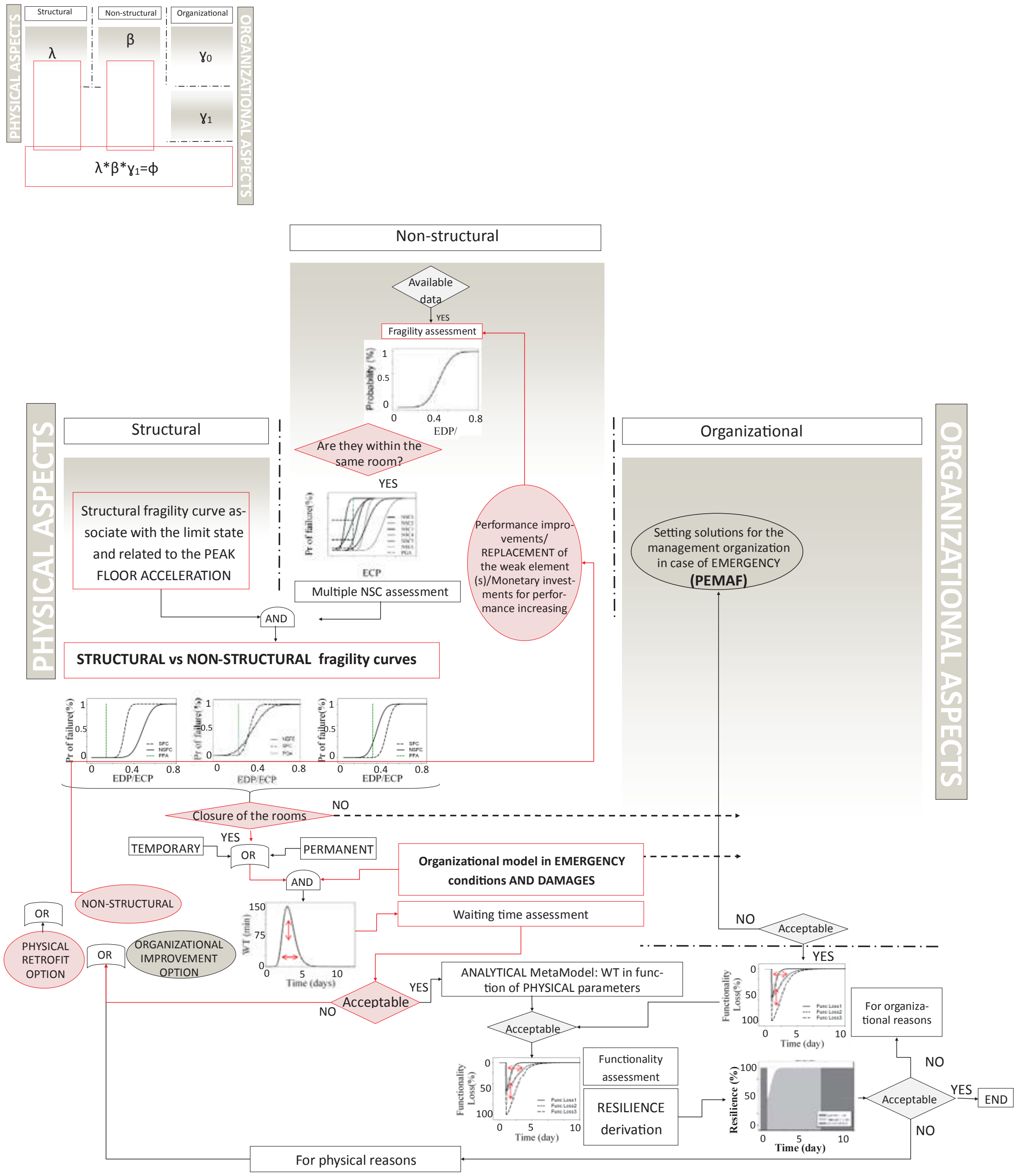
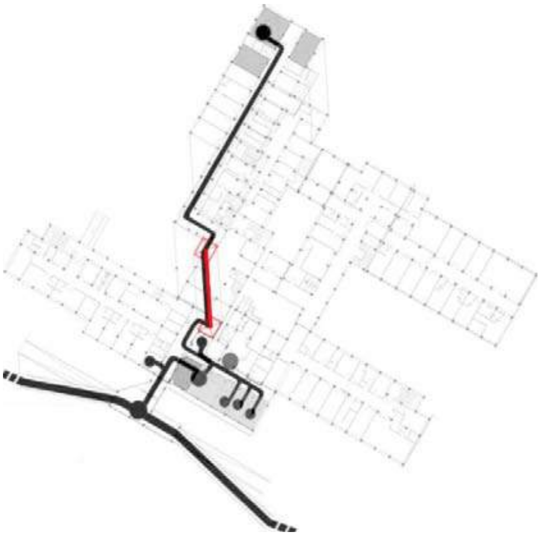


Figure 6. 30 Procedure flowchart: remarkable sub-inflow on the non-structural cause for the loss of functionality



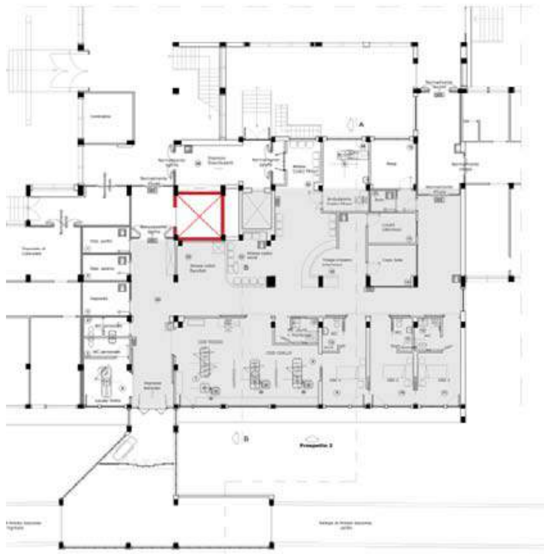
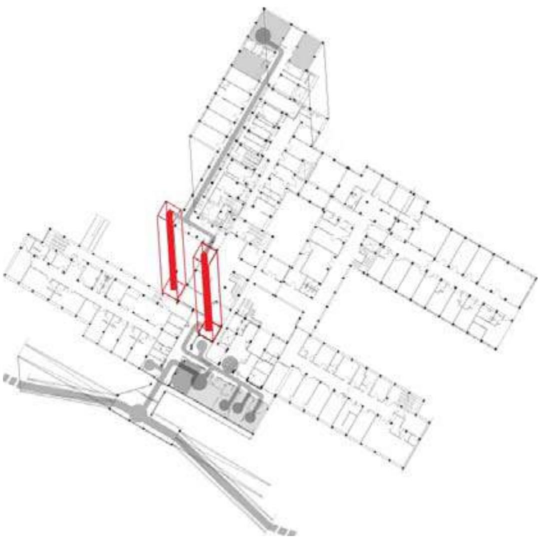


Figure 6. 31 a) Main patients paths in case of emergency where the only vertical connection is the elevator (left); b) zoom of the emergency department and location of the elevator.

A first model of the current situation has been performed under emergency conditions, then several downtimes have been applied to the elevator. In order to compare alternative organizational choices by the hospital, other hypothesized models with a redundant elevator have been run as well. The differences regarding the physical characteristics are shown in the architectural plans of Figure 6. 32.



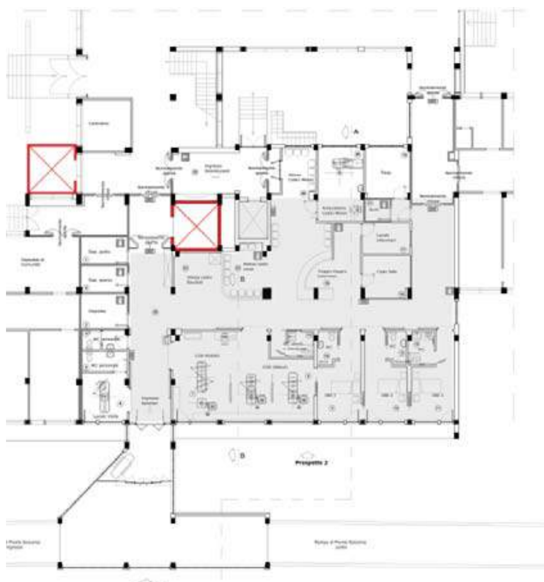


Figure 6. 32 a) Main patients' paths in case of emergency with redundant vertical connection (on the left); b) zoom of the emergency department and location of the elevators (on the right).

In total 8 models have been developed, as summarized in Table 6.8.

Table 6.8 Models developed with several downtimes (with and without redundancy element).

Model (name)	Redundancy (redund)	Downtime (DT)
Model_NOredund_NODT	NO	0 hours
Model_NOredund_DT24h	NO	24 hours
Model_NOredund_DT48h	NO	48 hours
Model_NOredund_DT72h	NO	72 hours
Model_YESredund_NODT	YES	0 hour
Model_YESredund_DT24h	YES	24 hours
Model_YESredund_DT48h	YES	48 hours
Model_YESredund_DT72h	YES	72 hours

The simulations include three days of emergency scenario and 26 days under normal conditions to restore normal waiting times for patients. Two variable conditions are considered: the presence/absence of a redundant elevator and a variable downtime which starts at time 0, due to the earthquake shock. The first model performed is the current setting model, which has been assumed as a reference point for all other examples, then it has been compared with the redundant-elevator models without downtime.

These first results, despite being expected, are of great help for comprehending the behaviour of the model: in case no downtime occurs the waiting time experienced by patients does not change drastically. In effect without downtime patients are divided between the two elevators, which work for a little amount of time and not uninterruptedly. The little discrepancy in the graph is probably due to some waiting patients in queue for the elevator, causing a delay in the normal transferring from the ER to the ORs. In case a redundant elevator is present, there will be no queues and the second elevator will compensate the temporary interruption of the service.

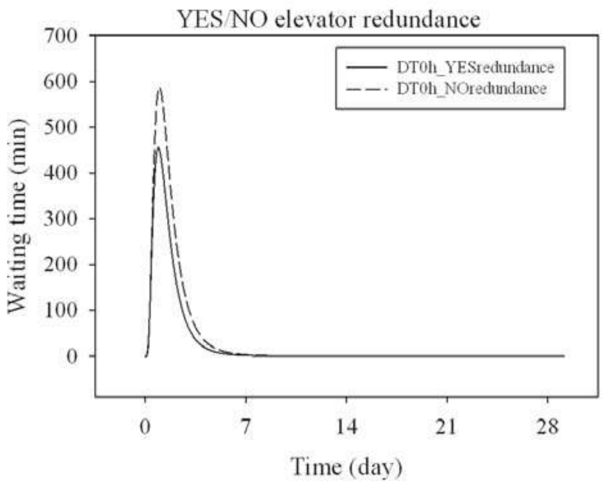


Figure 6. 33 Waiting time curves without downtime, with presence of a redundant elevator in the current setting model.

With a downtime of 24 hours the waiting time increases significantly (growing proportionally with the downtime hours). Figure 6. 34 clearly illustrates it (on the left) also showing the variation regarding the waiting time if a redundant elevator is available (on the right). Notwithstanding the increase in the downtime hours, the effects on the physical system are the same, and the waiting time variation is irrelevant. In these cases, the system works exactly as in presence of an undamaged elevator, which is the case of the current setting organizational system. Therefore it can be concluded that the methodology is effective in evaluating the role of redundant non-structural components.

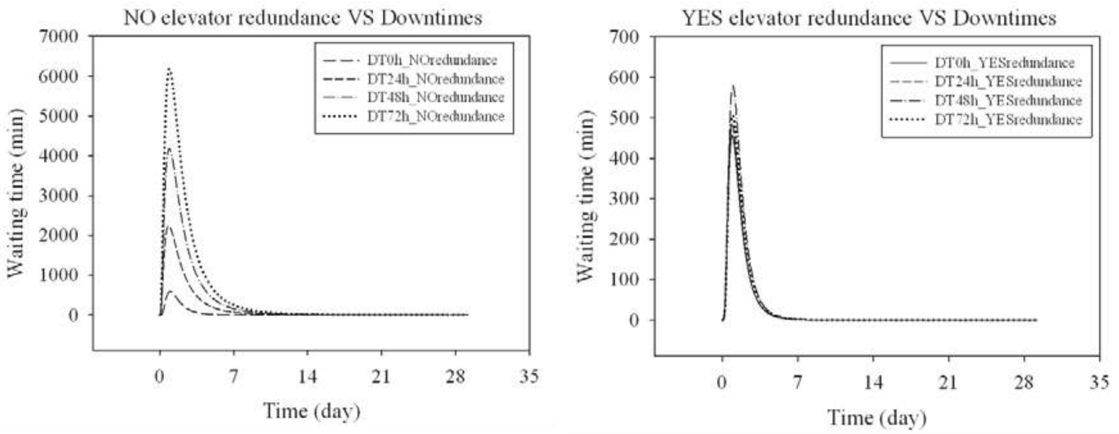


Figure 6. 34 a) Waiting time bell curve of the model with one elevator (NO-redundancy) on the left; and b) the model with two elevators (YES-redundancy) during three days of emergency and no one elevator downtime, on the right.

Beside the waiting time, it is interesting to consider the number of treated patients. As Figure 6. 35 shows, the number of treated patients do not change in case no downtime occurs, despite the number of elevators involved. The in-patients number is the same in all the simulations, since the input arrival rate of the model does not change; such as in the waiting time curve comparison, also the in/out-patient number does not change between the current system and a redundant system without downtimes.

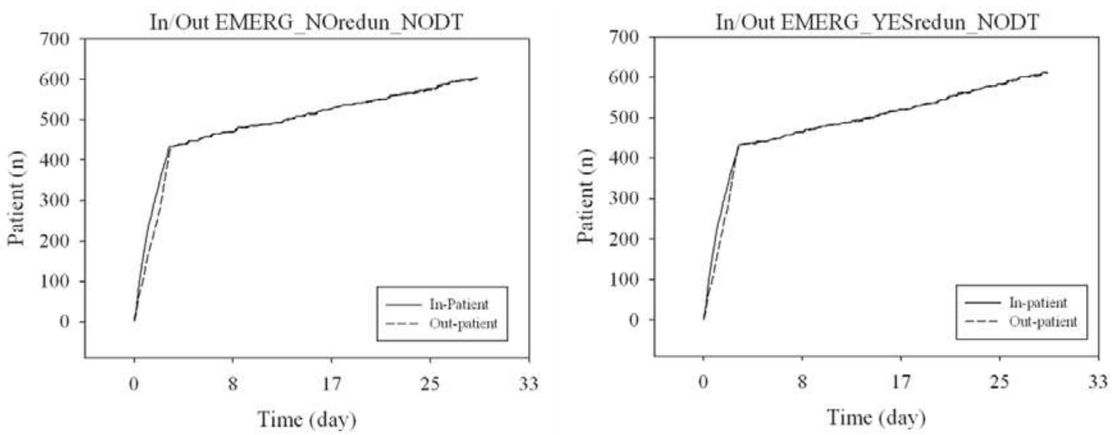


Figure 6. 35 Time history graph representing in-patients and out-patients of the model with one elevator (NO-redundancy)on the left, and the model with two elevators (YES-redundancy) during three days of emergency and no one elevator downtime, on the right.

On the one hand, these results suggest the uselessness of a redundant elevator, although the difference is undeniable considering the probable downtime that may occur to the elevator. On the other hand, great differences can be found not only regarding the waiting time curves, but also concerning the input-output patients graphs. However, assuming an interruption of the service for the existing elevator, which at this time has entrusted all inputs in the operating rooms, the gap between the waiting time curves and the time history of treated patients is significant. The effect of elevators' downtimes for the number of discharged patients is shown in Figure 6. 36:

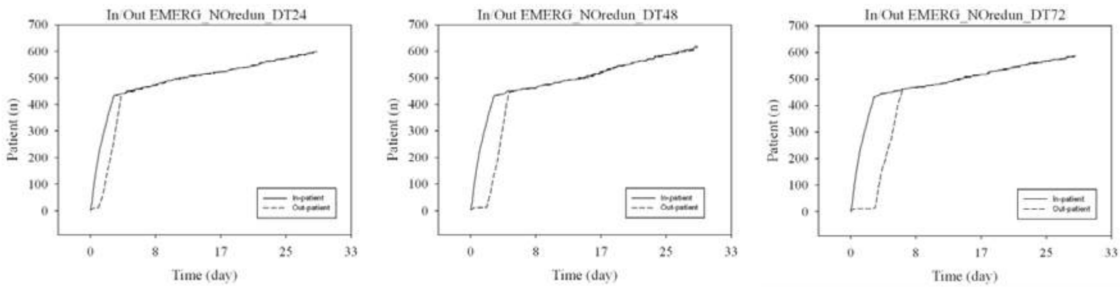


Figure 6. 36 In-patients and Out-patients time history of the model with one elevator (NO-redundancy) and different elevator downtimes.

This difference is well illustrated in Figure 6. 37, where a comparison is sketched for different downtimes determining a variable frequency of out-patients. With no downtime the system is able to discharge patients in a reasonable time, while increasing downtimes necessarily affect the discharge procedure.

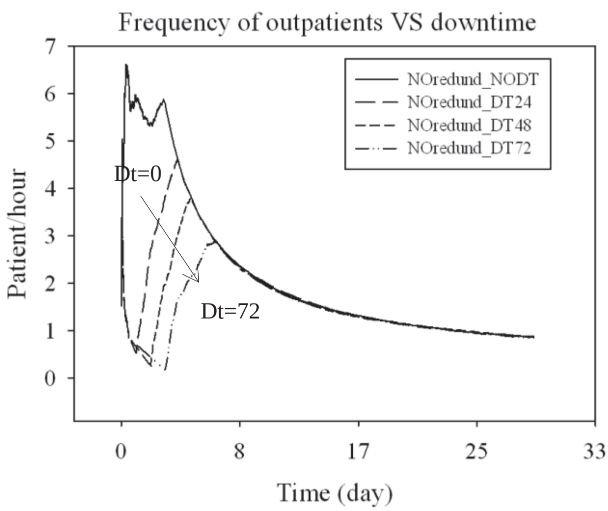


Figure 6. 37 In-patients and out-patients time history.

Analysing the waiting time peaks (see Table 9) it is interesting to note how the peaks of non-redundant models have a direct relationship with a longer downtime. This behavior is described in Figure 6. 38 (on the right), where the peaks of waiting time are plotted vs. the different downtimes occurred in the model. By the contrary, with a redundant model (or rather, with a redundant elevator) even if the downtimes increase, the redundant (additional) elevator compensates for loss of functionality of the damaged one, maintaining the waiting time curve and the associated peak of WT at the level of no-downtimes cases.

Table 6.9 Waiting time peaks registered during the performed models.

Model	Peak of waiting time (min)
Model_NOredund_Dt0h	586.0294
Model_NOredund_Dt24h	2232.6509
Model_NOredund_Dt48h	4186.3610
Model_NOredund_Dt72h	6190.1450
Model_YESredund_Dt0h	456.6369
Model_YESredund_DT24h	485.8595
Model_YESredund_DT48h	576.8624
Model_YESredund_DT72h	505.4978

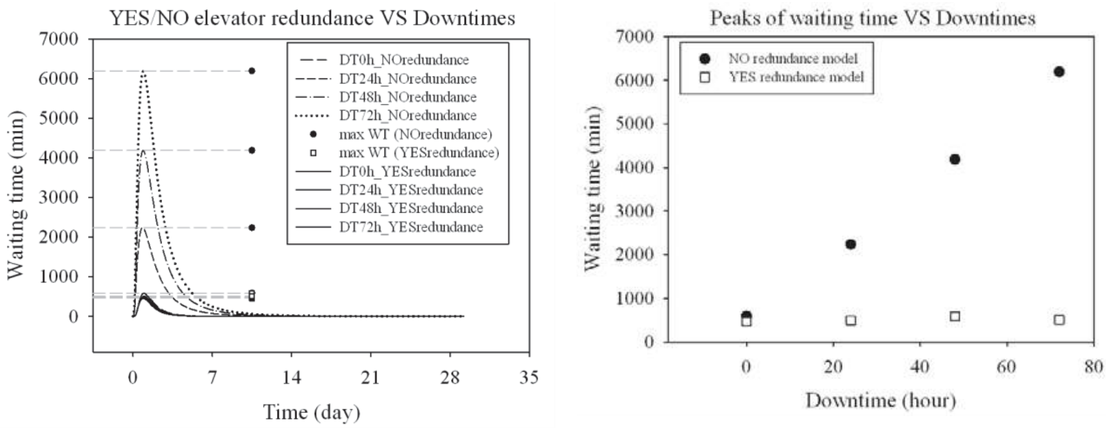


Figure 6. 38 Comparison between waiting time curves of all the models, and waiting time peaks (on the left), with their trend (on the right) vs. several downtimes.

6.3 Application #2: how to optimise the additional resources in an emergency

Figure 6.34 shows the flowchart of the hospital system functionality; by applying the proposed analytical approach, it is possible to improve the organizational setting of the emergency procedure, varying the available resources and picking up the parameters which more effectively affect the response of the emergency department.

By focusing on the organizational aspects, the multiple factors affecting the emergency procedures and their relationship can be investigated in terms of waiting time. In what follows an applicative example of this procedure is illustrated.

The resources, both hospital personnel and beds, are assumed as variables, while the arrival rate has been considered as constant for all the simulations (α=1). The variation of resources is assumed as the possibility to arrange multiple beds or to request additional medical staff. In other words, among all the parameters which seem to be the most relevant, a study has been carried out to identify the key ones.

The increasing resources are expressed in terms of:

- *n*: number of rooms for yellow codes treatments in case of emergency;
- *m*: number of resources in terms of increased units following the emergency procedures, corresponding to transporters, nurses, OSS, and doctors, i.e. *m* stands for the additional number of members involved.

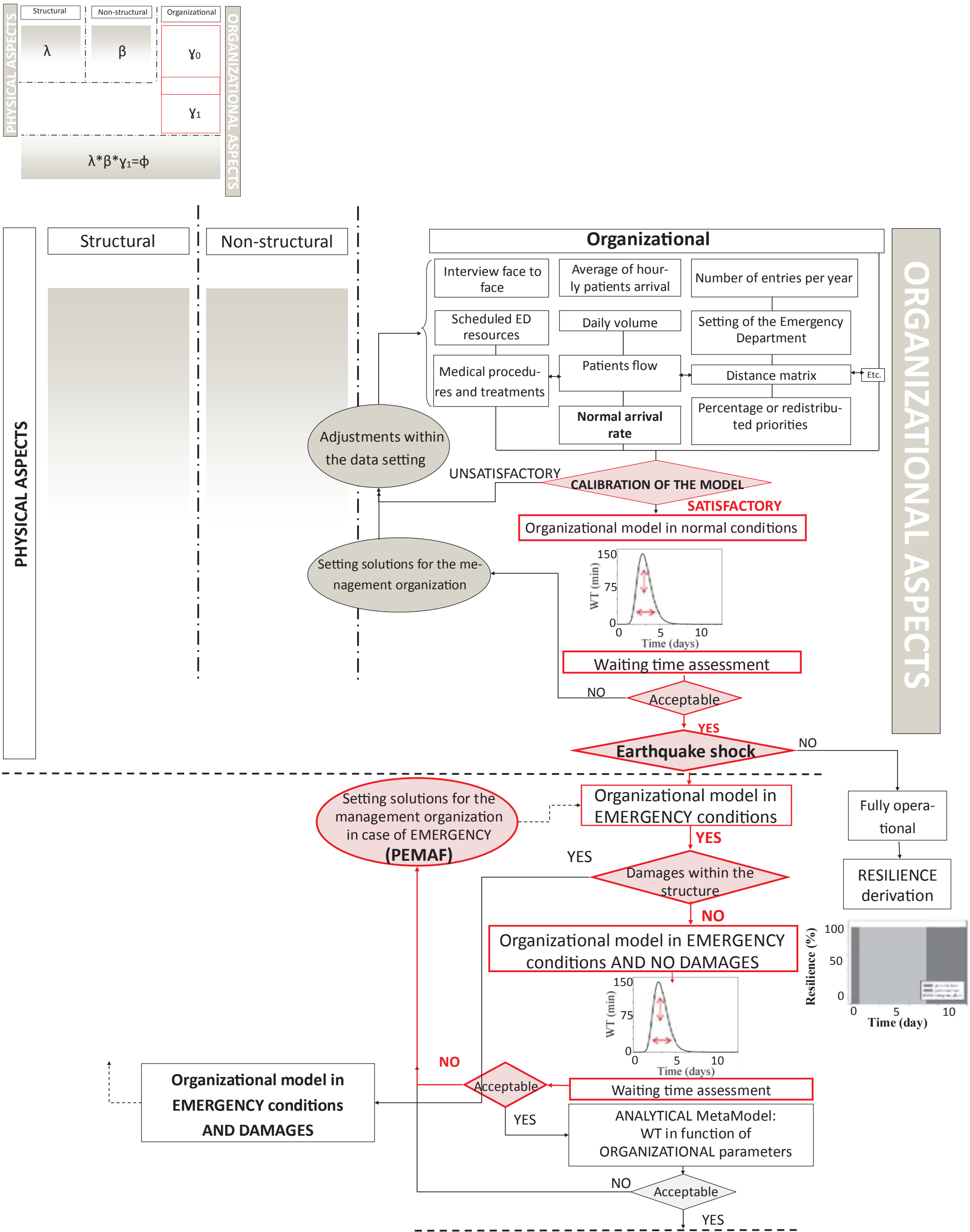


Figure 6. 39 Flowchart of the punctual steps to be taken into account in the study.

As a basic condition the current setting organizational model has been considered, following the emergency procedures in an emergency, that is:

- *n* = 4 (number of beds reserved to the yellow code patients);
- *m* = 5 (additional human resources, only referred to doctors).

Other resources are: 5 (nurses), 3 (OSSs) and 4 (transporters); however, only the number of additional doctors is taken into account. This basic model is called M_n4+0m since it implies 4 additional rooms and no additional medical resources with respect to those regulated by the emergency procedures.

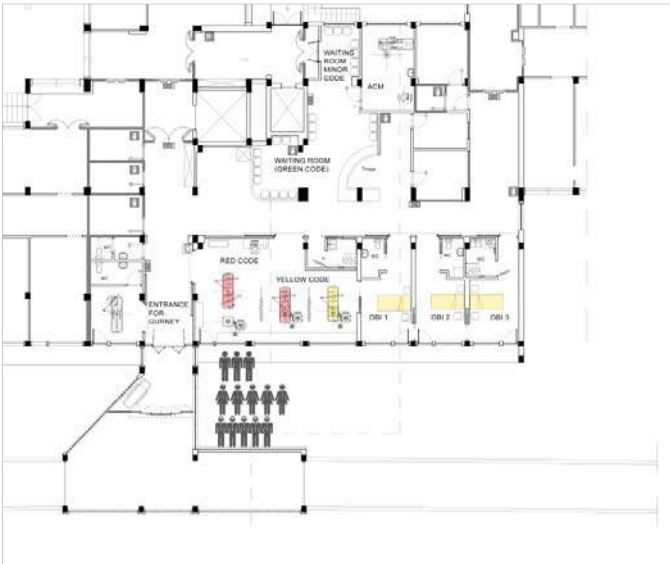


Figure 6. 40 Waiting time curves of different n *parameter (number of rooms) variation vs.* m *parameter (number of additional human resources)*

In the modified models, the number of rooms (*n*) has been increased from 4 to 10. The first two additional beds, i.e. those for green codes in normal scenarios, are located into the emergency department, while the other two additional beds are assumed. The number of resources (*m*) is increased two by two. The considered cases are listed in Table 6.10:

Table 6.10: Names and properties of the different models referred to in this section.

	n=4	**n=5**	**n=6**	**n=7**	**n=8**	**n=9**	**n=10**
+0m	M_n4+0m	M_n5+0m	M_n6+0m	M_n7+0m	M_n8+0m	M_n9+0m	M_n10+0m
+2m	M_n4+2m	M_n5+2m	M_n6+2m	Mn7+2m	M_n8+2m	M_n9+2m	M_n10+2m
+4m	M_n4+4m	M_n5+4m	M_n6+4m	M_n7+4m	M_n8+4m	M_n9+4m	M_n10+4m
+6m	-	-	-	-	M_n8+6m	M_n9+6m	M_n10+6m
+8m	-	-	-	-	-	-	M_n10+8m
+10m	-	-	-	-	-	-	M_n10+10m

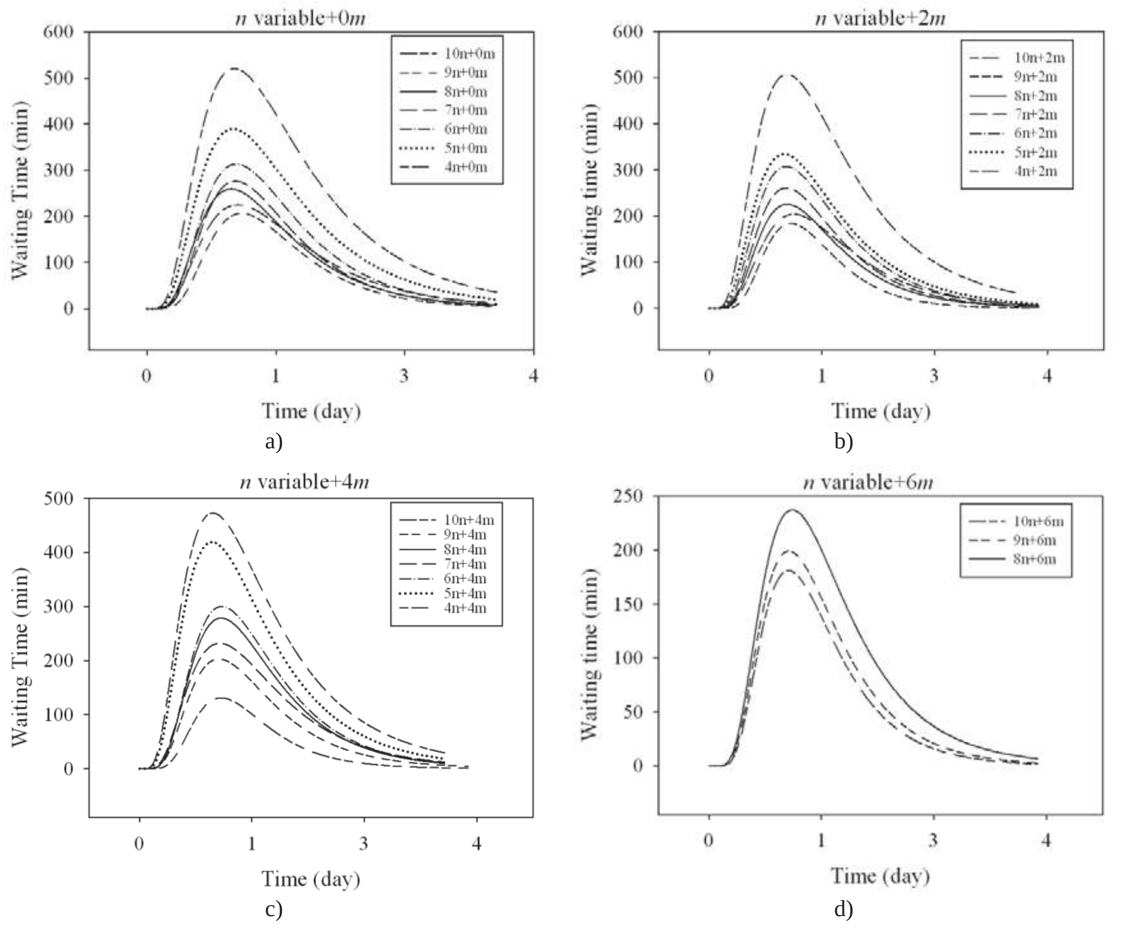
Despite all resources are increased, only the additional number of doctors is considered: this choice depends on the existing ratio between *n* and *m*, as shown in Table 6.10.

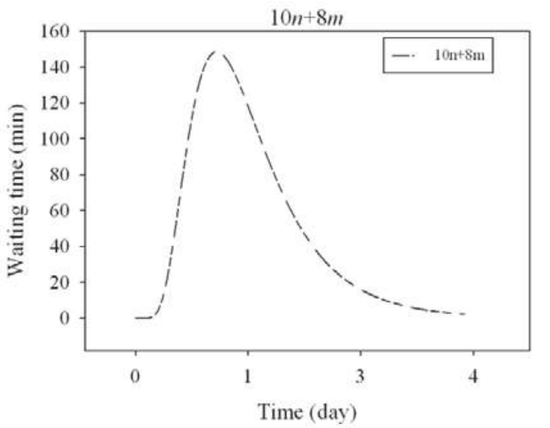
The actual *ratio* is equal to:

$$R = {}^{n}\!/_{m} = {}^{4}\!/_{5} = 0.8 \qquad \text{(Eq.6. 1)}$$

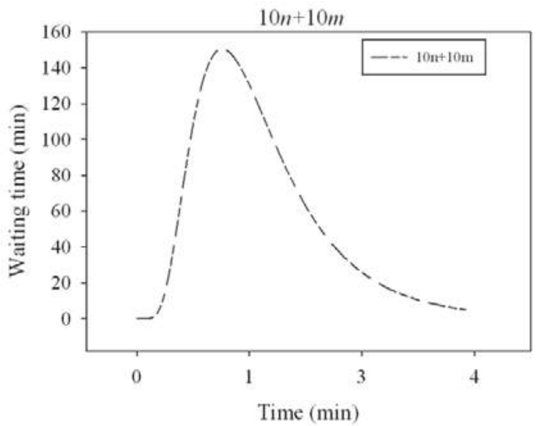
with n corresponding to the number of the available beds, and m to the number of doctors dedicated to the yellow-category of patients. In this case the number of doctors is 3, i.e. 5 doctors in total, with 2 of them dedicated to red codes, and 4 yellow-beds.

Accordingly the waiting time curves referred to yellow-code patients are assessed and compared. Multiple evaluations are made, investigating first the variation of the waiting time curves of models with a fixed number of medical personnel, but a variable number of available rooms. The results are graphically presented in the following plots (Figure 6. 41).





e)



f)

Figure 6. 41 Waiting time curves with fixed m *parameter (number of additional human resources) and* n *parameter (additional number of rooms) variable: a) no supplement resources; b) 2 supplement resources; c) 4 supplement resources; d) 6 supplement resources; e) 10 rooms and 8 supplement resources, and f) 10 supplement resources.*

With respect to these results it is worth to make some observations, especially concerning the increasing of rooms available for treating patients with a fixed *m*, i.e. the number of additional resources.

First of all, in graph (a) under normal conditions (without additional resources), a big difference in terms of waiting time occurs until 2 further rooms are added; after this improvement (from 3 to 10 rooms available), however, the difference in waiting time is not so relevant. By the contrary, the addition of two rooms considerably modifies the organizational response of the system, halving the waiting time. Thereafter, despite the consistent increase in the number of rooms, the waiting time does not decrease because of the staff availability.

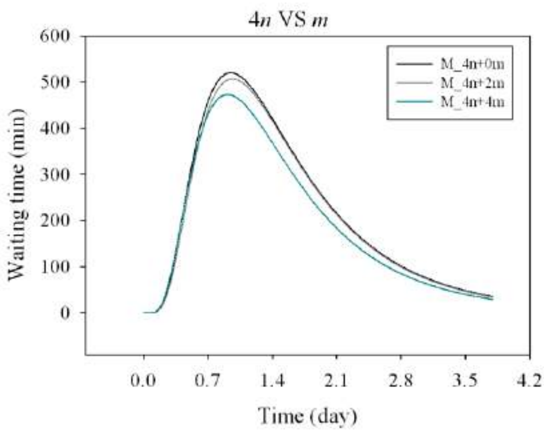
Another important observation regards the drastic reduction of the waiting time for a number of available rooms ranging between 4 and 5. The comparison between the first two graphs (cf. (a) and (b)) underlines that an additional number of doctors and nurses (*m* parameter) does not lead to a notable reduction of the waiting time: this is due to the impossibility to allocate patients in additional places/beds/rooms. However, the organizational model undeniably benefits from the addition of one or two beds. The graph in (c) shows that the waiting time more significantly varies when the *n/m* ratio reverts about 0.65 (cf. Table 6.11). In effect, the waiting time under the current conditions for the rooms involved does not change despite additional resources are employed. A similar situation is displayed by the waiting time associated with the curves in graph (d): the variation of the waiting time is not so evident as it is in the first three graphs because the ratio *n*/*m* is stable around the same value. The most significant decrease in waiting time is obtained when 10 rooms are made available and 8 or 10 human resources are added. The variation regarding the latter two cases is not relevant (they are associated with the same ratio of values).

Table 6.11 Ratios associated with different simulations: the bold-typed red ratio is associated with the current (real) emergency scenario.

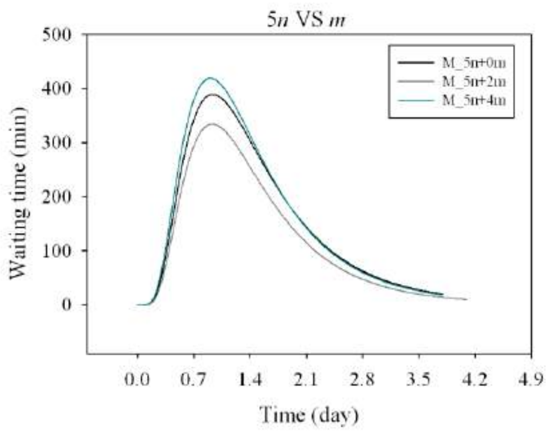
R=n/m	n=4	n=5	n=6	n=7	n=8	n=9	n=10
+0m	**0.8**	1	1.2	1.4	1.6	1.8	2
+2m	0.571429	0.714286	0.857143	1	1.142857	1.285714	1.428571
+4m	0.444444	0.555556	0.666667	0.777778	0.888889	1	1.111111
+6m	0.363636	0.454545	0.545455	0.636364	0.727273	0.818182	0.909091
+8m	0.307692	0.384615	0.461538	0.538462	0.615385	0.692308	0.769231
+10m	0.266667	0.333333	0.4	0.466667	0.533333	0.6	0.666667

Even the variation regarding the medical personnel (*m* parameter) with a fixed *n* (number of doctors) can be evaluated: Figure 6. 42 shows that the waiting time curves calculated by varying the *m* parameter are very close to each other. For instance in graph (a) the additional number of doctors during the emergency phase does not change the waiting time curve of the patients since they get no accommodation into the hospital. By including some little variations – all graphs well represent this behaviour – and, progressively, by increasing the number of rooms, the bell curves decrease. Exclusively in graph (d) it is possible to detect a slight difference between the curves: it is the result of the higher number of available rooms and of the satisfactory *n*/*m* assumption.

The last graph (Figure 6. 42) represents the waiting time curves associated with the ratio *R*=*n*/*m* value, around 0,8 and marked in red in Table 6.12.



a)



b)

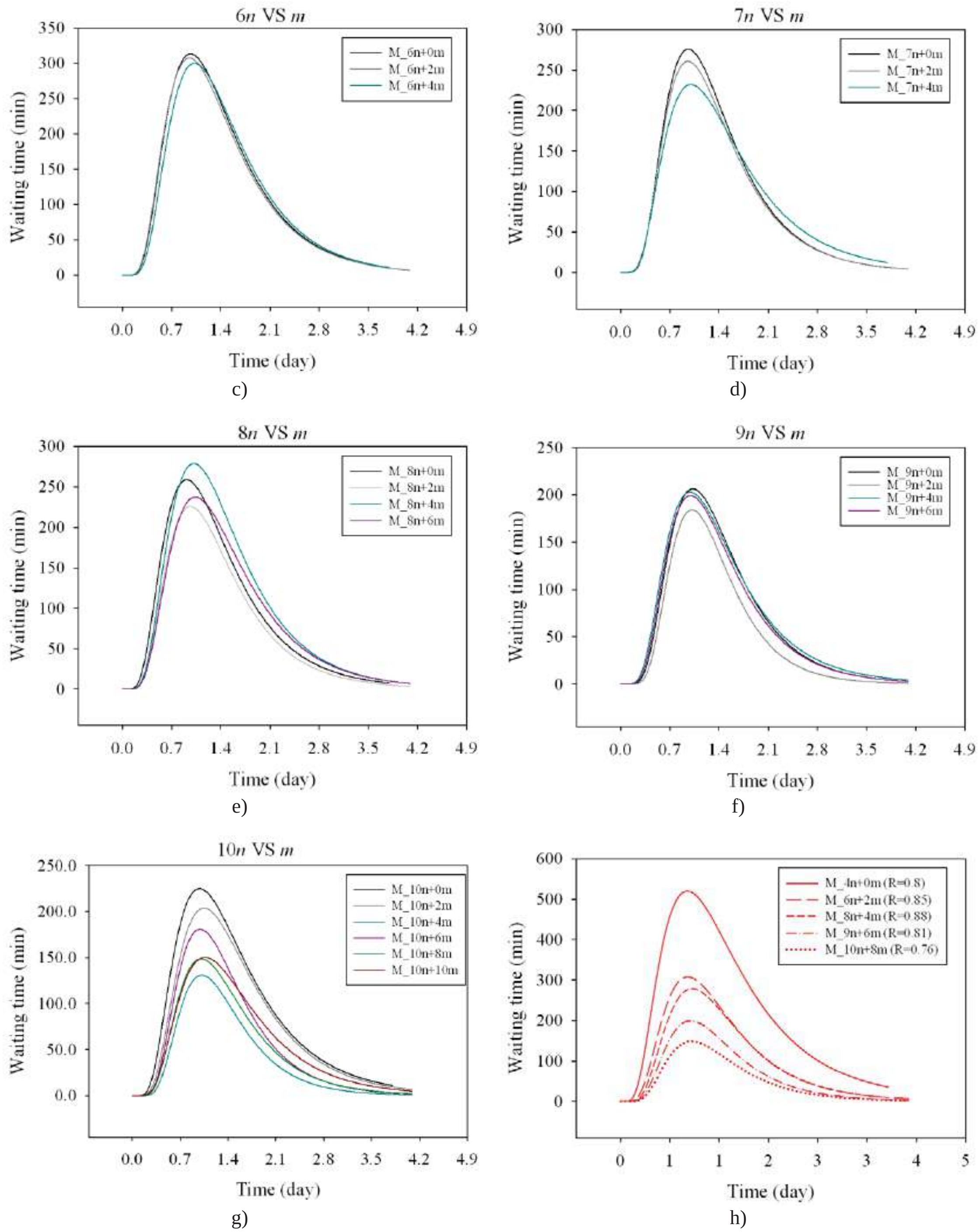


Figure 6. 42 Waiting time curves for different n *parameter (number of rooms) variation vs.* m *parameter(number of additional human resources)*

The last plotting (graph (h)) shows how the waiting time curves having the same *R* significantly decrease as a consequence of an increase in the *n* and *m* parameters respectively.

These results validate the assumption that the hospital performance is sensitive to the available resources in terms of medical staff and available beds. Comparing the best performances of the hospital with varying resources at its disposal, with the same *R* ratio, the best results are obtained when 2 doctors and 2 beds are added (model M_n6+2m in Table 6.12) since this case provides the most convenient waiting time. In Table 12 the models plotted in Figure 6. 42, case (h), corresponding to the *R* ratio indicated in Table 6.11, are typed in red.

Table 6.12 Summary of performed simulations: the bold-typed red names are associated with the best ratios n/m.

	n=4	n=5	n=6	n=7	n=8	n=9	n=10
+0m	**M_n4+0m**	M_n5+0m	M_n6+0m	M_n7+0m	M_n8+0m	M_n9+0m	M_n10+0m
+2m	M_n4+2m	M_n5+2m	**M_n6+2m**	Mn7+2m	M_n8+2m	M_n9+2m	M_n10+2m
+4m	M_n4+4m	M_n5+4m	M_n6+4m	M_n7+4m	**M_n8+4m**	M_n9+4m	M_n10+4m
+6m	-	-	-	-	M_n8+6m	**M_n9+6m**	M_n10+6m
+8m	-	-	-	-	-	-	**M_n10+8m**
+10m	-	-	-	-	-	-	M_n10+10m

It is worth to note how an increasing number of resources in terms of medical staff/personnel does not influence the organizational response of the system; by the contrary, an increased number of rooms/beds available crucially affects the hospital performance.

This result is not surprising: on the one hand, the working resources (doctors, nurses or Oss personnel) perform the standard procedures for a limited time; on the other hand, patients receiving treatment remain into the hospital for a period of time that goes from a minimum to a maximum estimable on the base of the calculated times registered in the statistical database of the hospital. In addition, the arrival rate is randomly generated and follows the trend displayed by the input provided by the organizational model. Accordingly, in case of emergency, a discrepancy shows up between these two variables: despite all difficulties, the human resources follow the procedures according to predictable times, while the number of arriving patients and their conditions cannot be easily predicted. As a consequence, the rate of occupancy of the rooms is much more influenced by the uncertainties deriving from the contingent scenario than from the operability of the medical staff. Therefore it is possible to state that:

- if $n=m$, all doctors work regardless of the occupancy of the rooms and the patients' arrival rate;
- if $n>m$, the system can be more efficient because the work of the doctors is not linked to the permanence of patients in the rooms, and they can work and take care of other patients by accommodating them in added beds/rooms;
- if $n<m$, the system does not improve and behaves exactly as in case $n=m$; in this specific case, however, many doctors cannot work due to the scarcity of beds/rooms available.

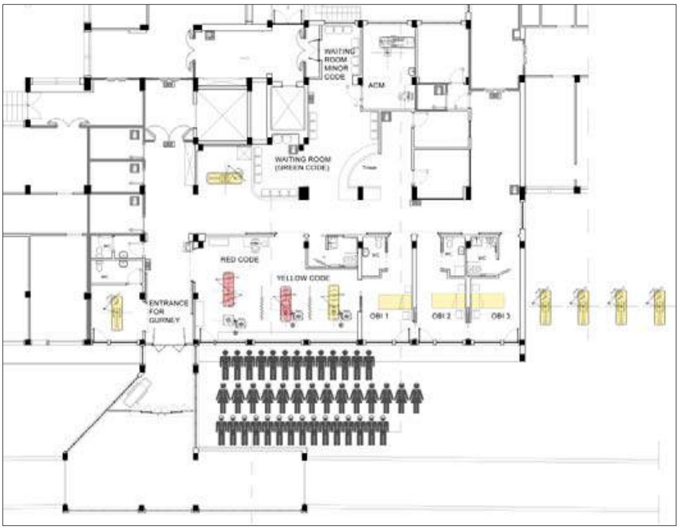


Figure 6. 43 Graphical setup of the model with the maximum number of additional human resources (m=+10) and the maximum number of available beds for yellow-code patients (n=10).

Figure 6. 43 graphically represents the setup of the model called M_n10+10m, where the maximum number of medical units and beds is available. The additional accommodations for yellow-code patients are assumed without taking into account the current architectural plan of the emergency department. This choice is exclusively due to mathematical reasons.

Plotting the waiting time peaks in function of the number of the additional resources (Figure 6. 44, on the left) or in function of the number of the rooms available (Figure 6. 44, on the right), it becomes clear that the increased number of operative resources is not so influent if compared with the increased number of available rooms; however, a little discrepancy among the peaks having the same *n* parameter can be observed. This is due to the remarkable patients' inflow, but this differences are not impressive as the variation of the peaks in function of the *n* parameter.

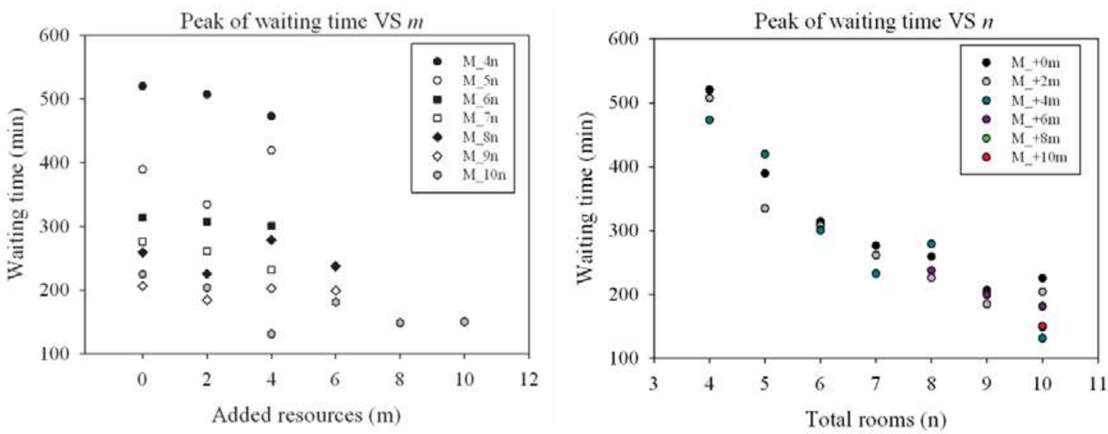


Figure 6. 44 Waiting time peaks in function of the additional resources (on the left), and in function of additional rooms available (on the right)

It is evident how the peak values change depending on the number of rooms available.
The behaviour seems to be the same for all *n* variations. In addition, analysing the peak variation vs. the *n* parameter, the sensitivity visibly changes depending on the *n* value. This is a confirmation of the ratio between the *n* parameter and the *m* parameter, which is essential to improve the system.

Figure 6. 45 shows (on the right) the best coupling among *m* values: a decreasing waiting time is more evident when associated with a specific X-coordinate (corresponding to the *n* value). By the contrary, focusing on a single X-value, the variation associated with the different additional resource is easier to catch. Another important factor is constituted by the arrival rate inflow (Figure 6. 45, on the left) since all the simulations were developed with α=1.0. Even if the assumed flow of patients is excessive, it is useful to investigate the behaviour of the organizational aspects subject to the other variables and, more specifically, depending on the number of rooms available.

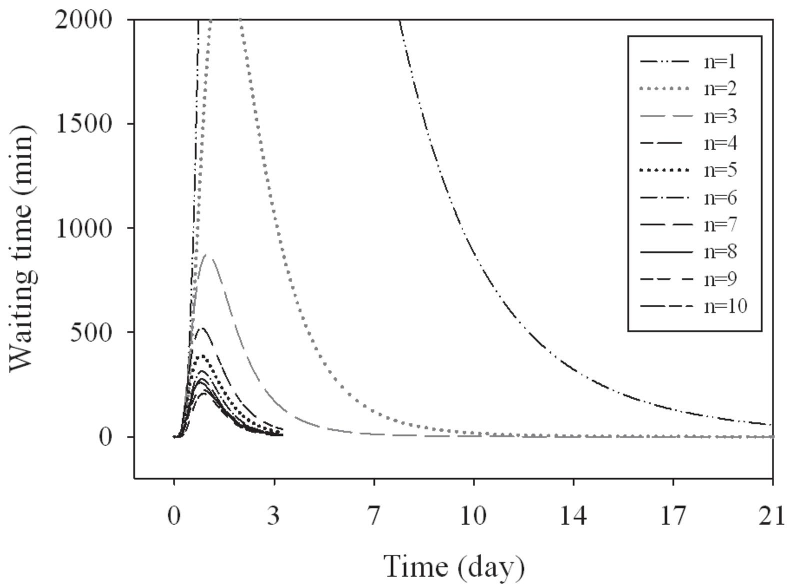


Figure 6. 45 Waiting time curves varying the n parameter (from n=1 to n=10), with α=1.0.

The simulations used in Ch. 5, having the same patients inflow and different *n* parameters, are extrapolated and then compared, in order to investigate the changes from *n*=1 (which is the maximum acceptable loss), up to *n*=10. Figure 6. 45 shows all the waiting time curves, for a patients inflow equal to α=1.0, a number of resources equal to those regulated by the emergency procedure (no additional resources, *m*=0) and several values of the *n* parameter. As evident, the difference between *n* values lower than the current layout and the waiting time curves representing *n>4* is remarkable. Therefore the unaltered behaviour for values of *n*>4 confirms the significance of having enough medical staff able to treat the patients accommodated in the rooms.

The analysis of the waiting time peaks (cf. Figure 6. 46) permits to conclude that the variation of the ratio between the number of available rooms and human resources notably compromises the behaviour of the system.

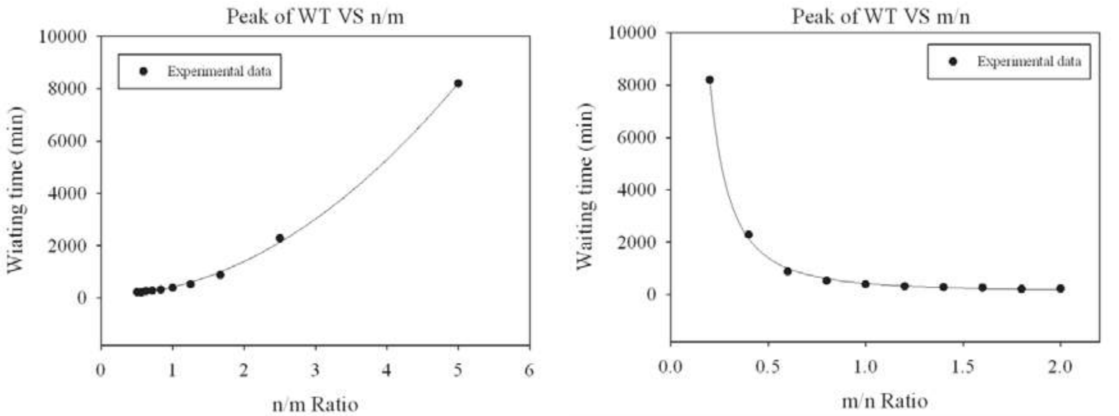


Figure 6. 46 Waiting time peaks as a function of the n/m (R*) ratio (on the left), and as a function of the* m/n (R^{-1}*) ratio (on the right side).*

For the first case, the variation of the peaks follows an exponential-growth-function with three parameters, as exemplified by the following equation:

$$f = a + b * \exp(c * x) \quad \text{(Eq.6. 2)}$$

where the three parameters are identified with the values indicated in Table 6.13.

Table 6.13 Parameters of the exponential-growth-function.

Parameters	Value
a	-15,094370
b	1327,1443
c	0,3982

On the one hand, the result indicates that the waiting time significantly increases at the increasing of the n/m ratio: for the latter having values <1, the peaks do not vary; however, when the ratio exceeds the value 2 the waiting time peaks increase considerably. On the other hand, considering the ratio *m/*n – which is the inverse of the previous one – the waiting time peaks decrease with values of the m/n ratio higher than 0.8, maintaining these values constant. The equation that better approximates the behaviour of these values is an inverse polynomial-second order (Eq.6. 3), whose values for the three parameters involved are indicated in Table 6.14.

$$f = a + \left(b/_x\right) + \left(c/_{x^2}\right) \quad \text{(Eq.6. 3)}$$

Table 6.14 Parameters of the inverse polynomial-second-order equation

Parameters	Value
a	90,8563
b	31,0383
c	8092,7213

By analysing the behaviour of these two ratios, i.e. *n/m* and *m/n*, in function of the increasing number of available rooms during an emergency (cf. Figure 6. 47, graph on the left) the values of the *m/n* ratio proportionally increase as a function of the *n* parameter, following a simple linear equation (as shown in (Eq.6. 4)):

$$f = a + b * x \quad \text{(Eq.6. 4)}$$

The two parameters involved are illustrated in Table 6.15:

Table 6.15 Parameters of the simple linear polynomial equation.

Parameters	Value
a	9,1563E-19
b	0,2

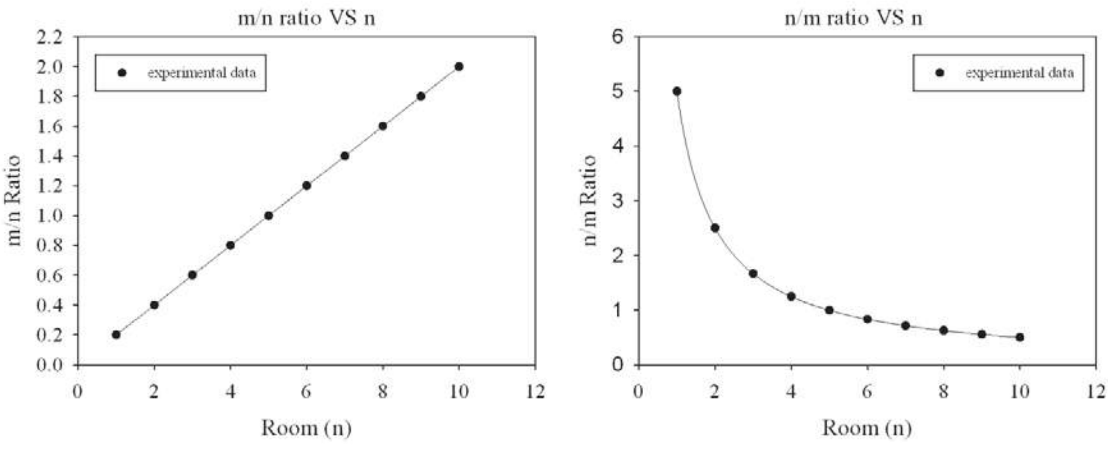


Figure 6. 47 Plotting of m/n *ratio vs. the* n *parameter (on the left), and* n/m *ratio vs.* n *parameter (on the right).*

As expected, the *n/m* ratio follows an inverse-first-order polynomial equation, corresponding to the general equation:

$$f = a + \left(b/_x\right) \quad \text{(Eq.6. 5)}$$

The two parameters defining the variation of *m/n* ratio are shown in Table 6.16:

Table 6.16 Parameters of the simple linear polynomial equation.

Parameters	Value
a	3,3492E-16
b	5,0

Chapter 7

Conclusions

This thesis develops an holistic methodology, based on fragility analysis, to evaluate the performance and the seismic resilience of hospital buildings. To this purpose, different fields, sometimes under investigated, have been studied and connected with each other. The resulting complex interconnection model, called “meta-model” in the text, is the most relevant achievement of this work.

The developed “meta-model” has been applied to a case study, i.e. a hospital located in Sansepolcro (Italy). In order to cover all the possible safety conditions occurring at the varying of the assumed seismic input, different scenarios have been considered and investigated. The proposed framework, representing both the physical integrity and the organizational optimization of the case-study, has been studied before and after the assumed emergency, consisting in an earthquake whose intensity is consistent with the seismicity of the area. The results of this study evidence the importance of considering the hospital building as a whole system, included the analysis of its structural and non-structural components, as well as the organizational models applied both in case of normal activities and emergency. Moreover, the proposed approach can represent a useful tool to optimize the planning of possible interventions aimed at improving both the safety of the hospital system and its efficiency, which in this study are measured in terms of waiting time experienced by patients. In the following sections the main outcomes of the research are recalled.

7.1 Research outcomes

Since the research has faced many different issues and fields, a first relevant result has been the recognition of the main lacks of knowledge affecting each of them. In order to control the safety and the efficiency of a hospital system, indeed many databases and tools must be available. The structural behaviour of secondary systems, in particular, seems to be not satisfactory; more knowledge and tools, like fragility curves, should be developed in order to include the non-structural components in the global analysis of hospital systems. In effect, the non-structural components are currently introduced in the buildings without any specific attention to the contribution provided by their global safety and performance. The performed analysis, however, clearly shows that the behaviour of non-structural components can largely affect the global safety of the whole structure, even compromising its functionality.

In this work structural and "comprehensive" (i.e. including both structural and non-structural components) fragility curves have been constructed for different limit states and different floors of the building. Only few non-structural components, i.e. the suspended ceilings and the cabinets, have been included in the analysis; all the other non-structural components, like piping system or gas network, have not been investigated in this thesis, since, at the current time, there are not available tools able to exhaustively describe their structural response. Accordingly, the best method to increase the current knowledge, as it has already been pursued in other countries, is to prompt a joint work with the companies supplying the non-structural components and their contents. The scientific community, together with the supplying companies, should have as a main objective the best possible implementation of the available databases regarding non-structural components. In particular, the standardisation of non-structural components should be aimed at increasing their performance in earthquake scenarios.

As regards the assumed case-study, however, the investigated non-structural components, i.e. the suspended ceilings and the cabinets, seem to fit the system since they do not affect its seismic performance.

The structural performance of the hospital system is well investigated. The proposed meta-model should be considered as a general framework to be implemented for specific purposes. A more careful choice, for instance, could be made about the ground motions selection, and a more detailed structural model, including the infill-wall contribution as well as alternative hysteretic models. The introduction of any additional model describing specific sub-systems would not compromise the effectiveness of the meta-model, but would rather constitute a further improvement.

One of the most relevant aspects underlined in this work is the use of "floor fragility curves" instead of the more common ones. Depending on the system under consideration and its location, in fact, the fragility curves referred to a specific storey should be adopted. The "floor fragility curves" allow to immediately determine the real Engineering Demand Parameter for non-structural components, wherever they are located. The coupling provided by these curves permits to compare the two physical elements for the described procedure, and to assess the organizational aspects, for instance prescribing the closure of different rooms. Accordingly, the "floor fragility curves" proposed in this work represent a "bridge-tool" for a multidisciplinary approach to this subject.

The dataset resulting from the evaluation of structural and non-structural elements not only permits to better describe the physical system, but also leads to include the organizational aspects and to determine the global response of the hospital system.

In this work a great effort has been made to assess the organizational aspects of the case study. The obtained results show how the organizational aspects strictly depend on all the other features that are indispensable to guarantee an efficient and safe response by the hospital. Moreover, the study highlights the importance of the effectiveness of the organizational plan, its procedures and features and how these elements suffer from the response of structural and non-structural performance once the waiting time reaches unacceptable levels.

Although both the model and the dataset need to be improved – many assumptions have been made in the analysis which can limit the generality of the achieved results – a first step towards a new idea of organizational assessment has been made. The calibration of the input dataset will probably need further improvements, like the seismic arrival rate; moreover, it would be desirable a collaboration with the “Department of the Civil Protection” for projecting a predictive model to assess the seismic resilience of the hospital network, to improve the available dataset and to support the practical activity concerning the results obtained from simulated scenarios. An adequate planning is essential for guaranteeing an efficient medical response in case of future earthquakes: therefore the possibility to test and to simulate changes within the investigated model would be an advantage both in terms of money and time saving, without having to wait future disasters for testing the prototype’s performances and its possible variations. To minimize the probability for a healthcare system to lose its functionality – especially considering its crucial role for satisfying the community’s needs in an emergency – the behaviour of the hospital structure and, consequently, the efficiency of the provided medical treatment can be only predicted taking into account every aspect of the system.

However, the emergency simulations performed by the hospital staff are fundamental for being adequately prepared in case of calamity: the human component cannot be totally reproduced by a machine, therefore doctors, nurses, sanitary operators and all people participating to the emergency procedures have to be trained to face each situation.

7.2 Future applications

The most significant result is the management of a complex system, thanks to the joint use of information coming from different fields and subjects, which merge into an exclusive process with a final outcome.

The performed study shows how the proposed methodology can be applied to a real case study. Even if the investigation is not completed (because of the scarcity of data on non-structural components), several possible applications are performed, which offer interesting and useful information for hospital managers, hospital supervisors and politicians.

The methodology can be enriched by considering additional data regarding a specific hospital, or by studying a greater number of hospitals, involving the whole healthcare network: accordingly, the research could be improved both in a “vertical” direction and in a “horizontal” perspective.

Special attention has been paid to the many possible applications of this methodology, for instance by adding different fields, like the economic one, together with an implementation of the available data. The hypothesis regarding the future improvement of the procedure is real and close to be achieved, both for the single healthcare facility and the regional medical system.

7.2.1 Further achievements in single hospitals

The economic management of healthcare facilities is a complex issue, especially where investments do not guarantee adequate results in terms of increased performance. In case of emergency, the medical staff must face dramatic situations, like the impossibility to treat patients, although no structural damages have occurred to the system. Unfortunately this has been the most recurrent scenario during the last earthquakes, even if large amounts of money have been invested for the seismic restoration of the structure.

Combining technical and economical knowledge and costs, a more convenient selection of the proper interventions could be made which is able to ensure the target efficiency even in emergency conditions. Such additional information within the methodology would allow managers and investors to better plan the expenses, to make focused interventions, and to guarantee a good maintenance of the entire system. As shown in Figure 6.43, the economic loss could be measured in different steps of the flowchart, due to the different costs associated with the failure. For example, if an earthquake strikes and a disruption of functionality occurs due to the suspended ceiling system failure, different levels of economic loss could be taken into account.

If no preventive actions are made and the functionality of the system is compromised, the economic loss could be very high; however, if cautionary actions are made with specific attention to non-structural components, the budget needed for increasing the seismic performance of the elements could be lower and no interruption of the service may occur.

Accordingly this approach gives the possibility to define the element representing the “weakest ring” of the chain, in order to identify the best strategy to manage the whole system and the best way to invest money for its improvement. The study on redundant elements is an applicative example: the relative cost for a new elevator can be compared with the total cost related to the impossibility to treat any patient during the emergency. In this specific case the costs to be compared are: the costs for the installation of the elevator and its maintaining versus the costs for transferring each patient to another hospital, without counting the costs in terms of human life (which are not measurable). Even the possibility to validate the emergency procedures of the hospital (PEMAF in Italy) is an interesting application of the current procedure, as revealed by application#2. Sensitive parameters, such as the ratio n/m, can be identified: this permits to take faster and well-aware decisions with consequent enhancements both during the emergency phase and the post-disaster period.

7.2.2 The network level applications

The methodology and its applications can be extended at an higher level, i.e. the regional medical system. The applications discussed for a single facility can be applied on a larger scale. The economic development can be used on the urban and inter-urban scale, taking into account the regional healthcare framework, the interconnections among hospitals, the distances and the time needed to reach other facilities, as well as the available resources in that region. In this case the monetary interest regards the costs for every patient to be transferred, each unavailable care-unit and the funds for the re-establishing of the interrupted medical service.

In case of emergency, decisions must be rapidly taken time, and all resources are to be used for transferring patients to places able to accommodate them. The costs of these procedures are high and often exceed the expected costs.

It is worth to note that the regional Italian healthcare network is based on a pyramidal organization; consequently, not all the hospitals are able to care a specific injury and the support of an higher-level hospital is needed. The methodology permits to analyse the resources needed in terms of medical staff, i.e. doctors and nurses, beds and medical services, but also ambulances, transportation equipment, and all is necessary to connect the network. In this sense, the redundant analysis on the elements is very useful, as it includes not only the components within the hospital, but the whole provided “medical service”, the road network, the essential water, gas and electrical networks. Therefore the identification of weak elements for the extended chain would be of significant help within the maxi-emergency programs of the region.

On the one hand, a supported collaboration with the Civil Protection is desirable and potentially fruitful, since one of its competences is the management of the territorial resources under disaster conditions. On the other hand, data regarding single hospitals in terms of time and resilience performance are essential for obtaining good results when a big area is in an emergency.

The use of this methodology by each single hospital will permit a complete overview of the entire healthcare system. This last goal can be represented by a cobweb, in which each fibre is composed by a hospital. The use of the methodology could represent a tool for the Civil Protection in defining different procedures and plans, dependent on several emergency scenarios, with consequent better organized decisional programs by politicians and administrative personnel.

7.3 A multidisciplinary perspective

The most important issue concerning this research field, as already underlined, crucially regards the need for a multidisciplinary approach.

The starting point of this work necessarily relied on the simultaneous investigation of multiple areas and the available input data were gathered from the fields involved. As a consequence, the work strongly relies on the comparison between various datasets and, to compensate the lack of information, on the formulation of various assumptions. Furthermore, the presented methodology intends to cope with the shortcomings of suitable methods noticed in the current literature. More specifically, the proposed methodology aims at stressing the strict interplay of the non-structural elements of the hospital, that are essential for an adequate and continuous operability of the system, with proper structural elements. In other words, the methodology correlates the physical features of the system, i.e. non-structural and structural elements, with its organizational aspects, that are currently considered in a mere qualitative sense. A methodology that is able to identify a single component as the cause of a loss of functionality offers a great advantage not only for the prevention phase, but also during the emergency. To develop such a methodology a multidisciplinary approach must be adopted, where multifaceted knowledge and various data, subjects and competences are simultaneously taken into account.

7.3.1 A greater awareness among experts

Such multidisciplinary approach highlights the necessity of awareness for all the operators involved in the process. For instance, engineers must be aware of the significance of the non-structural components and the functions imposed by the architectural features; in addition, both engineers and architects should combine their knowledge to improve the efficiency of internal contents along with manufacturing companies; the latter should conform to the standards established by the code and, in cooperation with the experts, improve their products.

The awareness concerning the medical knowledge can only be expressed by taking into account all the functional tools into the hospital as well as the conditions under which they maintain their functionality. Medical treatments are essential, but doctors must be able to operate in safe conditions and in a functional place.

The good performance of individual functions is certainly a necessary condition, but it is not sufficient for the hospital to offer its global service to the community.

7.3.2 A new resilience coordinator for the heath-care facilities

Nowadays there are great expectations regarding the full specialization of each sector; all systems have been evolving along with their users and are increasingly becoming more complex “machines”. Very often innovative components are developed and located in old contexts, but they reveal to be not useful since they cannot be fully exploited.

Perhaps the best solution may be to combine the specialist subjects (that necessarily produce improvements) into a global management, reinstating a figures able to supervise multiple areas of interest. Accordingly the common purpose, say the interest in providing timely and continuous health support to the population, will be strengthened. Such a reference figure, able to coordinate the specific interventions in individual areas of expertise, will not complicate the existing hierarchy (as it may seem); by the contrary, it will better organize the “system”.

The evaluation of a hospital as a “complex apparatus” must be made by a skilled person having different competences and being able to communicate with any kind of specialist in order to completely understand the system. In effect, complex systems are often overlooked even by engineers that, given their background, tend to omit human features, medical and architectural aspects, that is: all those aspects that over time have been proved to be of crucial importance and therefore not less relevant than the structural elements making up the building.

This new figure must be aware of the close link between:

- environment and organizational factors;
- medical features and instrumentations;
- scientific management of each single component and flexible management in case of emergency.

Furthermore this person must have a strong sense of renovation, must be flexible and able to interact with people having different scientific backgrounds and expertise.

Although this study paves the way for a deeper comprehension of the strict interplay between physical damages, structural and non-structural performances, organizational response and their effect on loss of functionality, more efforts are needed for the development of such “new figure” able to efficiently manage the seismic resilience of a hospital. Only in this way the developed methodology will really have beneficial effects on the final performance of the healthcare facility within a community.

It is evident that in the future the functionality and resilience of hospital buildings should be analysed in terms of “coexistence”: this does not mean that every specialist has to know every aspect involved, but that cooperation and organization must be ensured. This new integrated approach represents the future of hospitals as it will guarantee a level of resilience suitable to face any kind of situation.

7.4 Future developments

The seismic resilience of hospital buildings represents a research field that crucially needs further analyses.

Future research should be extended to a a wider range of hospitals, with variable size and different patients' categories. Further studies may permit to standardize the calibration of the organizational model and simpler and better planned procedures may be tested. Moreover a larger amount of tested hospitals could provide more data about the difficulties arising from patients' medical treatment, which would deliver fruitful results for evaluating seismic resilience.

At the same time, further investigations should deal with non-structural components: more laboratory tests are needed and a stable cooperation between engineers and suppliers should be established. A fruitful achievement in this area could be the economic quantification of seismic resilience, by carefully coupling the monetary loss for each element contributing to the whole functionality of the hospital: as a result, hospital managers would be able to consider another variable for making decisions and planning mitigation actions.

The seismic resilience of hospital buildings will not be satisfactorily comprehended until all the parties involved jointly participate in its improvement and, most importantly, until each of them makes efforts to improve their performance.

The main aim of this thesis is to offer a concrete contribution to mankind's safety and, from a theoretical viewpoint, to increase the scientific interest in a dynamic field where multidisciplinary and continuous research is both needed and promising.

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Appendices

Appendix a): Non-structural components list

In this Appendix is shown a list of non-structural components, deriving from several different lists of literature. The main non-structural components are grouped according to their function, and are strictly referred to health-care facilities.

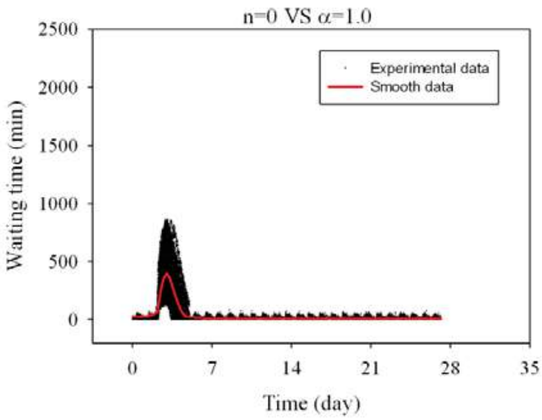
Table 1Non-structural components list derived from literature and grouped by main functions of them. The aim of the list is to take into account all the possible “secondary elements” which may be within a hospital.

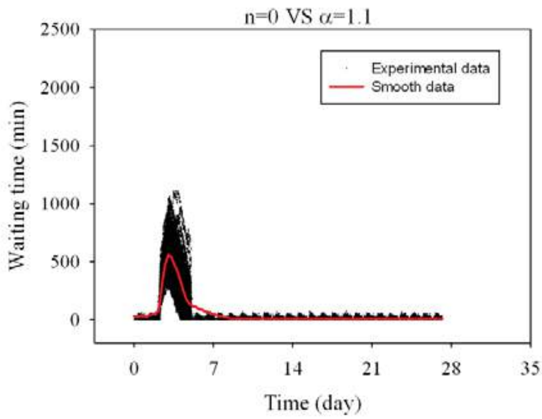
Critical system	Electrical system	Generators
		Electrical equipment, cables and cables ducts
		Control panel
		Lighting system for critical areas of teh hospital
		External electrical systems
	Telecommunications system	Antenna and antenna bracing
		Low-voltage systems
		Alternative communications systems
		Anchors and braces for telecommunications equipments and cables
		Internal communications systems
	Water supply system	Water tanks
		Water storage tanks
		Alternative water distribution network
		Water distribution system
		Supplementary pumping system
	Fuel storage (gas, gasoline, diesel)	Fuel tanks
		Distribution system (valves, hoses and connections)
	Madical Gases (oxygen, nitrogen, etc.)	Anchors for medical gas tanks, cylinders and related equipment

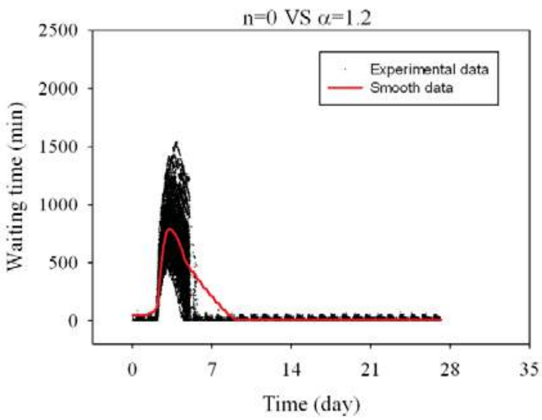
		Medical gas distribution system
Heating, ventilation, and air conditioning (HVAC) systems in critical areas	Supports for ducts	
	Pipes, connections, valves	
	Anchors for heating and/or hot water equipment	
	Anchors for air-conditioning equipment	
	HVAC equipment (boiler, air-conditioning systems, exhaust, etc.)	
Office and storeroom furnishings and equipment (fixed and movable) including computers, printers, etc.	Anchors for shelving and shelf contents	
	Computers and printers	
	Office furnishings and other equipment	
Medical and laboratory equipment and supplies used for diagnosis and treatment	Medical equipment in operating theaters and recovery rooms	
	Radiology and imaging equipment	
	Laboratory equipment	
	Medical equipment in emergency services unit	
	Medical equipment in intensive or intermediate care unit	
	Equipment and furnishings in the pharmacy	
	Equipment in starilization unit	
	Medical equipment for neonatal care	
	Medical equipment and supplies for burn management	
	Madical equipment for nuclear medicine and radiation therapy	
	Madical equipment in other services	
	Anchors for shelving and medical contents	
Architectural elements	Doors and entrances	
	Windows and shutters	
	Others elements of the building envelope (outside walls, facings, etc.)	
	Roofing	
	Parapets	
	Perimeters walls and fencing	
	Outside elements (cornices, ornaments, etc.)	
	Inside circulation (stairs, corridors, elevators, exit doors, etc.)	
	Internal walls and partitions	
	False or suspended ceilings	
	Internal and external lighting systems	
	Fire protection system	
	Elevator system	
	Stairways	
	Floor coverings	
	Hospital access routes	
	Other architectural elements, including emergency signs	

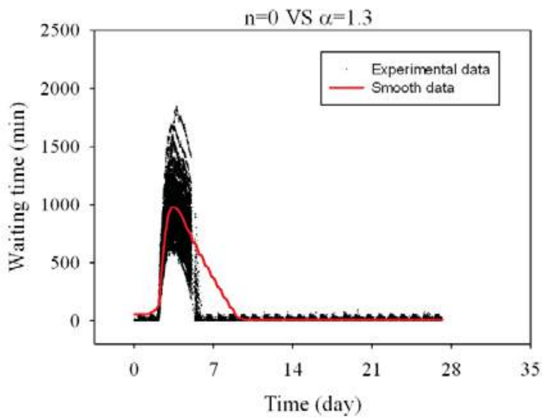
Appendix b): Permanent closures into organizational model simulations (model: case 1)

In this Appendix are presented the results from the case 1- organizational model. The results are grouped according to the steps described into Chapter5: the first group show the data clouds, then are presented the fitted curves. This order is followed for each varied variable. The second part of the appendix shows the coefficient deriving from the dynamic fit-nonlinear regression analysis, grouped according to the varied variable. The last part of the appendix describes the *a, b, c* parameters variation, both graphically and with the sub-parameters values.









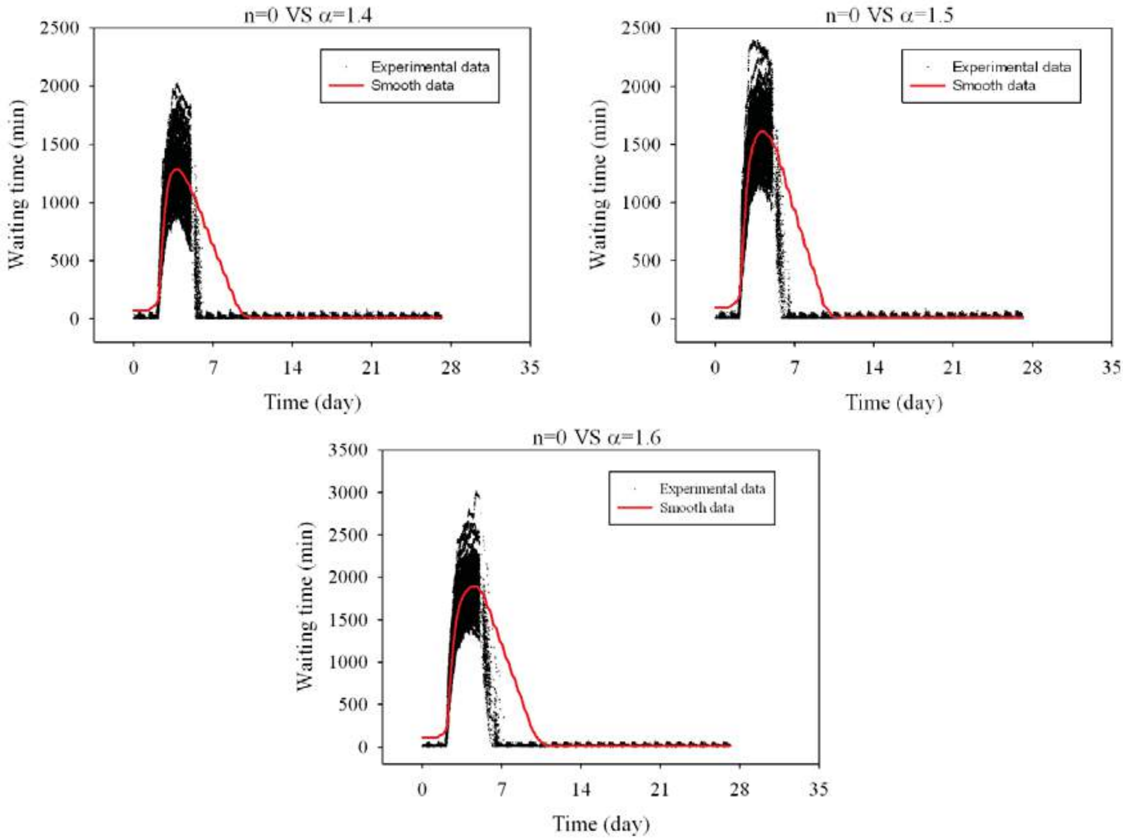
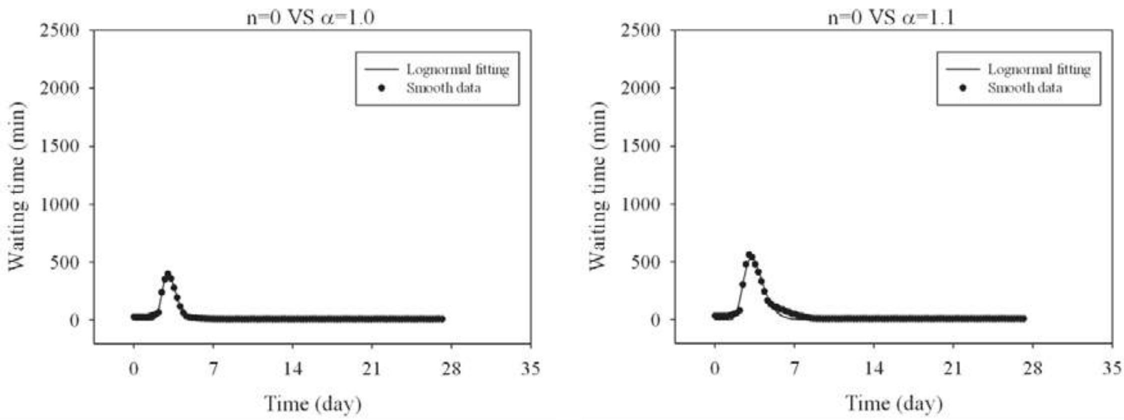


Figure 1 Results from simulations of the organizational model in emergency conditions without room closures (n=0), and increasing arrival rate (from 1.0 to 1.6). Simulations run with three emergency days and 26 normal days. Emergency procedures always activated, both in terms of resources and patients paths. Data clouds (experimental data into legend) from organizational model and smooth analysis with third polynomial degree negative exponential smoother (red medium dash line).



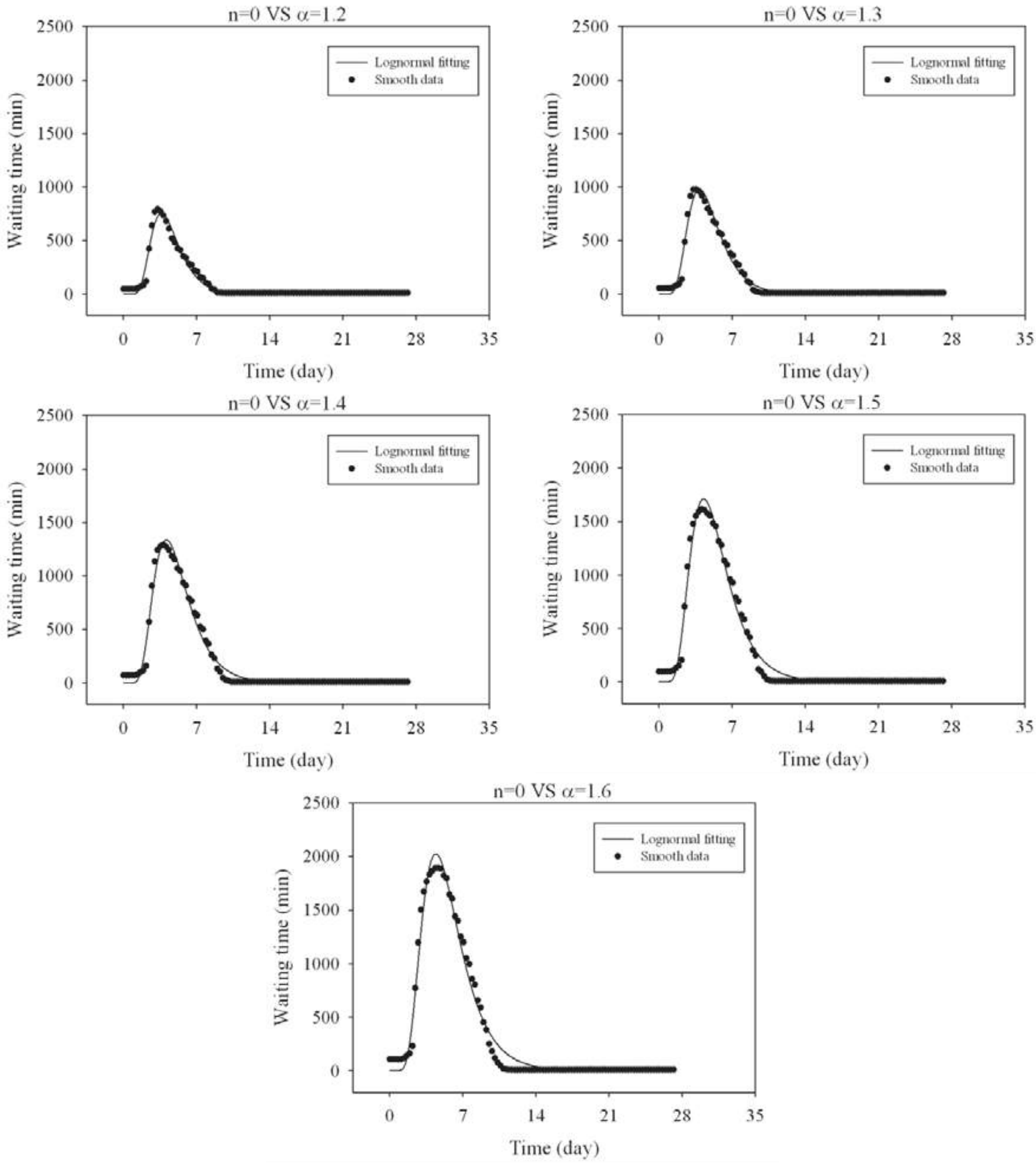
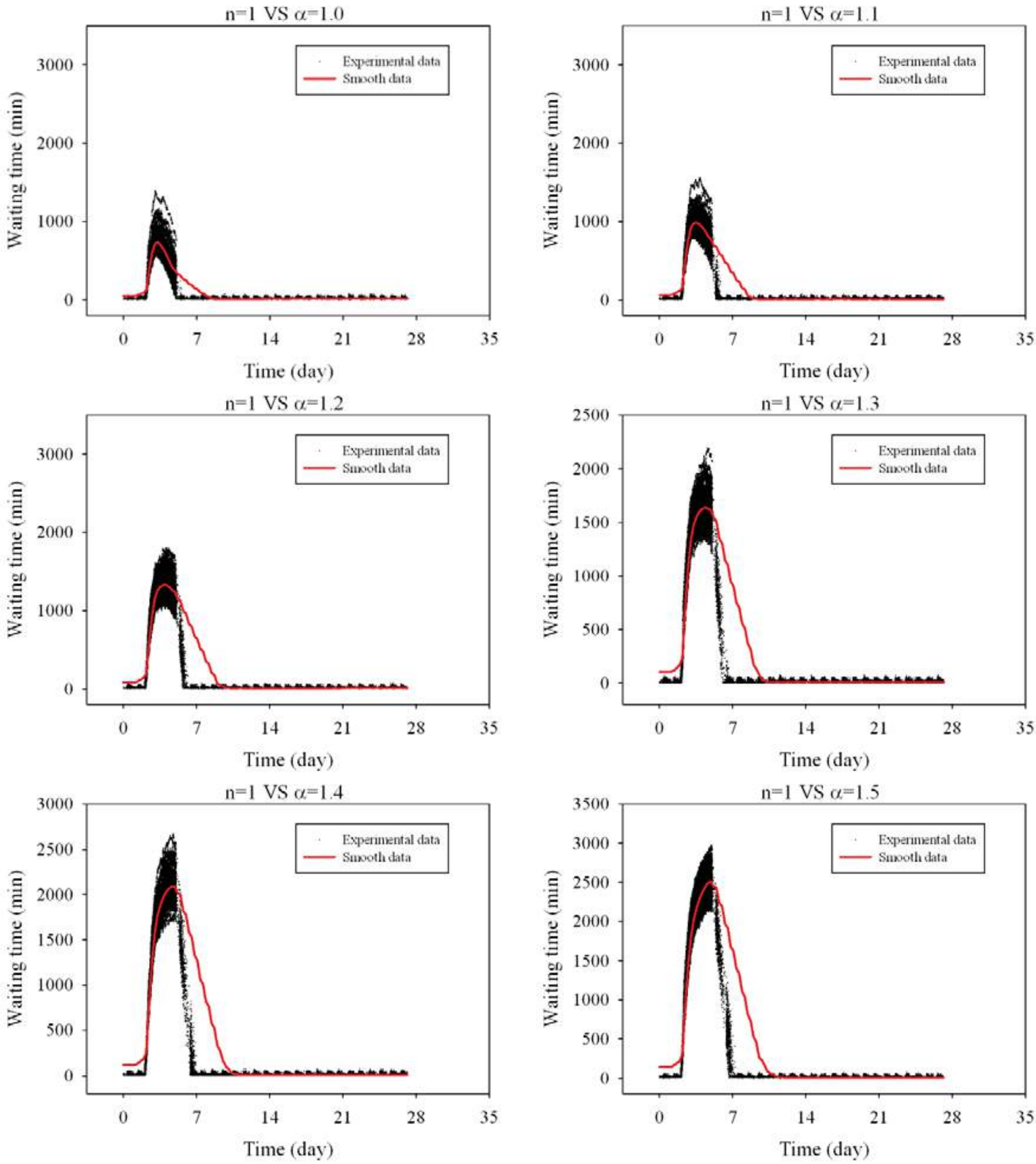


Figure 2 Results from simulations of the organizational model in emergency conditions without room closures (n=0), and increasing arrival rate (from 1.0 to 1.6). Simulations run with three emergency days and 26 normal days. Emergency procedures always activated, both in terms of resources and patients paths. Smooth analysis with third polynomial degree negative exponential smoother (black dotted line), and lognormal fitting with three parameters.


n=1 VS α=1.0
n=1 VS α=1.1
n=1 VS α=1.2
n=1 VS α=1.3
n=1 VS α=1.4
n=1 VS α=1.5
Experimental data
Smooth data
Waiting time (min)
Time (day)

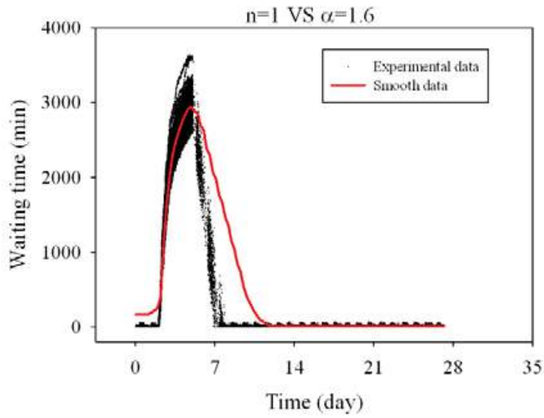
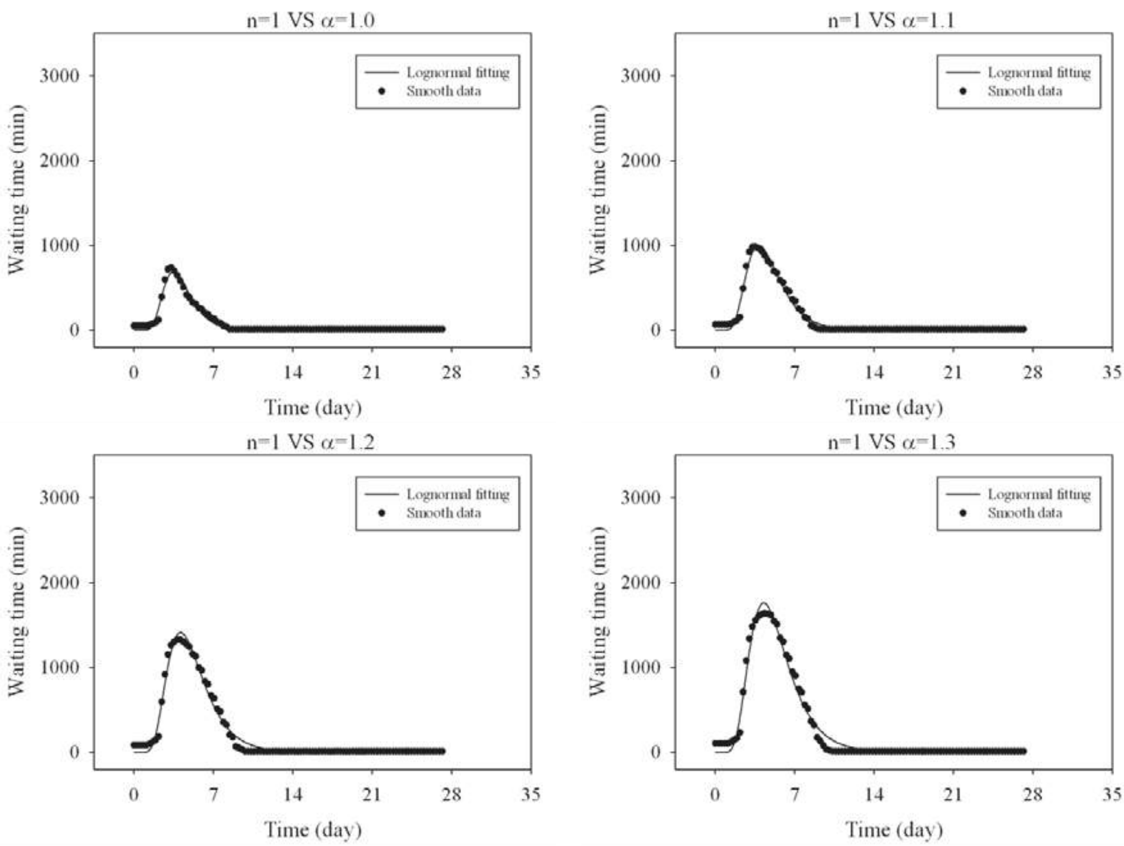


Figure 3 Results from simulations of the organizational model in emergency conditions with the closure of one room (n=1), and increasing arrival rate (from 1.0 to 1.6). Simulations run with three emergency days and 26 normal days. Emergency procedures always activated, both in terms of resources and patients paths. Data clouds (experimental data into legend) from organizational model and smooth analysis with third polynomial degree negative exponential smoother (red medium dash line).



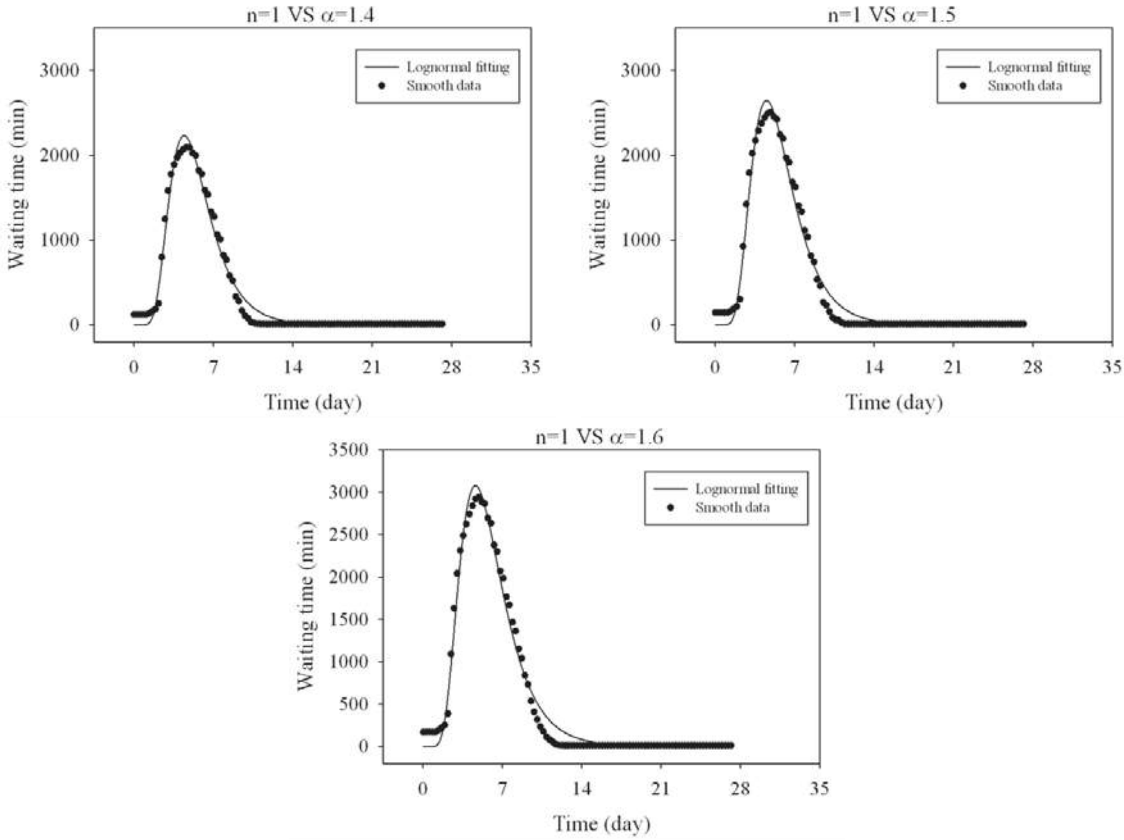
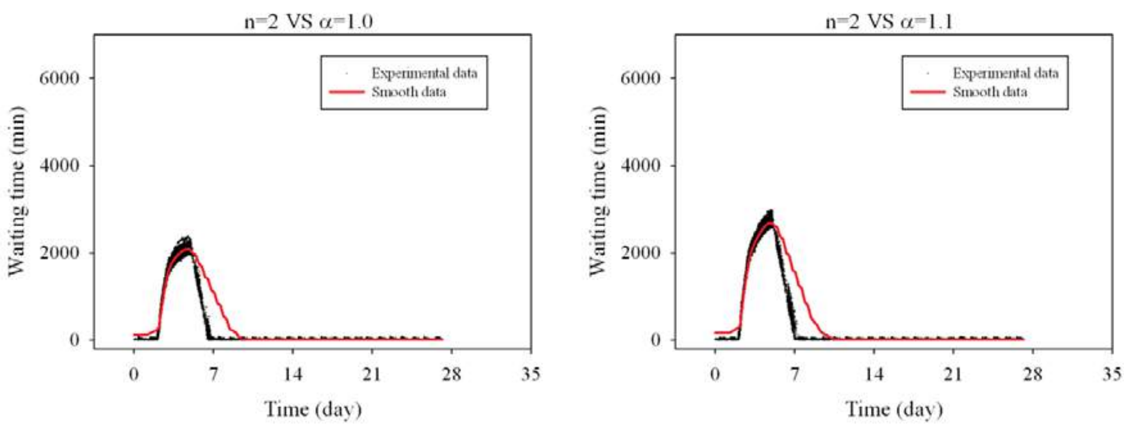


Figure 4 Results from simulations of the organizational model in emergency conditions with the closure of one room (n=1), and increasing arrival rate (from 1.0 to 1.6). Simulations run with three emergency days and 26 normal days. Emergency procedures always activated, both in terms of resources and patients paths. Smooth analysis with third polynomial degree negative exponential smoother (black dotted line), and lognormal fitting with three parameters.



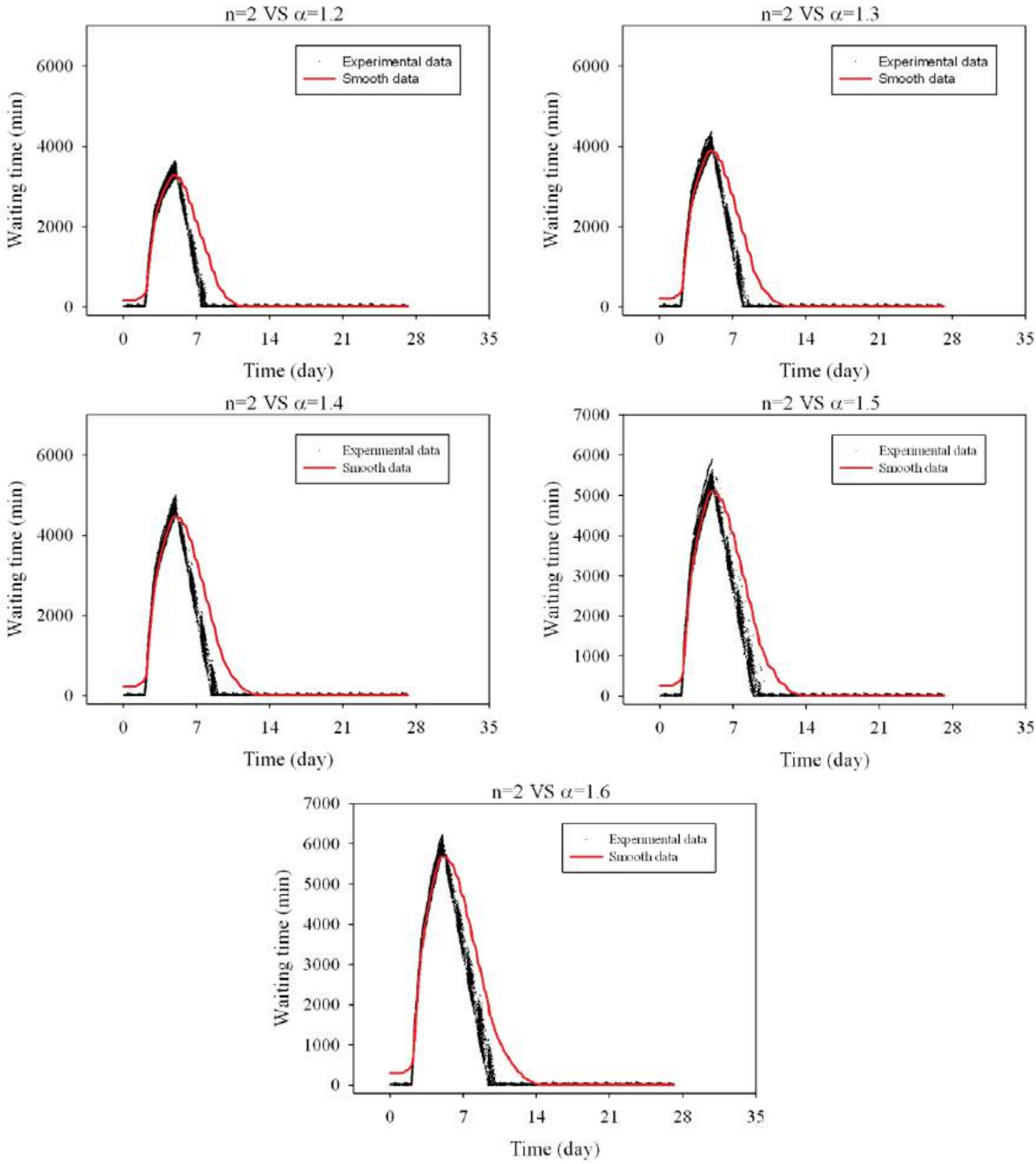
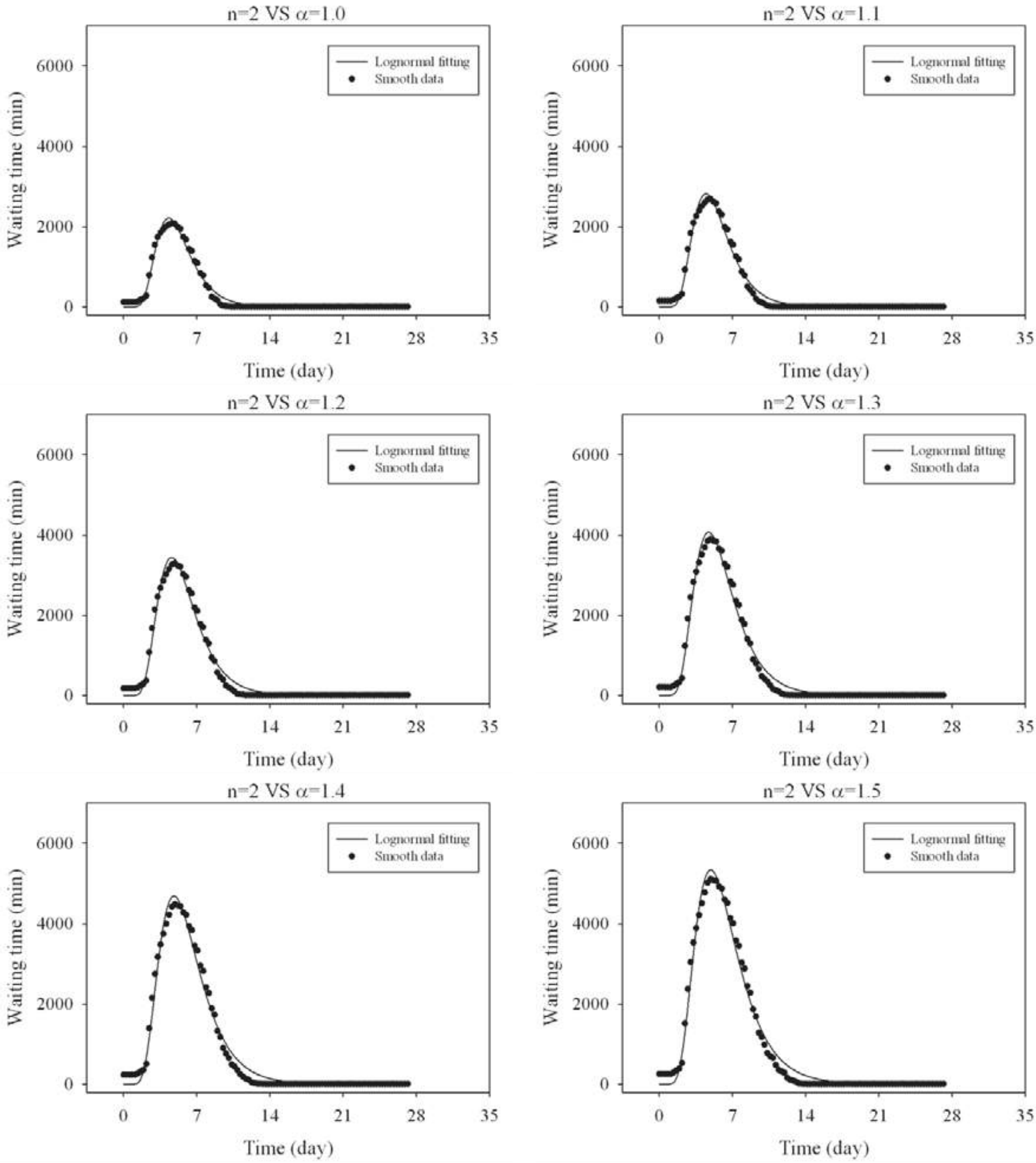


Figure 5 Results from simulations of the organizational model in emergency conditions with the closure of two rooms (n=2), and increasing arrival rate (from 1.0 to 1.6). Simulations run with three emergency days and 26 normal days. Emergency procedures always activated, both in terms of resources and patients paths. Data clouds (experimental data into legend) from organizational model and smooth analysis with third polynomial degree negative exponential smoother (red medium dash line).


n=2 VS α=1.0
n=2 VS α=1.1
n=2 VS α=1.2
n=2 VS α=1.3
n=2 VS α=1.4
n=2 VS α=1.5
Lognormal fitting
Smooth data
Waiting time (min)
Time (day)
0
2000
4000
6000
0
7
14
21
28
35

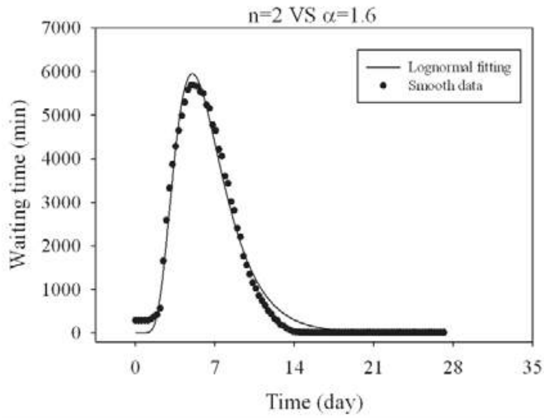
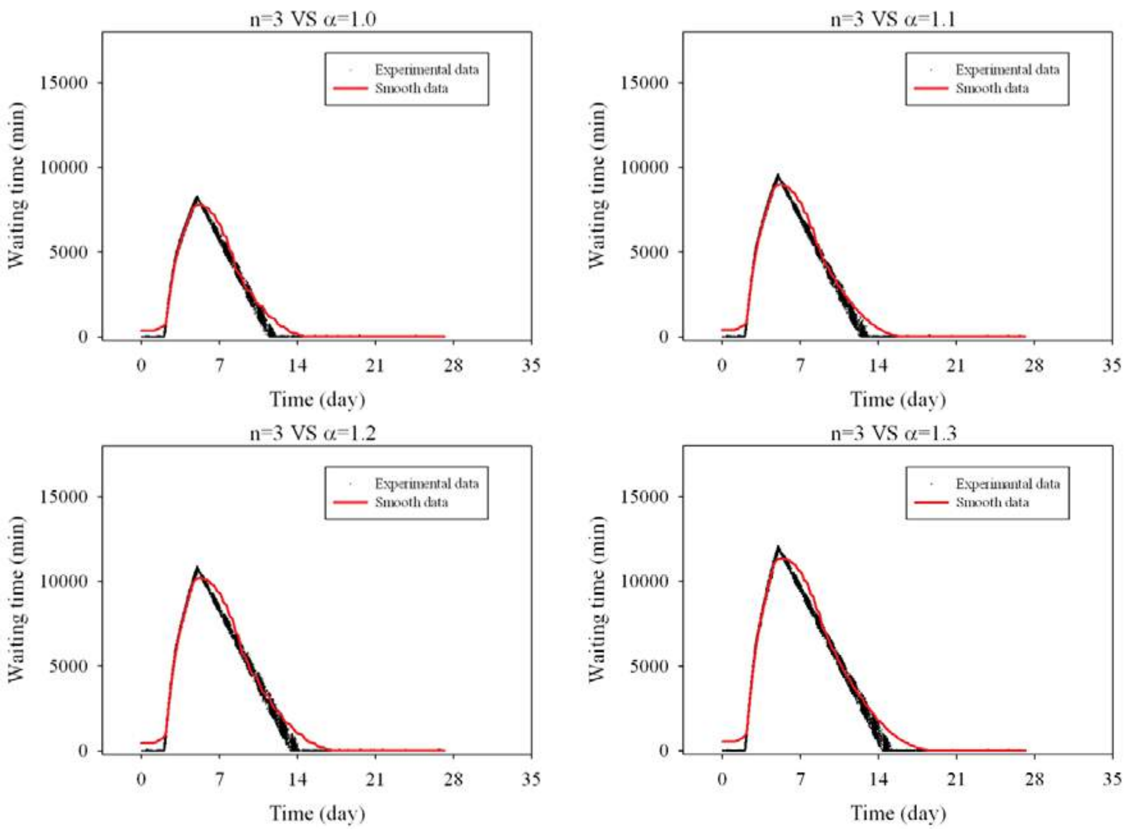


Figure 6 Results from simulations of the organizational model in emergency conditions with the closure of two rooms (n=2), and increasing arrival rate (from 1.0 to 1.6). Simulations run with three emergency days and 26 normal days. Emergency procedures always activated, both in terms of resources and patients paths. Smooth analysis with third polynomial degree negative exponential smoother (black dotted line), and lognormal fitting with three parameters



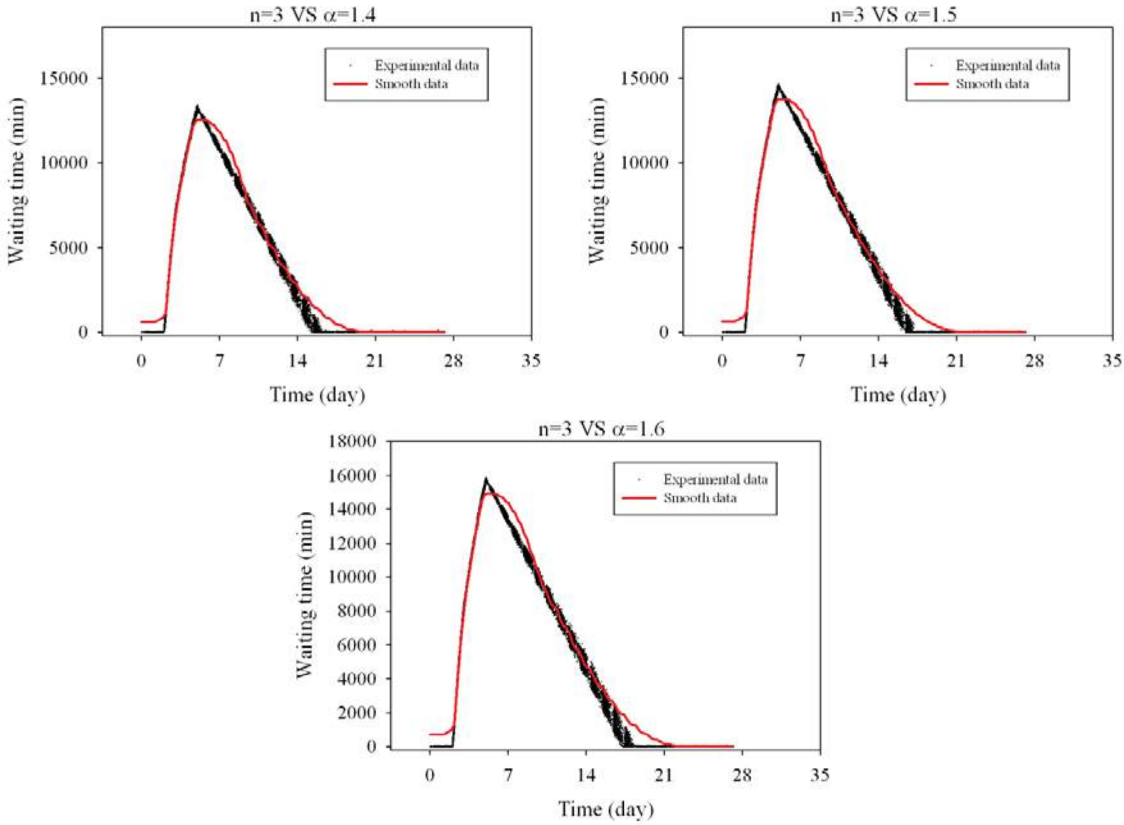
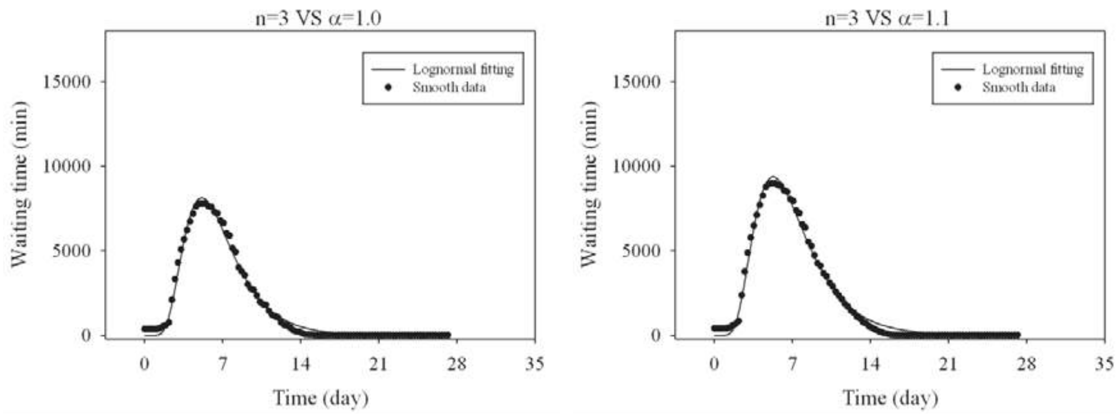


Figure 7 Results from simulations of the organizational model in emergency conditions with the closure of three rooms (n=3), and increasing arrival rate (from 1.0 to 1.6). Simulations run with three emergency days and 26 normal days. Emergency procedures always activated, both in terms of resources and patients paths. Data clouds (experimental data into legend) from organizational model and smooth analysis with third polynomial degree negative exponential smoother (red medium dash line).



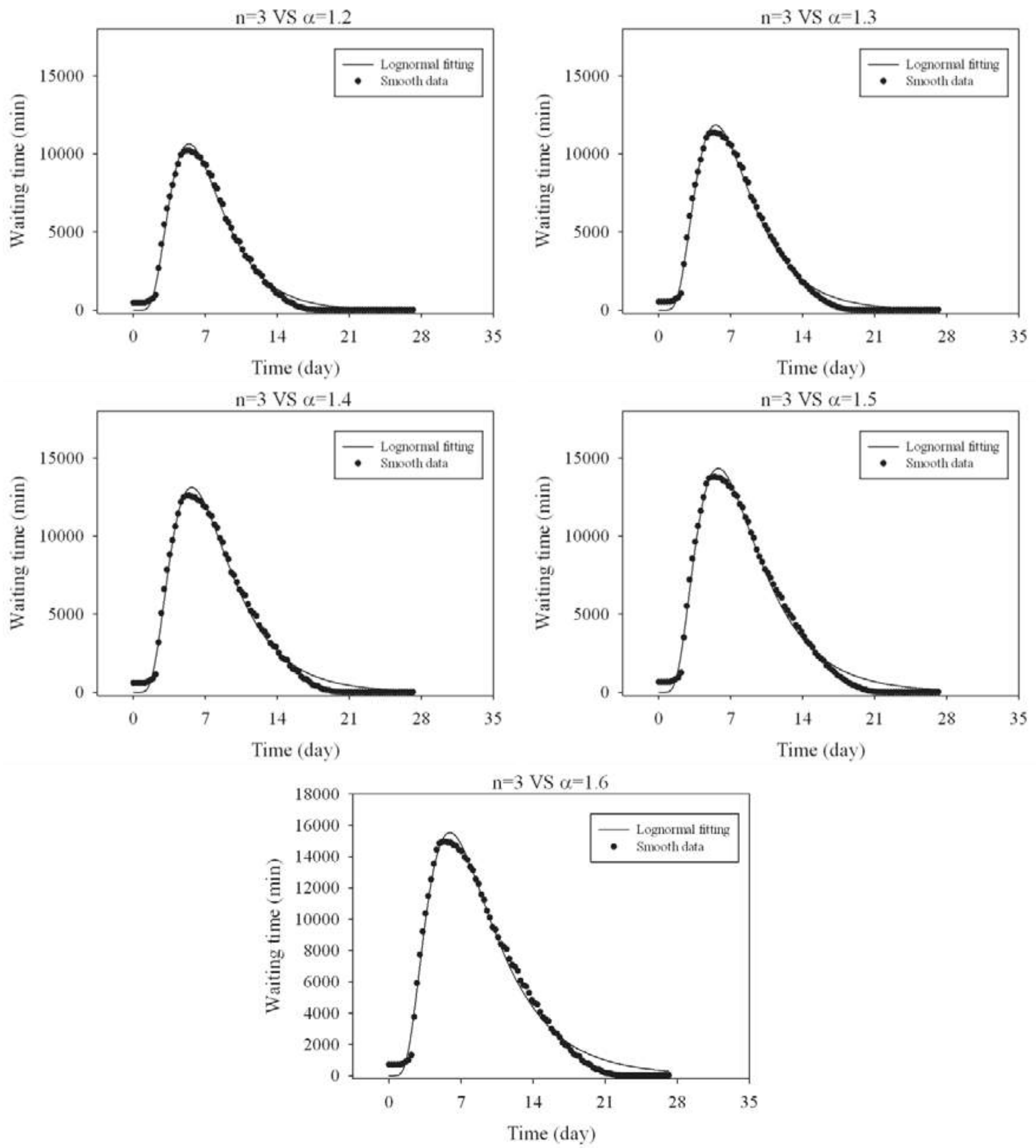


Figure 8 Results from simulations of the organizational model in emergency conditions with the closure of three rooms (n=3), and increasing arrival rate (from 1.0 to 1.6). Simulations run with three emergency days and 26 normal days. Emergency procedures always activated, both in terms of resources and patients paths. Smooth analysis with third polynomial degree negative exponential smoother (black dotted line), and lognormal fitting with three parameter

Table 2 Coefficient deriving from the dynamic fit-nonlinear regression analysis of the models with n=0.

Model (name)	**Parameters**		
	a	**b**	**c**
Model_n0E_ α=1.0	1744236	0.1957	4470.938
Model_n0E_ α=1.1	2547769	0.2583	4907.4
Model_n0E_ α=1.2	4175566	0.3698	5940.189
Model_n0E_ α=1.3	5808548	0.3887	6418.565
Model_n0E_ α=1.4	8479162	0.4009	6865.804
Model_n0E_ α=1.5	11353831	0.41	7214.502
Model_n0E_ α=1.6	13917735	0.4135	7482.819

Table 3 Coefficient deriving from the dynamic fit-nonlinear regression analysis of the models with n=1.

Model (name)	**Parameters**		
	a	**b**	**c**
Model_n1E_ α=1.0	3644783	0.342	5596.745
Model_n1E_ α=1.1	5883396	0.3795	6328.052
Model_n1E_ α=1.2	8919542	0.3901	6826.676
Model_n1E_ α=1.3	11577560	0.3952	7121.395
Model_n1E_ α=1.4	15207661	0.3961	7375.213
Model_n1E_ α=1.5	18506309	0.4013	7587.265
Model_n1E_ α=1.6	22109093	0.411	7818.534

Table 4 Coefficient deriving from the dynamic fit-nonlinear regression analysis of the models with n=2.

Model (name)	**Parameters**		
	a	**b**	**c**
Model_n2E_ α=1.0	14622650	0.3731	7086.107
Model_n2E_ α=1.1	19288887	0.3768	7339.918
Model_n2E_ α=1.2	24374307	0.3869	7629.918
Model_n2E_ α=1.3	29684196	0.3963	7884.429
Model_n2E_ α=1.4	35024762	0.4031	8107.121
Model_n2E_ α=1.5	40881879	0.4129	8340.206
Model_n2E_ α=1.6	46583831	0.4219	8550.887

Table 5 Coefficient deriving from the dynamic fit-nonlinear regression analysis of the models with n=3.

Model (name)	**Parameters**		
	a	**b**	**c**
Model_n3E_ α=1.0	65031913	0.4291	8781.418
Model_n3E_ α=1.1	77823395	0.4495	9199.311
Model_n3E_ α=1.2	91429363	0.4674	9588.988
Model_n3E_ α=1.3	1.05E+08	0.4867	10017.18
Model_n3E_ α=1.4	1.2E+08	0.5038	10426.57
Model_n3E_ α=1.5	1.36E+08	0.5225	10856.77
Model_n3E_ α=1.6	1.52E+08	0.5403	11301.53

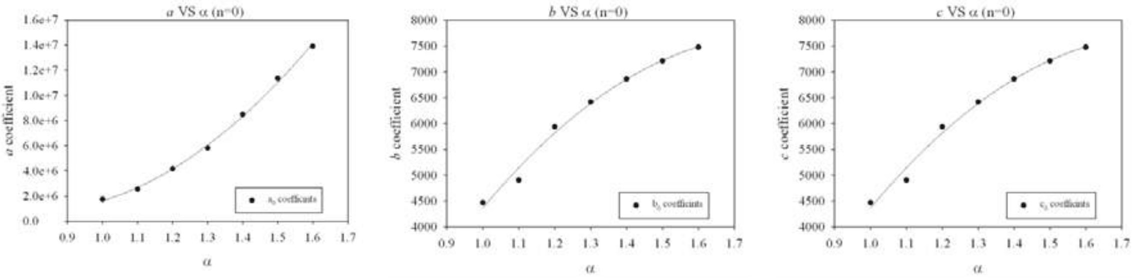


Figure 9 a_0, b_0, and c_0 parameters for the model with n=0

Table 6 a0, a1, a2, b0, b1, b2, c0, c1, and c2 parameters value for n=0.

a parameter	value	b parameter	value	c parameter	value
$\mathbf{a_0}$	13341705	$\mathbf{b_0}$	-1.72302	$\mathbf{c_0}$	-9073.94
$\mathbf{a_1}$	-3.2E+07	$\mathbf{b_1}$	2.893702	$\mathbf{c_1}$	18587.65
$\mathbf{a_2}$	20370804	$\mathbf{b_2}$	-0.97726	$\mathbf{c_2}$	-5146.97

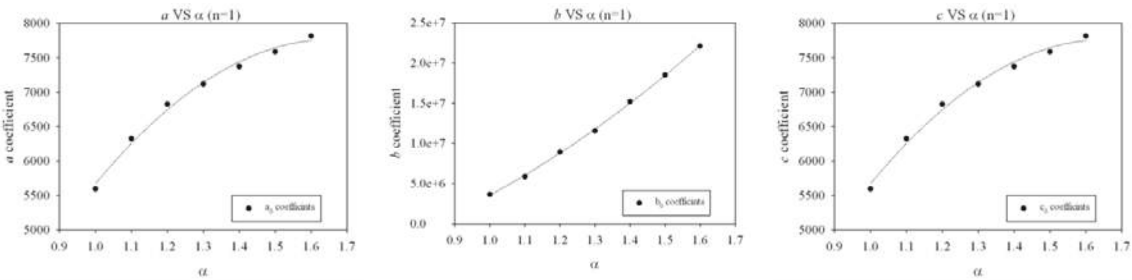


Figure 10 a_0, b_0, and c_0 parameters for the model with n=1

Table 7 a0, a1, a2, b0, b1, b2, c0, c1, and c2 parameters value for n=1

a parameter	value	b parameter	value	c parameter	value
$\mathbf{a_0}$	-8299700	$\mathbf{b_0}$	-0.0738	$\mathbf{c_0}$	-5454.35
$\mathbf{a_1}$	-147056	$\mathbf{b_1}$	0.6315	$\mathbf{c_1}$	15902.76
$\mathbf{a_2}$	11997065	$\mathbf{b_2}$	-0.2076	$\mathbf{c_2}$	-4779.59

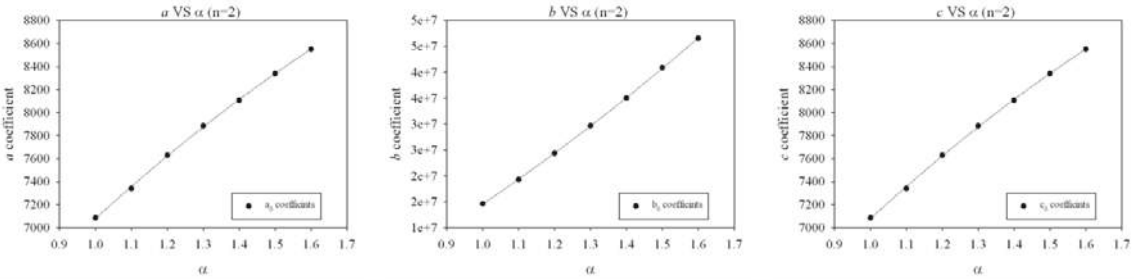


Figure 11 a_0, b_0, and c_0 parameters for the model with n=2

Table 8 a0, a1, a2, b0, b1, b2, c0, c1, and c2 parameters value for n=2

a parameter	**value**	**b parameter**	**value**	**c parameter**	**value**
$\mathbf{a_0}$	-2.2E+07	$\mathbf{b_0}$	0.3257	$\mathbf{c_0}$	3550.151
$\mathbf{a_1}$	25309661	$\mathbf{b_1}$	0.0226	$\mathbf{c_1}$	4199.624
$\mathbf{a_2}$	10831447	$\mathbf{b_2}$	0.0236	$\mathbf{c_2}$	-671.268

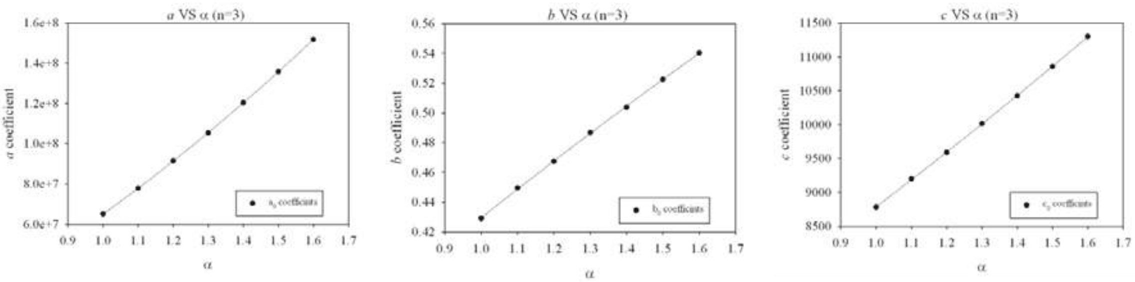


Figure 12 a_0, b_0, and c_0 parameters for the model with n=3

Table 9 a0, a1, a2, b0, b1, b2, c0, c1, and c2 parameters value for n=3.

a parameter	**value**	**b parameter**	**value**	**c parameter**	**value**
$\mathbf{a_0}$	-2.7E+07	$\mathbf{b_0}$	0.2197	$\mathbf{c_0}$	5174.395
$\mathbf{a_1}$	59674180	$\mathbf{b_1}$	0.2258	$\mathbf{c_1}$	3256.677
$\mathbf{a_2}$	32690091	$\mathbf{b_2}$	-0.016	$\mathbf{c_2}$	356.337

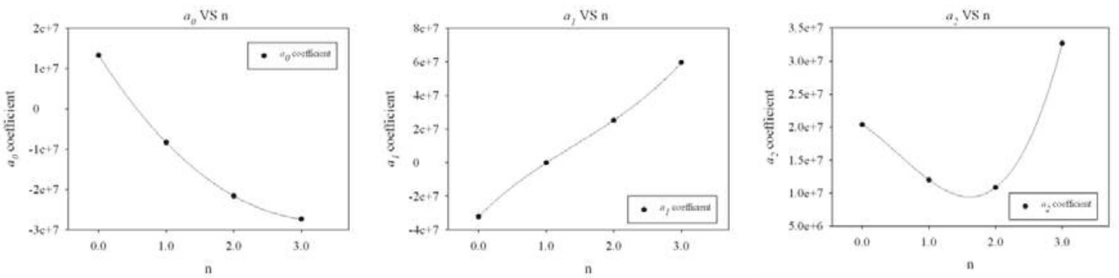


Figure 13 a_0, a_1, a_2 parameters for the variation of n.

Table 10 a_0, a_1, a_2 values of parameters for the variation of n.

a_0 parameter	**value**	**a_1 parameter**	**value**	**a_2 parameter**	**value**
a_{00}	13341705	**a_{10}**	-3.2E+07	**a_{20}**	20370804
a_{01}	-2.6E+07	**a_{11}**	40324760	**a_{21}**	-6705754
a_{02}	4612817	**a_{12}**	-1.1E+07	**a_{22}**	-4304009
a_{03}	-143284	**a_{13}**	2566341	**a_{23}**	2636023

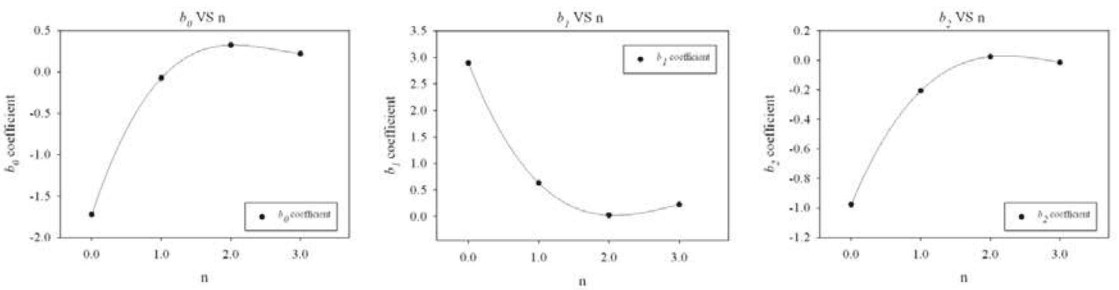


Figure 14 a_0, a_1, a_2 parameters for the variation of n.

Table 11 b_0, b_1, b_2 values of parameters for the variation of n.

b_0 parameter	**value**	**b_1 parameter**	**value**	**b_2 parameter**	**value**
b_{00}	-1.723	b_{10}	2.8937	b_{20}	-0.9773
b_{01}	2.5222	b_{11}	-3.3693	b_{21}	1.1281
b_{02}	-0.997	b_{12}	1.2473	b_{22}	-0.4031
b_{03}	0.124	b_{13}	-0.1402	b_{23}	0.0446

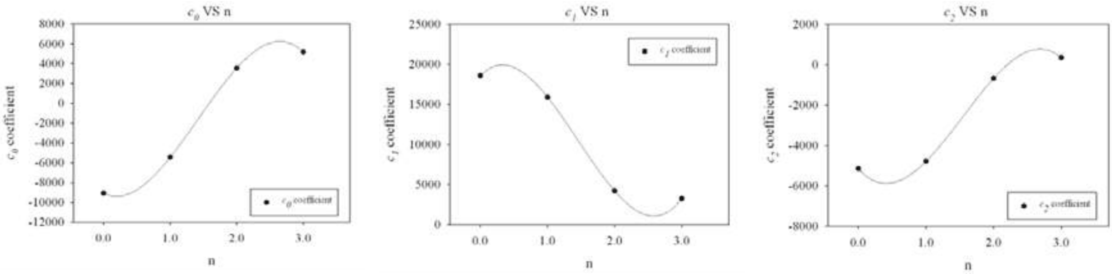


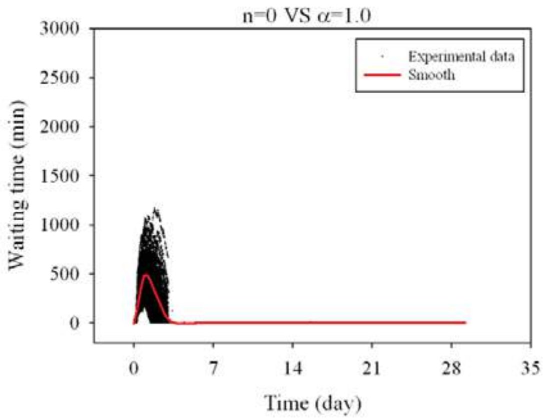
Figure 15 b_0, b_1, b_2 parameters for the variation of n.

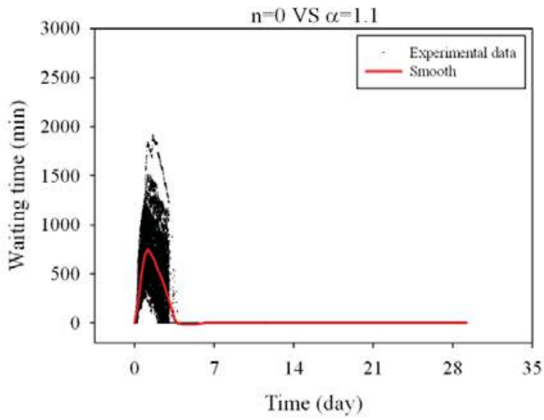
Table 12 c_0, c_1, c_2 values of parameters for the variation of n.

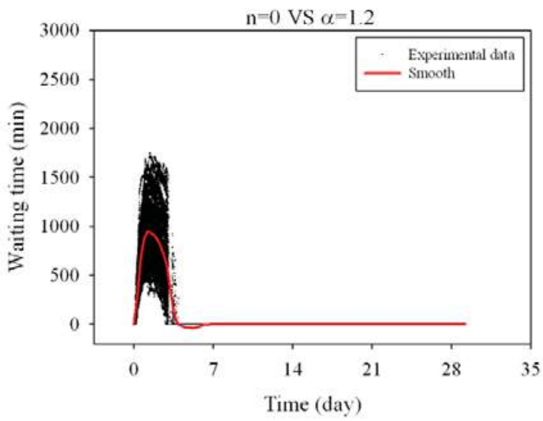
c_0 parameter	**value**	**c_1 parameter**	**value**	**c_2 parameter**	**value**
c_{00}	-9073.94	**c_{10}**	18587.65	**c_{20}**	-5146.97
c_{01}	-3327.92	**c_{11}**	8417.052	**c_{21}**	-3776.97
c_{02}	9075.038	**c_{12}**	-14398.3	**c_{22}**	5281.295
c_{03}	-2127.53	**c_{13}**	18587.65	**c_{23}**	-1136.94

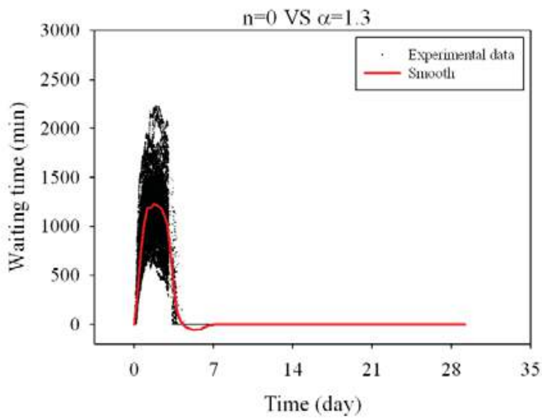
Appendix c): Permanent closures into organizational model simulations (model: case 2)

In this Appendix are presented the results from the case 2- organizational model. The results are grouped according to the steps described into Chapter5: the first group show the data clouds, then are presented the fitted curves. This order is followed for each varied variable. The second part of the appendix shows the coefficient deriving from the dynamic fit-nonlinear regression analysis, grouped according to the varied variable. The last part of the appendix describes the *a*, *b*, *c* parameters variation, both graphically and with the sub-parameters values.









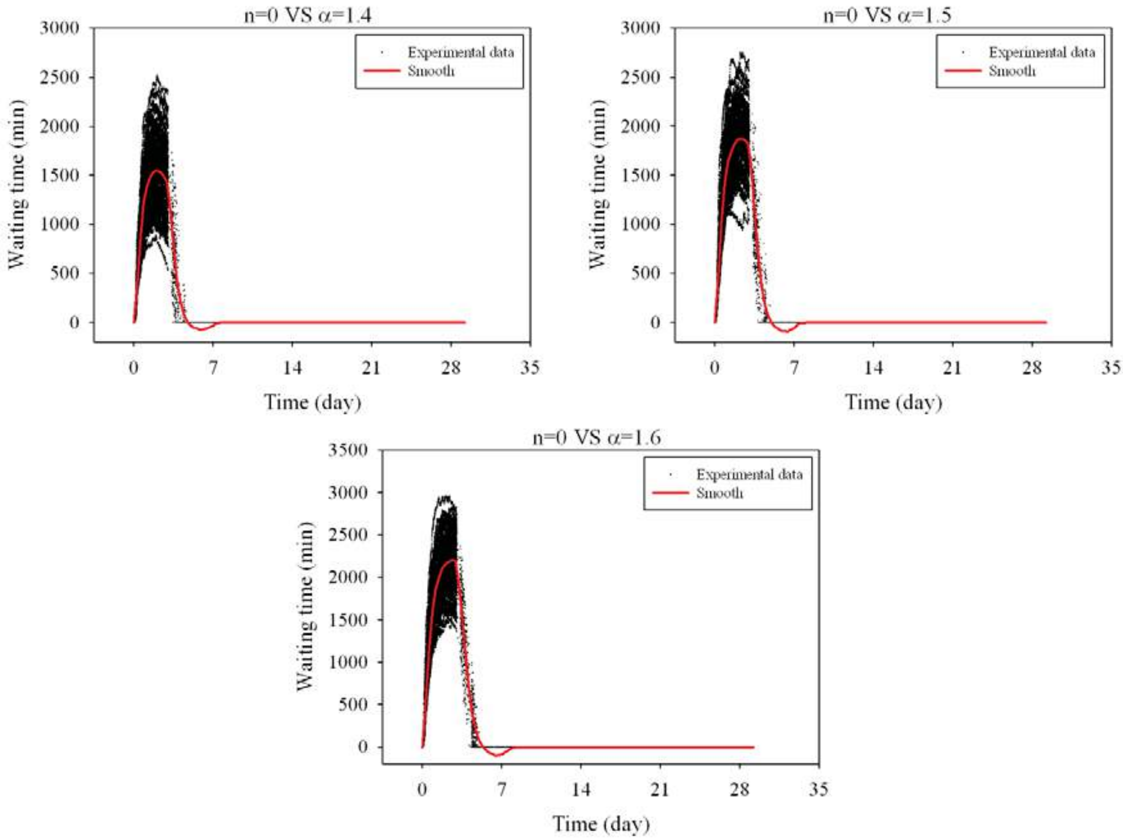
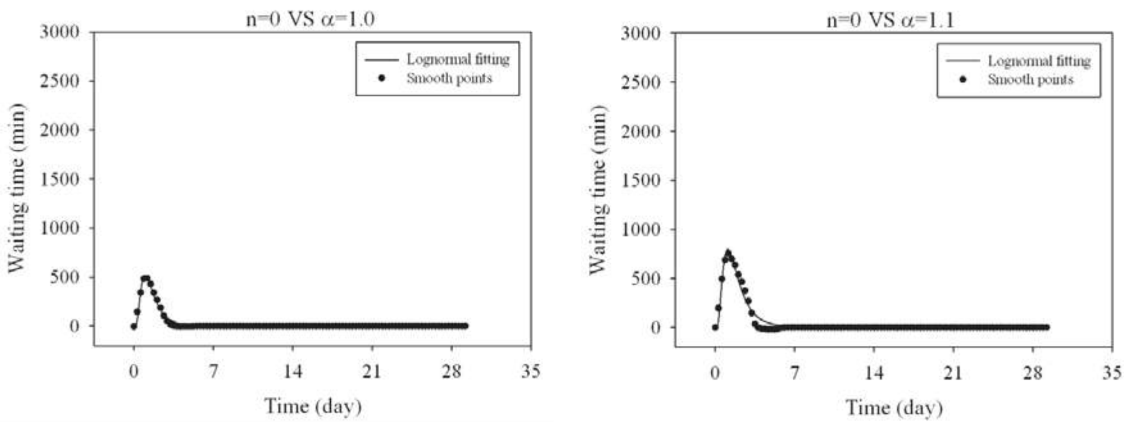


Figure 16 Results from simulations of the organizational model in emergency conditions without room closures (n=0), and increasing arrival rate (from 1.0 to 1.6). Simulations run with three emergency days and 26 normal days. Data clouds (experimental data into legend) from organizational model and smooth analysis with third polynomial degree negative exponential smoother (red medium dash line).



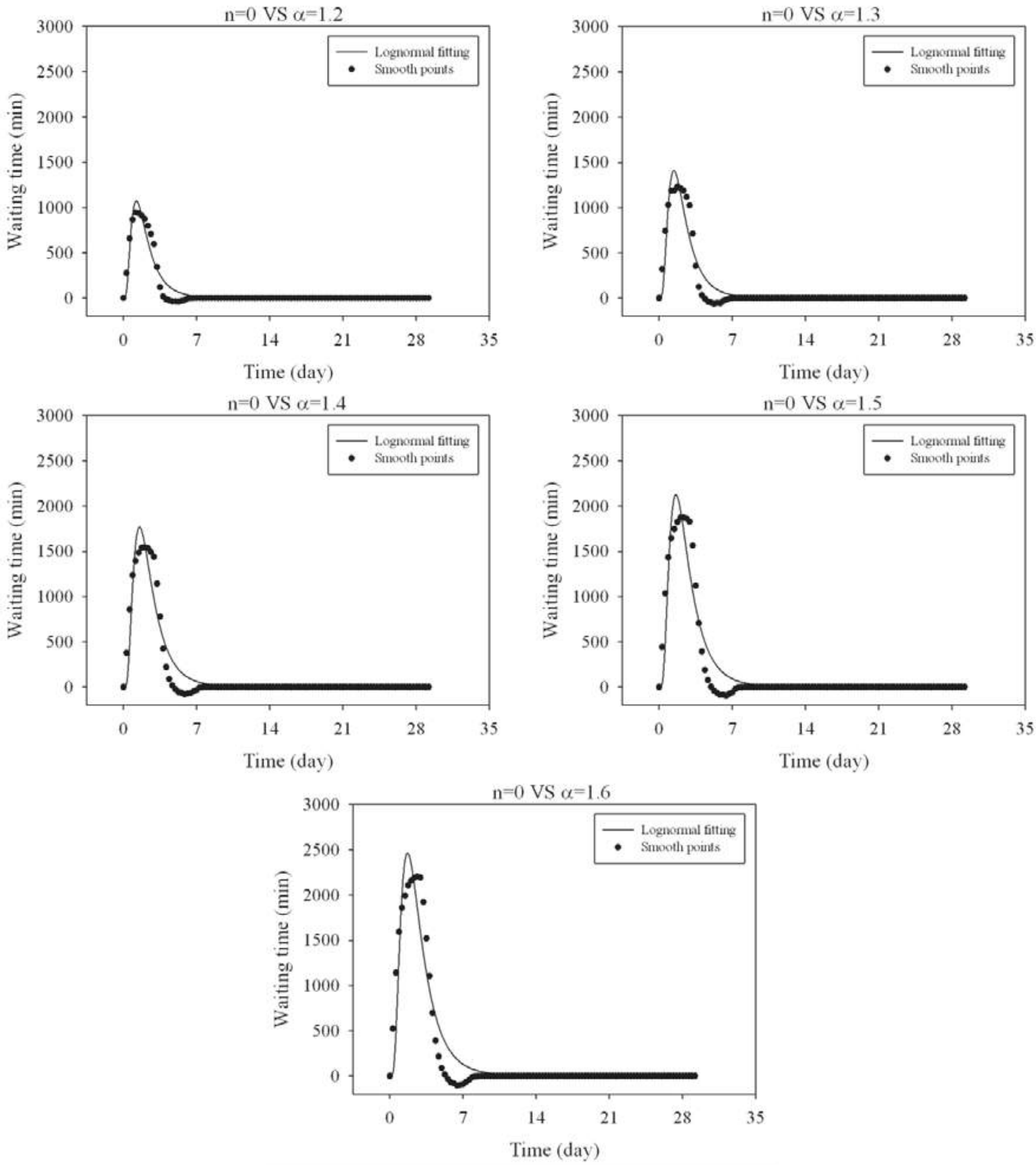
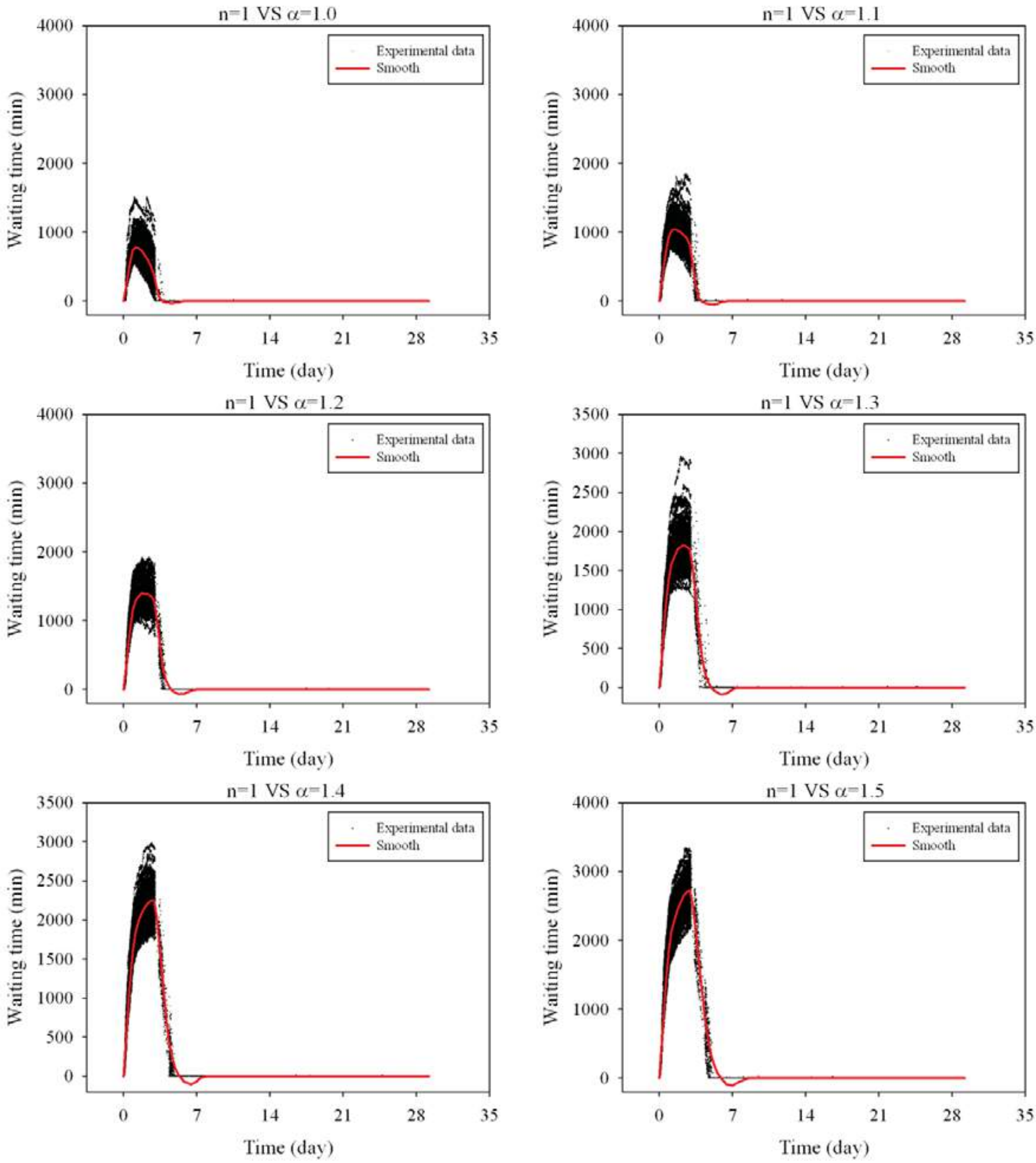


Figure 17 Results from simulations of the organizational model in emergency conditions without room closures (n=0), and increasing arrival rate (from 1.0 to 1.6). Simulations run with three emergency days and 26 normal days. Smooth analysis with third polynomial degree negative exponential smoother (black dotted line), and lognormal fitting with three parameters.


n=1 VS α=1.0
n=1 VS α=1.1
n=1 VS α=1.2
n=1 VS α=1.3
n=1 VS α=1.4
n=1 VS α=1.5
Experimental data
Smooth
Waiting time (min)
Time (day)
0
7
14
21
28
35
0
500
1000
1500
2000
2500
3000
3500
4000

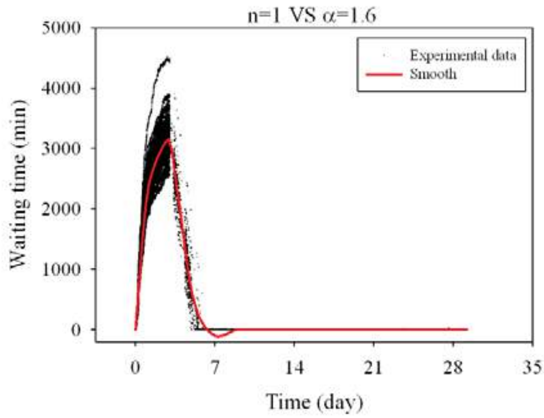
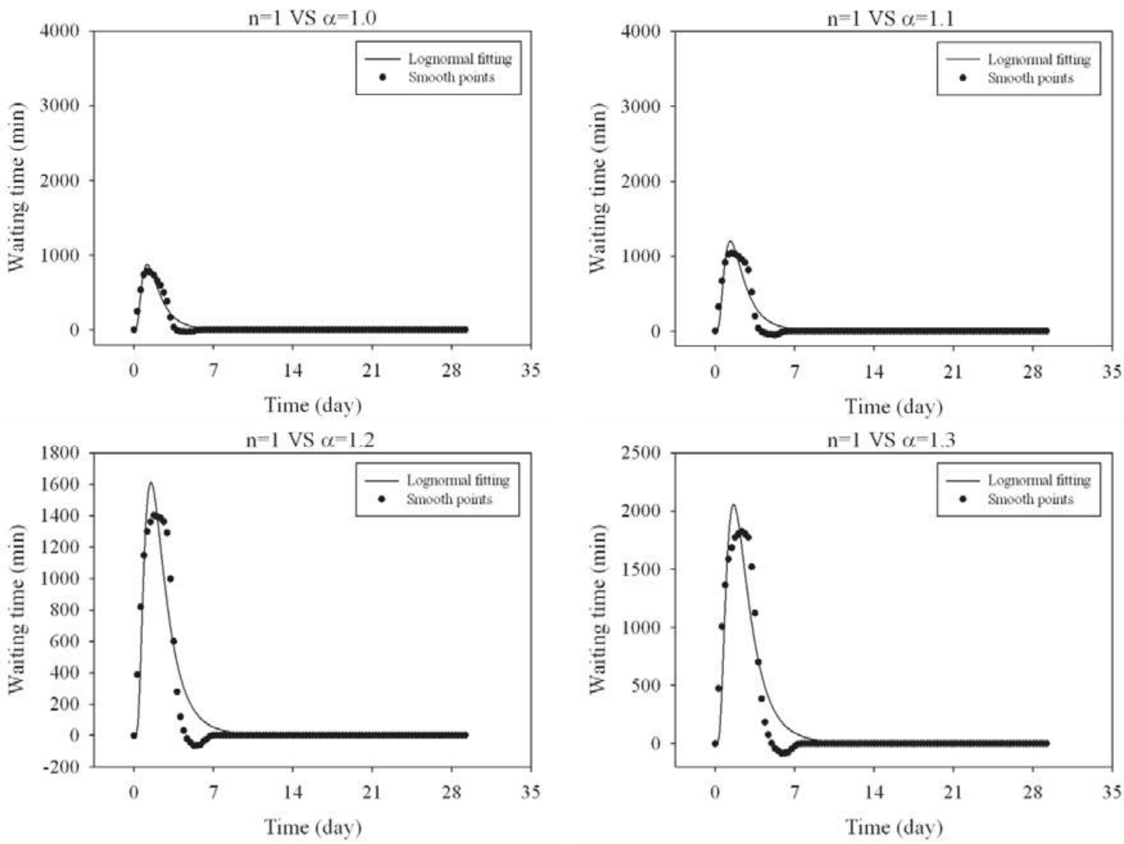


Figure 18 Results from simulations of the organizational model in emergency conditions with the closure of one room (n=1), and increasing arrival rate (from 1.0 to 1.6). Simulations run with three emergency days and 26 normal days. Data clouds (experimental data into legend) from organizational model and smooth analysis with third polynomial degree negative exponential smoother (red medium dash line).



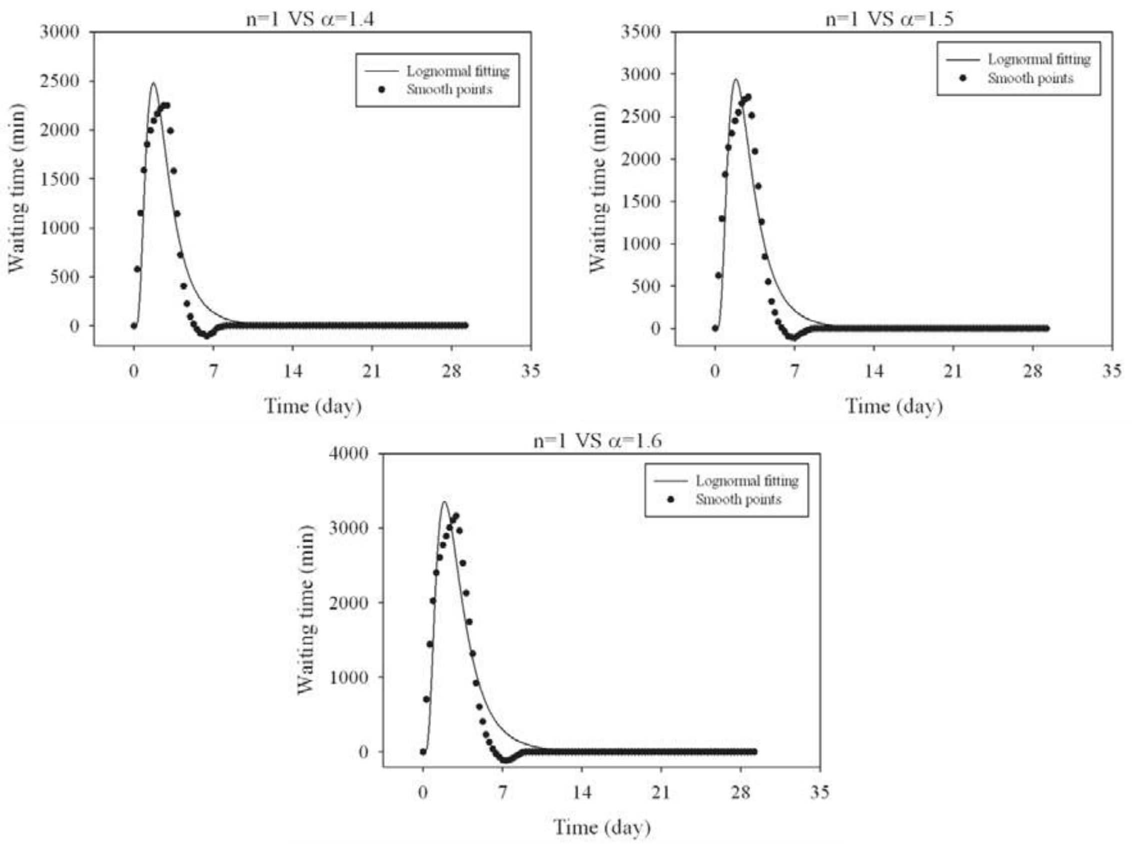
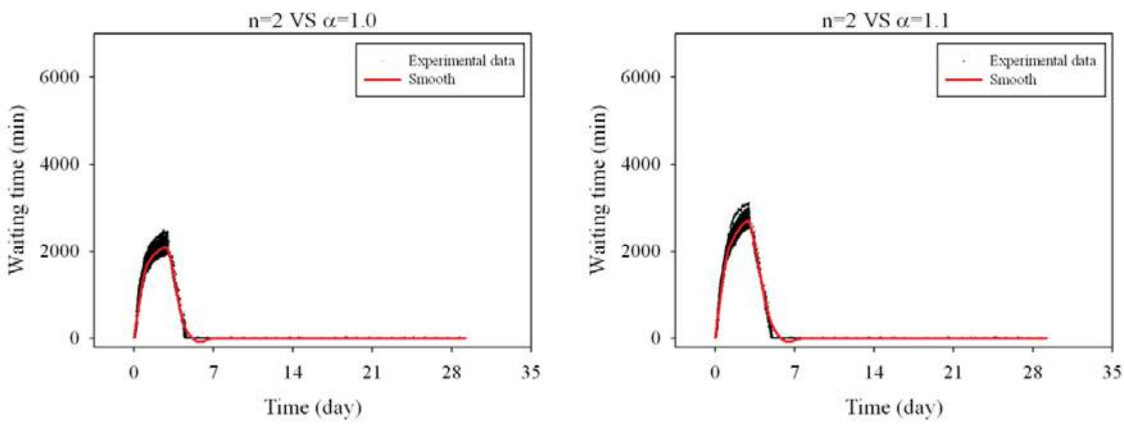


Figure 19 Results from simulations of the organizational model in emergency conditions with the closure of one room (n=1), and increasing arrival rate (from 1.0 to 1.6). Simulations run with three emergency days and 26 normal days. Smooth analysis with third polynomial degree negative exponential smoother (black dotted line), and lognormal fitting with three parameters.



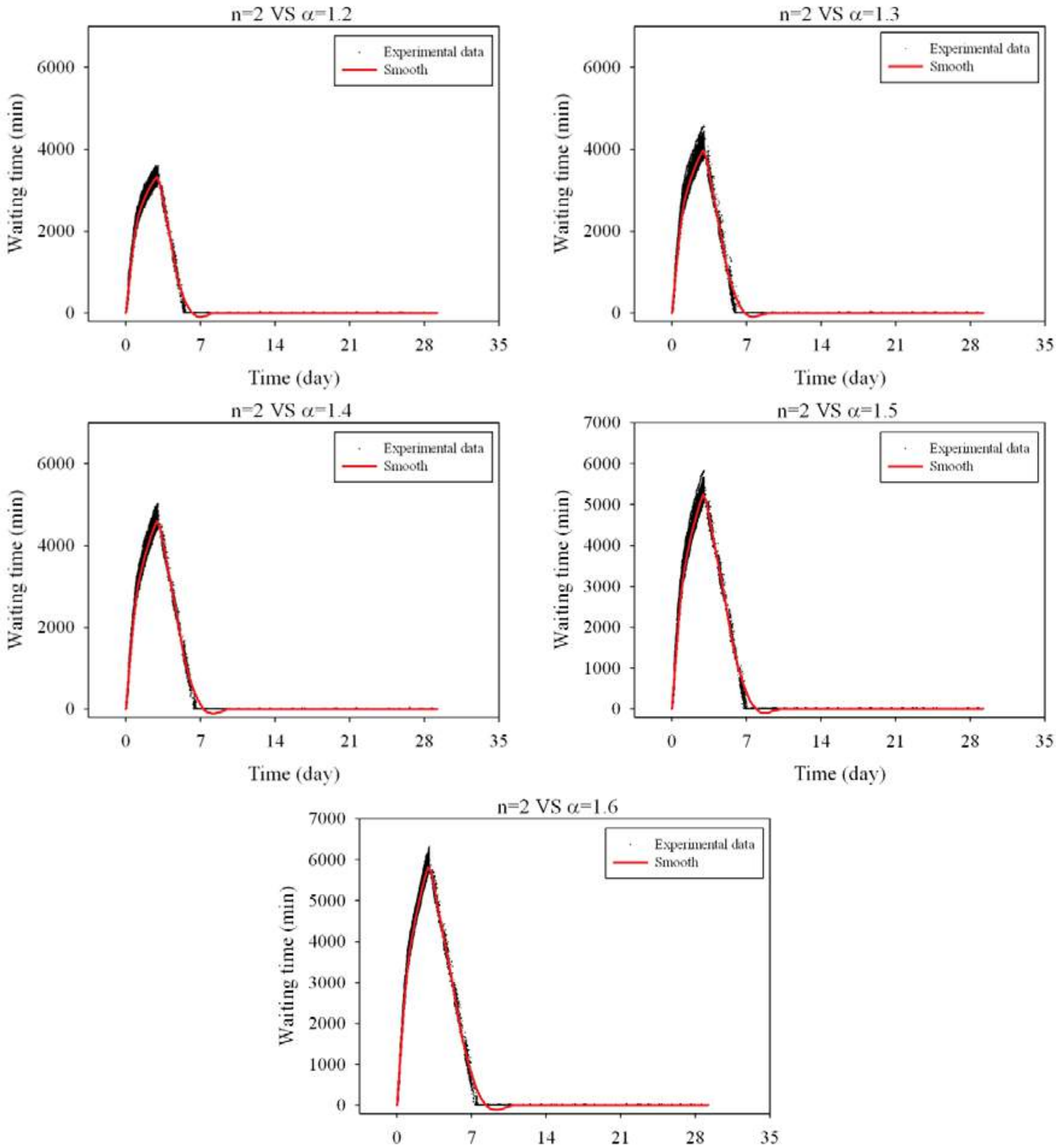
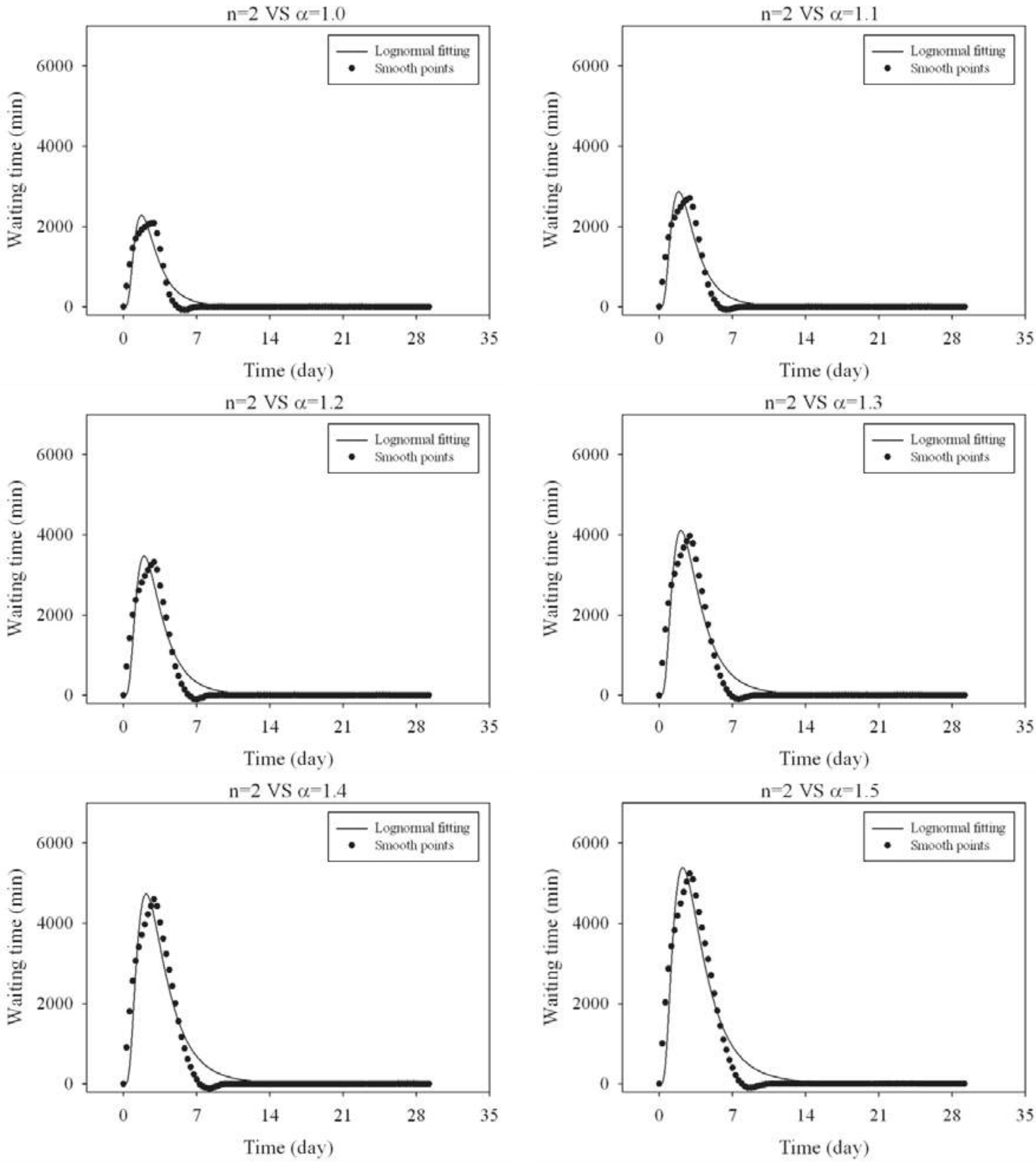


Figure 20 Results from simulations of the organizational model in emergency conditions with the closure of two rooms (n=2), and increasing arrival rate (from 1.0 to 1.6). Simulations run with three emergency days and 26 normal days. Data clouds (experimental data into legend) from organizational model and smooth analysis with third polynomial degree negative exponential smoother (red medium dash line).


n=2 VS α=1.0
n=2 VS α=1.1
n=2 VS α=1.2
n=2 VS α=1.3
n=2 VS α=1.4
n=2 VS α=1.5
Lognormal fitting
Smooth points
Waiting time (min)
Time (day)
0
2000
4000
6000
0
7
14
21
28
35

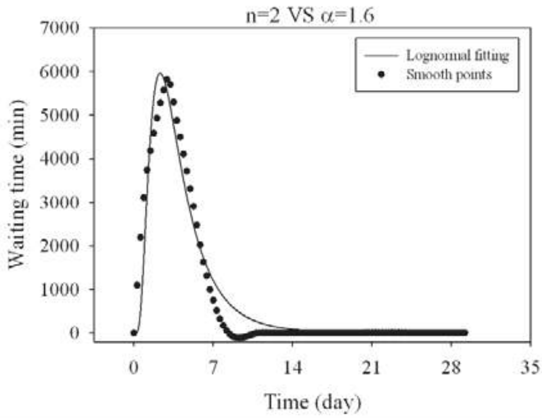
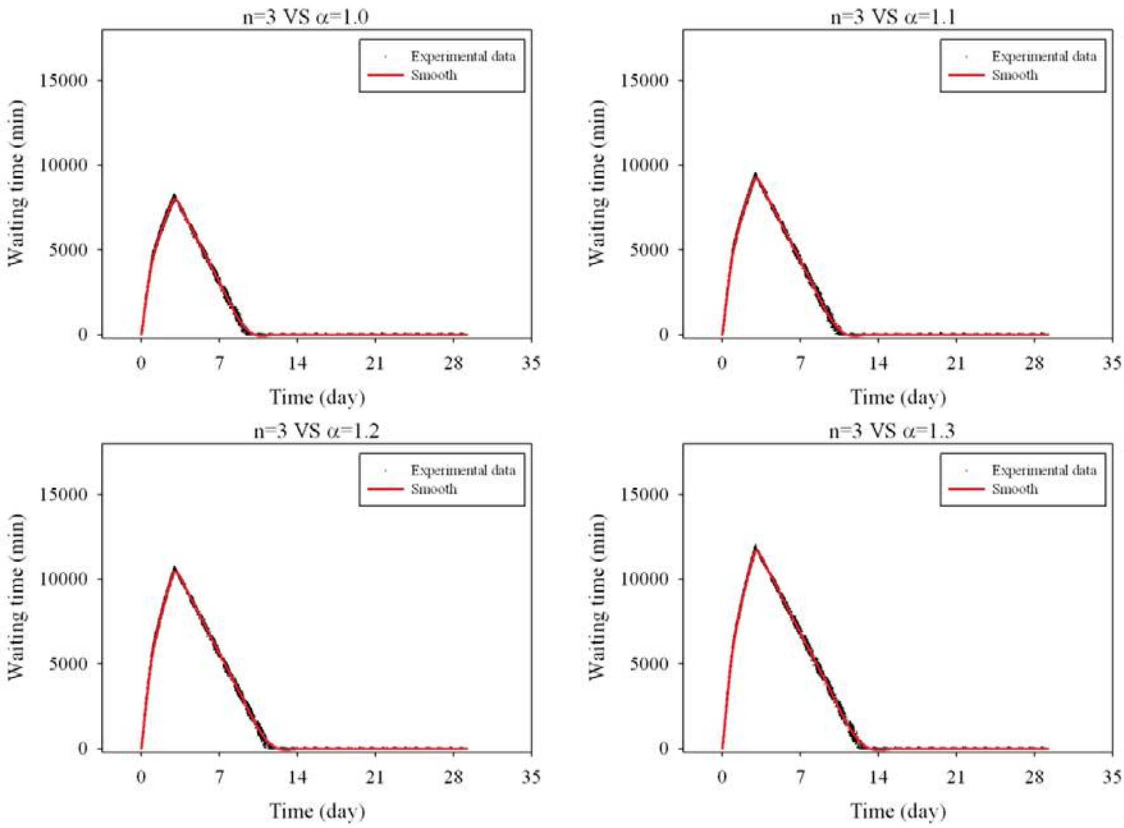


Figure 21 Results from simulations of the organizational model in emergency conditions with the closure of two rooms (n=2), and increasing arrival rate (from 1.0 to 1.6). Simulations run with three emergency days and 26 normal days. Smooth analysis with third polynomial degree negative exponential smoother (black dotted line), and lognormal fitting with three parameters



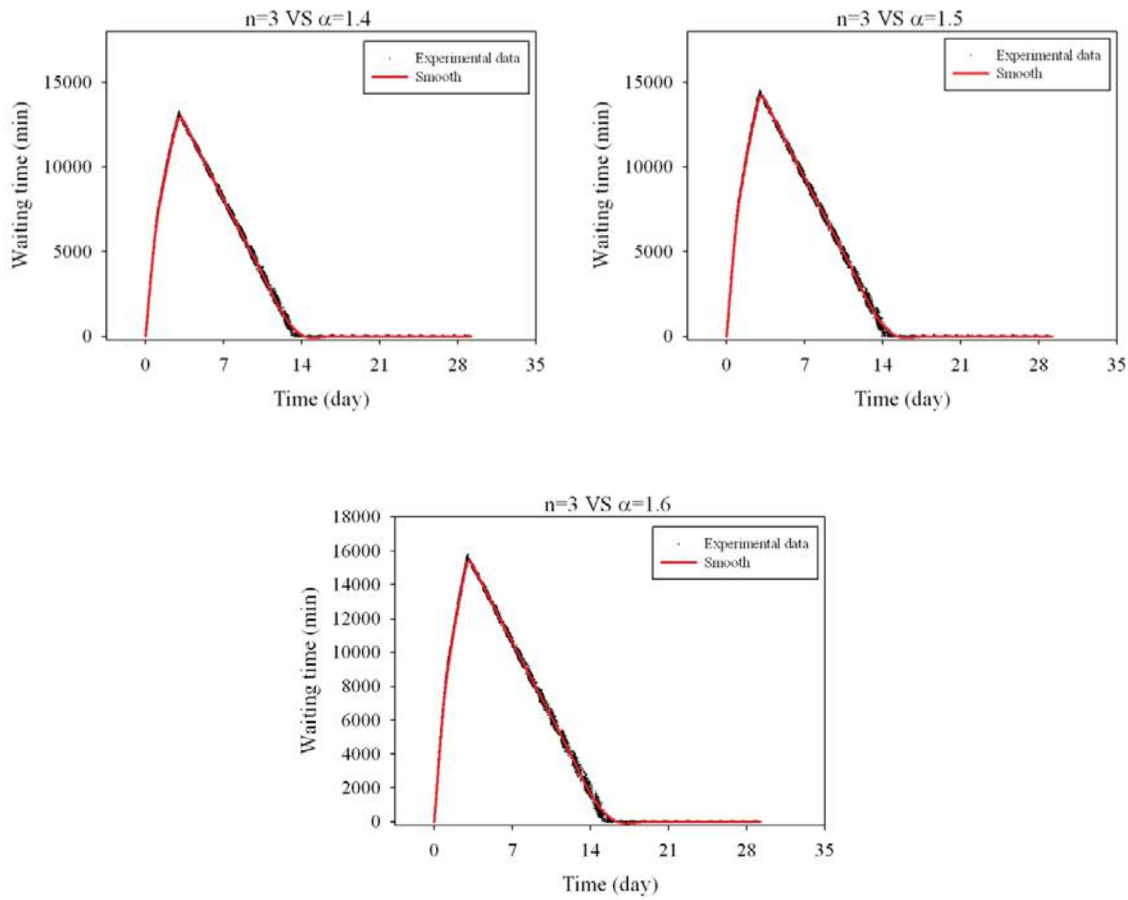
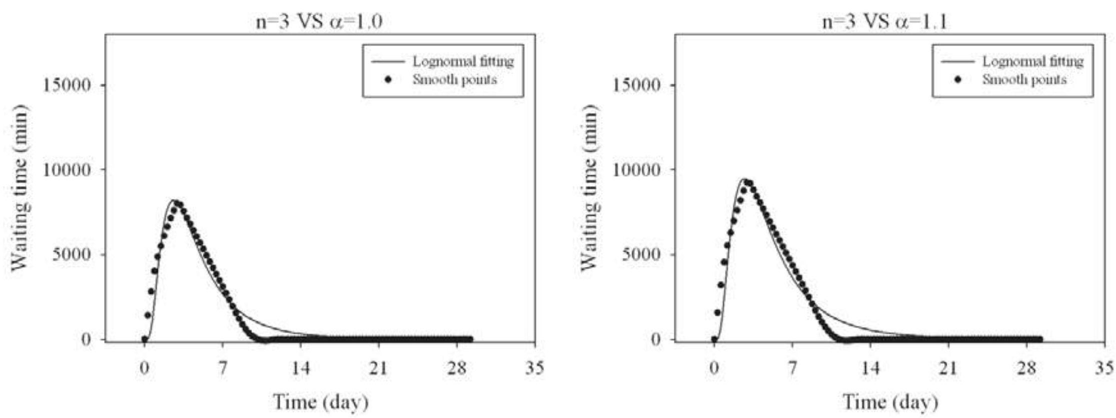


Figure 22 Results from simulations of the organizational model in emergency conditions with the closure of three rooms (n=3), and increasing arrival rate (from 1.0 to 1.6). Simulations run with three emergency days and 26 normal days. Data clouds (experimental data into legend) from organizational model and smooth analysis with third polynomial degree negative exponential smoother (red medium dash line).



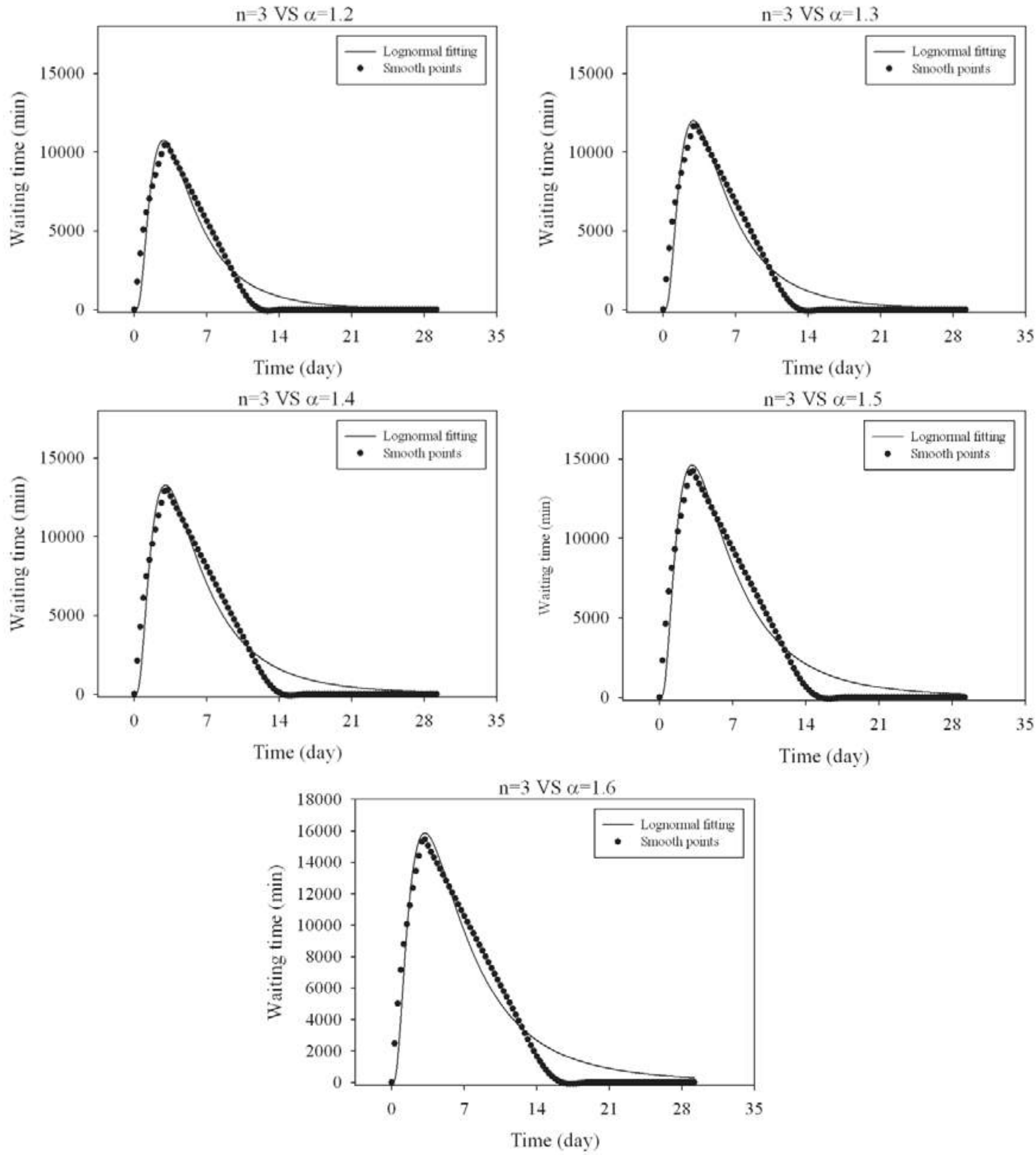


Figure 23 Results from simulations of the organizational model in emergency conditions with the closure of three rooms (n=3), and increasing arrival rate (from 1.0 to 1.6). Simulations run with three emergency days and 26 normal days. Smooth analysis with third polynomial degree negative exponential smoother (black dotted line), and lognormal fitting with three parameters

Table 13 Coefficient deriving from the dynamic fit-nonlinear regression analysis of the models with n=0.

Model (name)	Parameters		
	a	b	c
Model_n0_ α=1.0	858222.3	0.5791	1949.654
Model_n0_ α=1.1	1525402	0.6076	2292.202
Model_n0_ α=1.2	2283117	0.619	2567.834
Model_n0_ α=1.3	3387885	0.5903	2855.197
Model_n0_ α=1.4	4610620	0.5877	3096.354
Model_n0_ α=1.5	5801531	0.5879	3238.725
Model_n0_ α=1.6	7075789	0.5867	3405.085

Table 14 Coefficient deriving from the dynamic fit-nonlinear regression analysis of the models with n=1

Model (name)	Parameters		
	a	b	c
Model_n1_ α=1.0	1749397	0.6134	2409.71
Model_n1_ α=1.1	2731793	0.6045	2731.369
Model_n1_ α=1.2	4081929	0.5921	3012.408
Model_n1_ α=1.3	5642244	0.5877	3257.462
Model_n1_ α=1.4	7199898	0.5858	3442.867
Model_n1_ α=1.5	9083488	0.5884	3666.479
Model_n1_ α=1.6	10811933	0.5964	3841.212

Table 15 Coefficient deriving from the dynamic fit-nonlinear regression analysis of the models with n=2.

Model (name)	Parameters		
	a	b	c
Model_n2_ α=1.0	6594559	0.5814	3423.595
Model_n2_ α=1.1	8997888	0.5815	3711.193
Model_n2_ α=1.2	11566543	0.5823	3947.3
Model_n2_ α=1.3	14440232	0.5931	4193.504
Model_n2_ α=1.4	17446236	0.5973	4409.664
Model_n2_ α=1.5	20711623	0.6106	4637.206
Model_n2_ α=1.6	23895294	0.6188	4846.966

Table 16 Coefficient deriving from the dynamic fit-nonlinear regression analysis of the models with n=3.

Model (name)	Parameters		
	a	b	c
Model_n3_ α=1.0	37778471	0.6637	5744.024
Model_n3_ α=1.1	46356620	0.6859	6188.518
Model_n3_ α=1.2	55531183	0.7075	6635.338
Model_n3_ α=1.3	65104093	0.7264	7062.341
Model_n3_ α=1.4	75571382	0.7456	7510.056
Model_n3_ α=1.5	86738268	0.7647	7965.149
Model_n3_ α=1.6	98521919	0.7827	8437.179

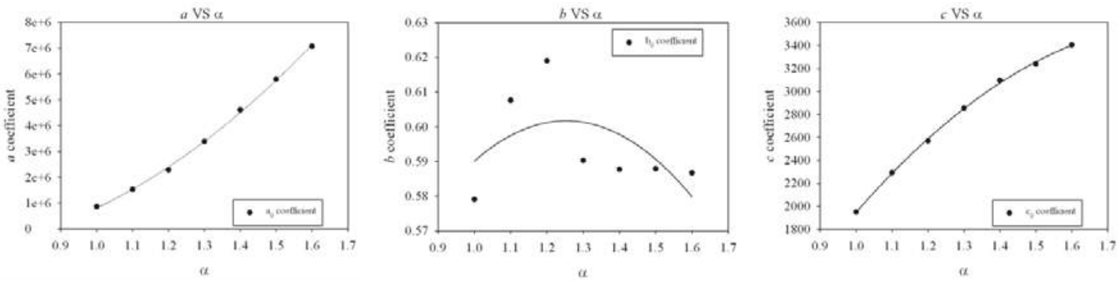


Figure 24 a, b, c parameters variation for n=0.

Table 17 a0, a1, a2, b0, b1, b2, c0, c1, and c2 parameters value for n=0.

a parameter	value	b parameter	value	c parameter	value
a_0	617863.3	b_0	0.3171	c_0	-3600.11
a_1	-6282453	b_1	0.4543	c_1	7499.357
a_2	6472985	b_2	-0.1813	c_2	-1951.97

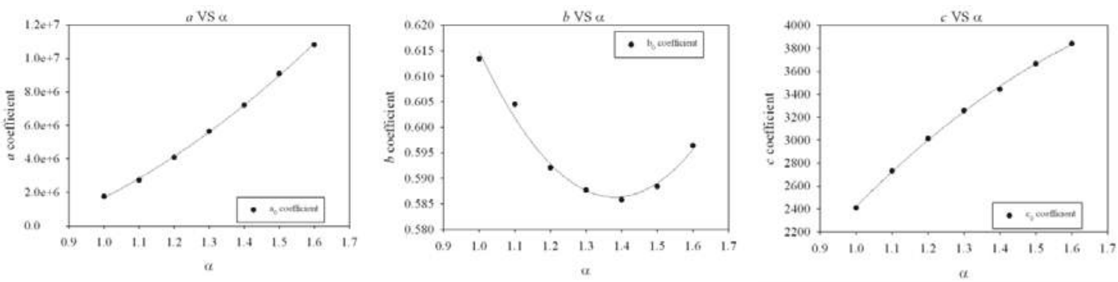


Figure 25 a, b, c parameters variation for n=1.

Table 18 a0, a1, a2, b0, b1, b2, c0, c1, and c2 parameters value for n=1.

a parameter	value	b parameter	value	c parameter	value
a_0	-1512248	b_0	0.9602	c_0	-2108.93
a_1	-4425030	b_1	-0.5411	c_1	5887.297
a_2	7609760	b_2	0.1958	c_2	-1358.41

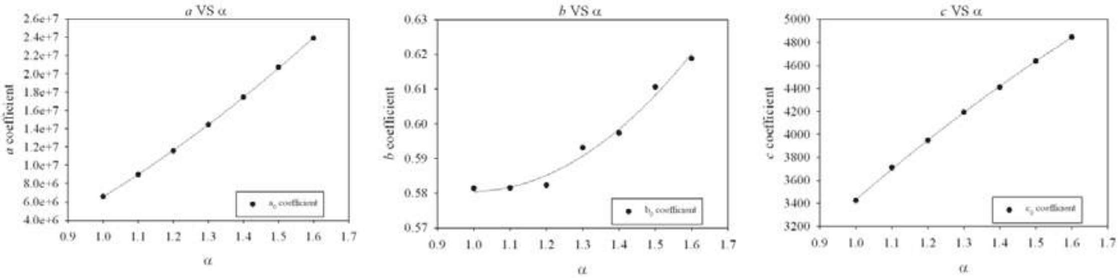


Figure 26 a, b, c parameters variation for n=2.

Table 19 a0, a1, a2, b0, b1, b2, c0, c1, and c2 parameters value for n=2.

a parameter	value	b parameter	value	c parameter	value
a_0	-7870083	b_0	0.6853	c_0	143.341
a_1	5324776	b_1	-0.2117	c_1	3874.782
a_2	9107142	b_2	0.1069	c_2	-585.836

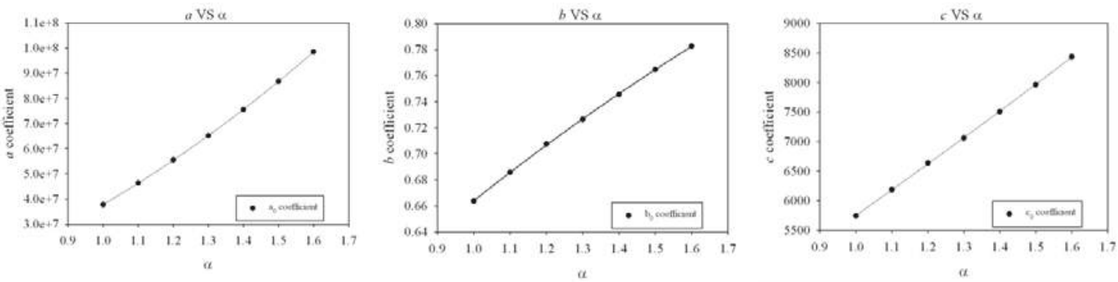


Figure 27 a, b, c parameters variation for n=3.

Table 20 a0, a1, a2, b0, b1, b2, c0, c1, and c2 parameters value for n=3.

a parameter	value	b parameter	value	c parameter	value
a_0	-10330306	b_0	0.404	c_0	1703.556
a_1	15104349	b_1	0.2992	c_1	3784.533
a_2	33068910	b_2	-0.0392	c_2	262.4661

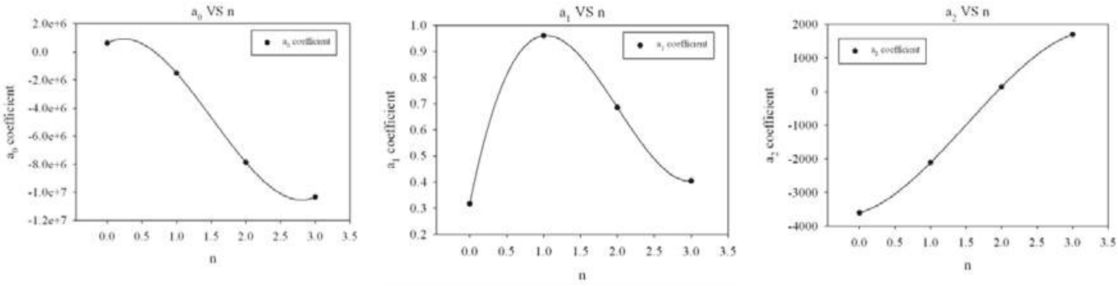


Figure 28 a_0, a_1, a_2 parameters for the variation of n.

Table 21 a_0, a_1, a_2 values of parameters for the variation of n.

a_0 parameter	**value**	**a_1 parameter**	**value**	**a_2 parameter**	**value**
a_{00}	617863.34	**a_{10}**	-6282453.44	**a_{20}**	6472985.08
a_{01}	-1512248.17	**a_{11}**	-4425030.40	**a_{21}**	7609760.13
a_{02}	-7870082.62	**a_{12}**	5324775.88	**a_{22}**	9107142.25
a_{03}	-10330305.75	**a_{13}**	15104349.05	**a_{23}**	33068909.97

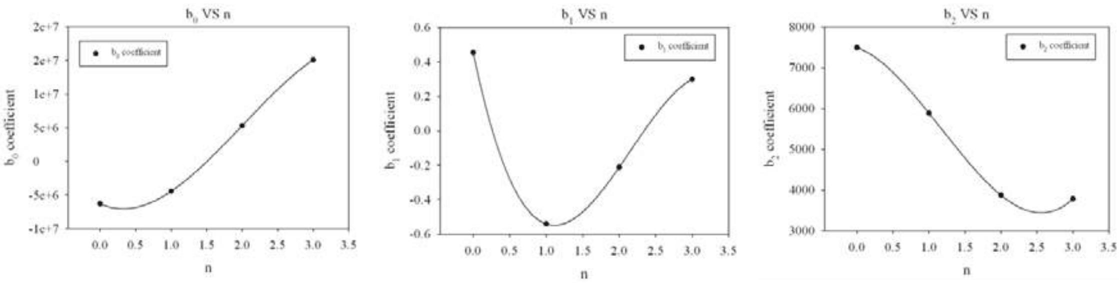


Figure 29 a_0, a_1, a_2 parameters for the variation of n.

Table 22 b_0, b_1, b_2 values of parameters for the variation of n.

b_0 parameter	**value**	**b_1 parameter**	**value**	**b_2 parameter**	**value**
b_{00}	0.32	**b_{10}**	0.45	**b_{20}**	-0.18
b_{01}	0.96	**b_{11}**	-0.54	**b_{21}**	0.20
b_{02}	0.69	**b_{12}**	-0.21	**b_{22}**	0.11
b_{03}	0.40	**b_{13}**	0.30	**b_{23}**	-0.04

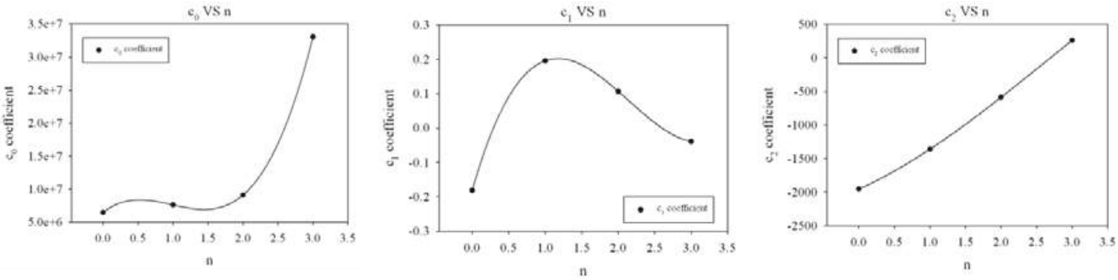


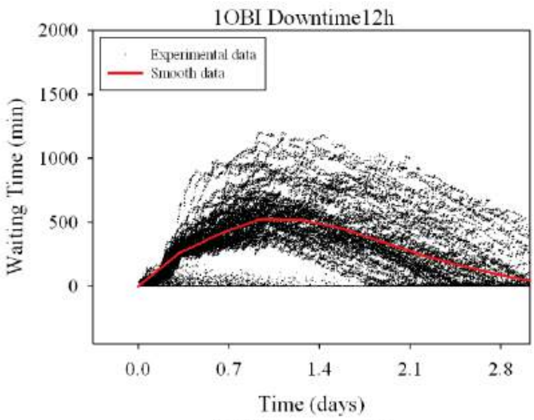
Figure 30 b_0, b_1, b_2 parameters for the variation of n.

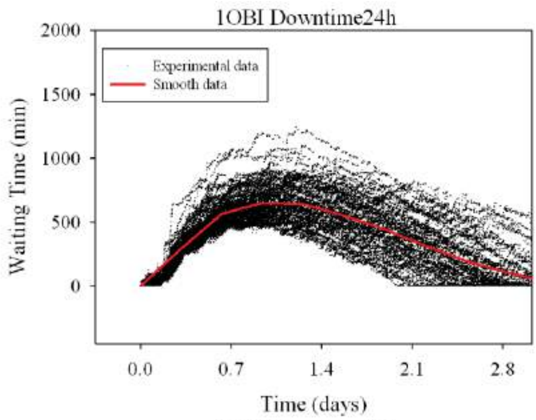
Table 23 c_0, c_1, c_2 values of parameters for the variation of n.

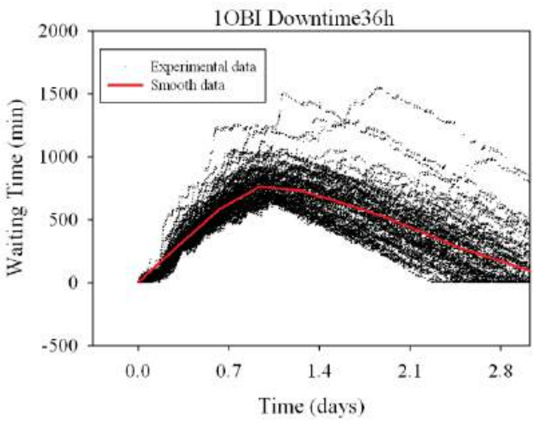
c_0 parameter	**value**	**c_1 parameter**	**value**	**c_2 parameter**	**value**
c_{00}	-3600.11	**c_{10}**	7499.36	**c_{20}**	-1951.97
c_{01}	-2108.93	**c_{11}**	5887.30	**c_{21}**	-1358.41
c_{02}	143.34	**c_{12}**	3874.78	**c_{22}**	-585.84
c_{03}	1703.56	**c_{13}**	3784.53	**c_{23}**	262.47

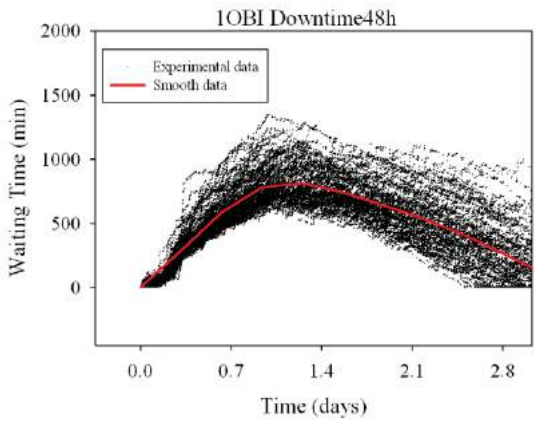
Appendix d): Temporary closures into organizational model simulations (model: case 3)

In this Appendix are presented the results from the case 3- organizational model. The results are grouped according to the steps described into Chapter5: the first group show the data clouds, then are presented the fitted curves. This order is followed for each varied variable. The second part of the appendix shows the coefficient deriving from the dynamic fit-nonlinear regression analysis, grouped according to the varied variable. The last part of the appendix describes the *a, b, c* parameters variation, both graphically and with the sub-parameters values.









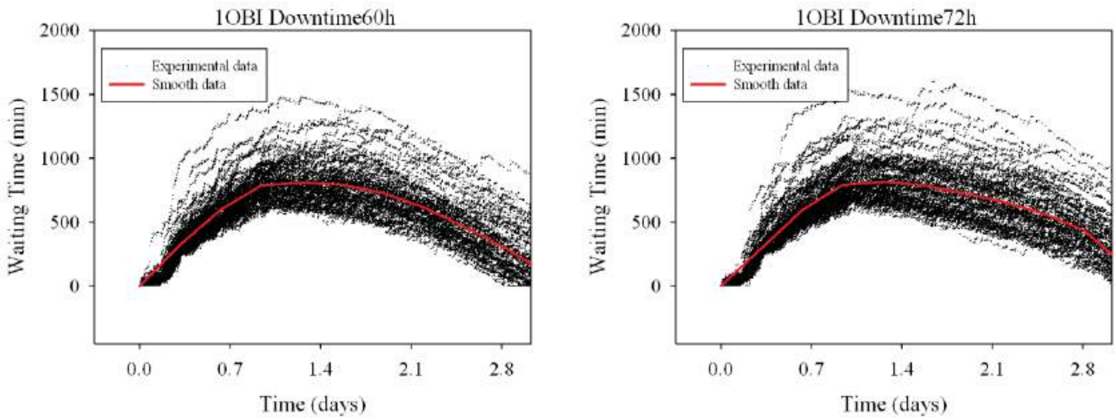
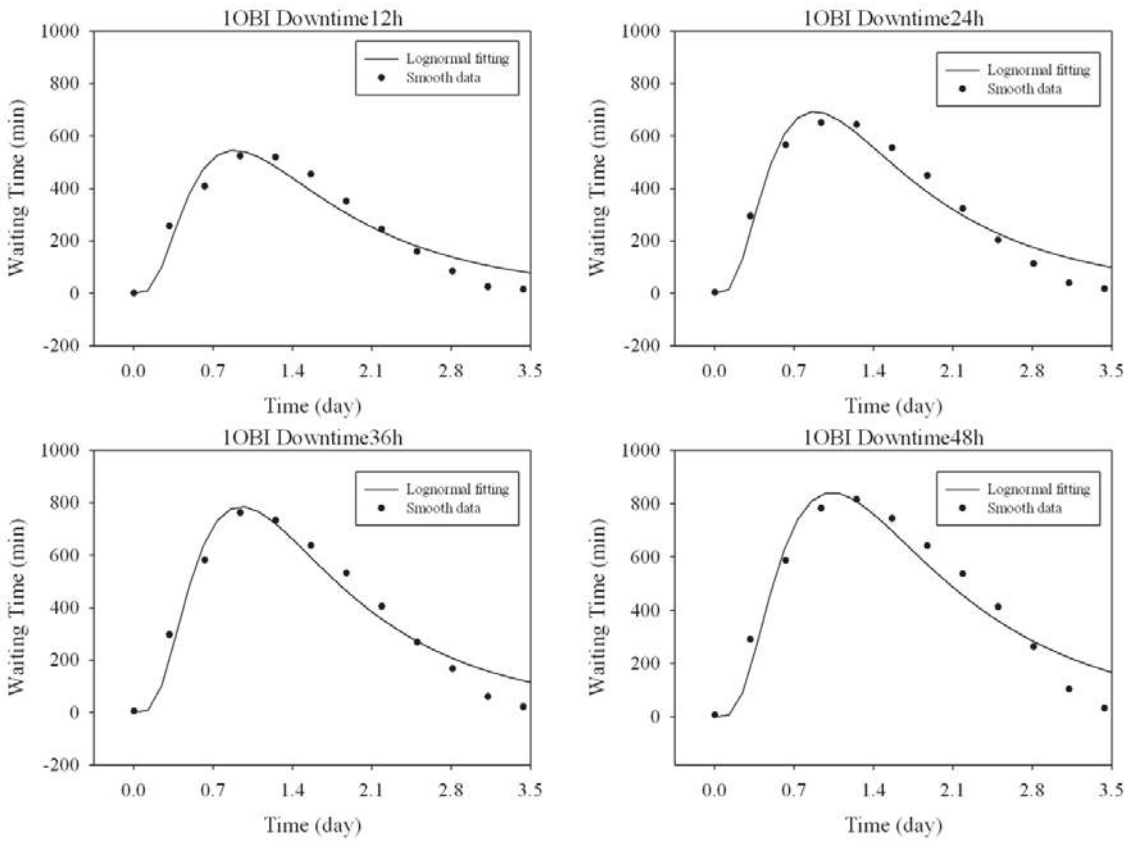


Figure 31 Results from simulations of the organizational model in emergency conditions with one closed room (n=1), and increasing the downtime (from 12 hours to 72 hours). Simulations run with three emergency days and 26 normal days. Data clouds (experimental data into legend) from organizational model and smooth analysis with third polynomial degree negative exponential smoother (red medium dash line).Focus on the emergency days.



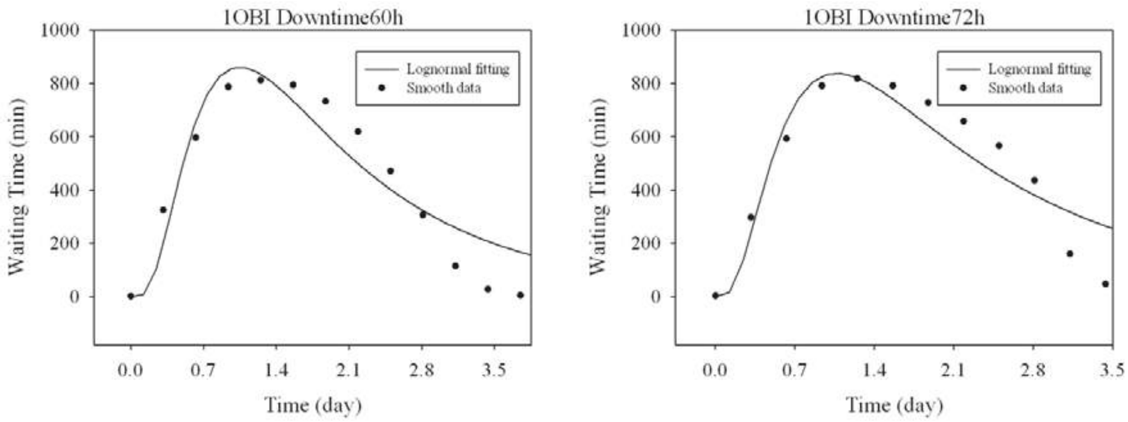
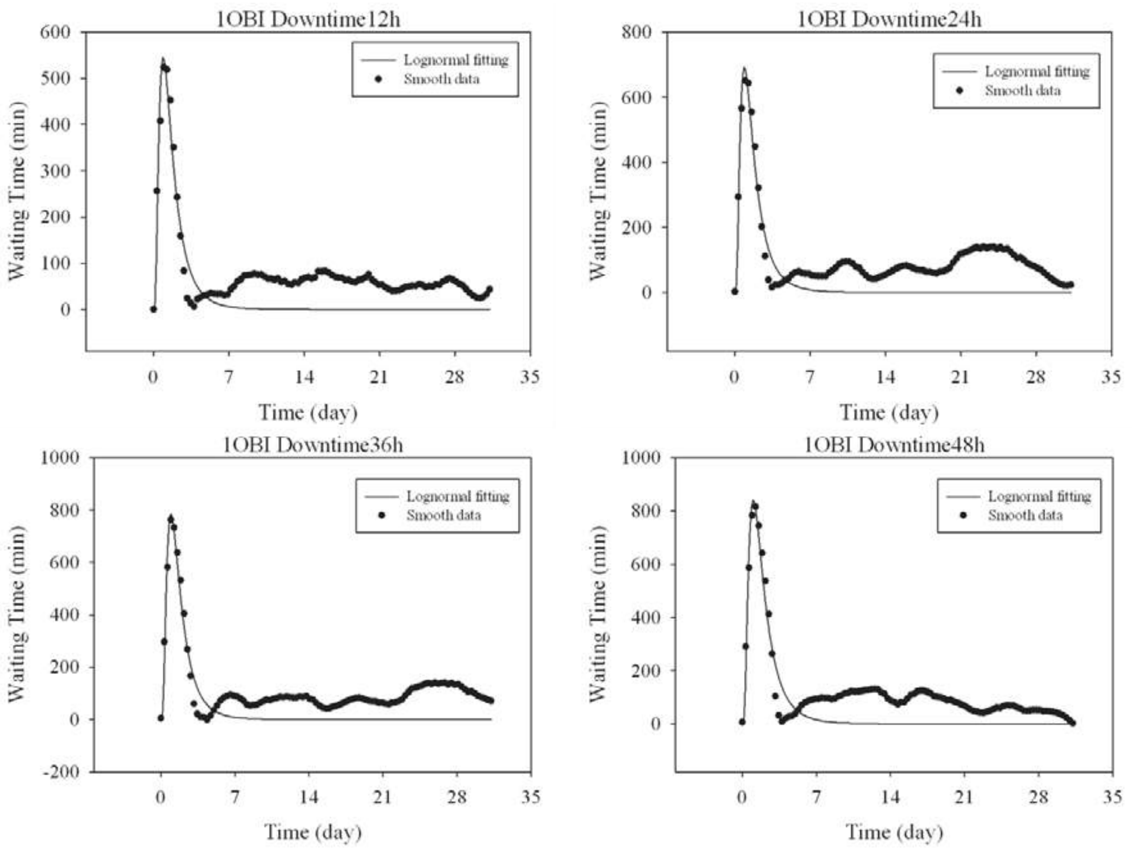


Figure 32 Results from simulations of the organizational model in emergency conditions with one closed room (n=1), and increasing downtime (from 12 hours to 72 hours). Simulations run with three emergency days and 26 normal days. Smooth analysis with third polynomial degree negative exponential smoother (black dotted line), and lognormal fitting with three parameters. Focus on the three emergency days.



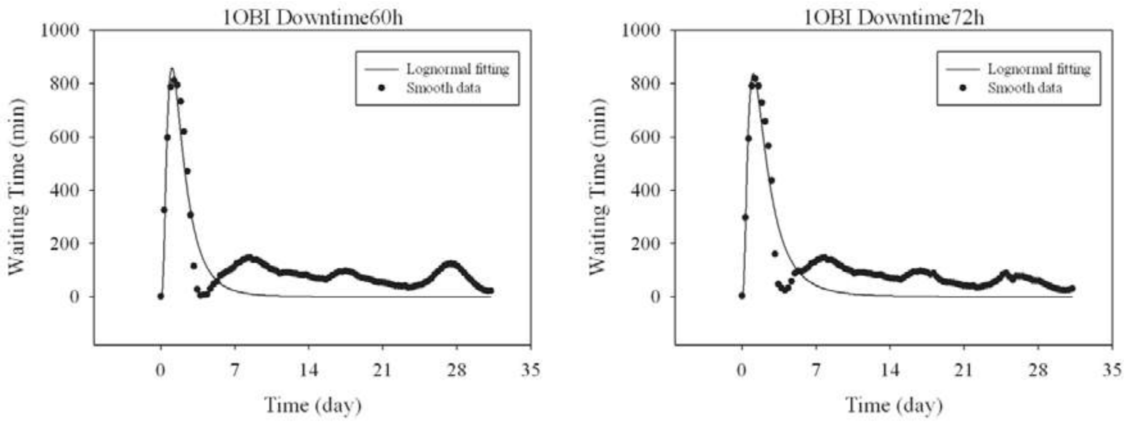
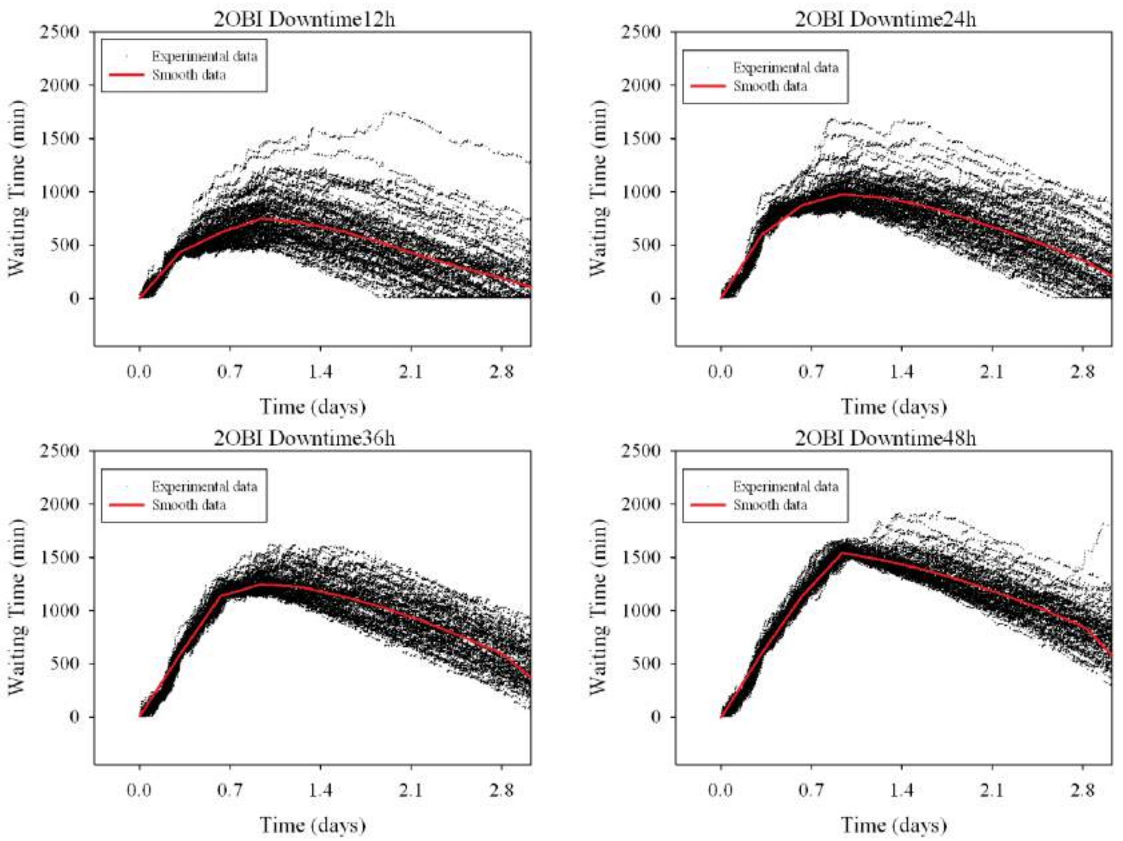


Figure 33 Results from simulations of the organizational model in emergency conditions with one closed room (n=1), and increasing downtime (from 12 hours to 72 hours). Simulations run with three emergency days and 26 normal days. Smooth analysis with third polynomial degree negative exponential smoother (black dotted line), and lognormal fitting with three parameters.



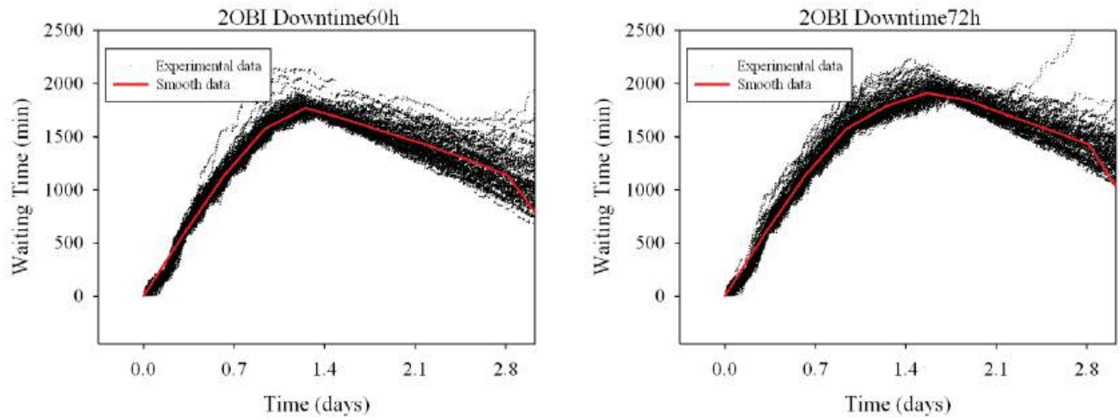
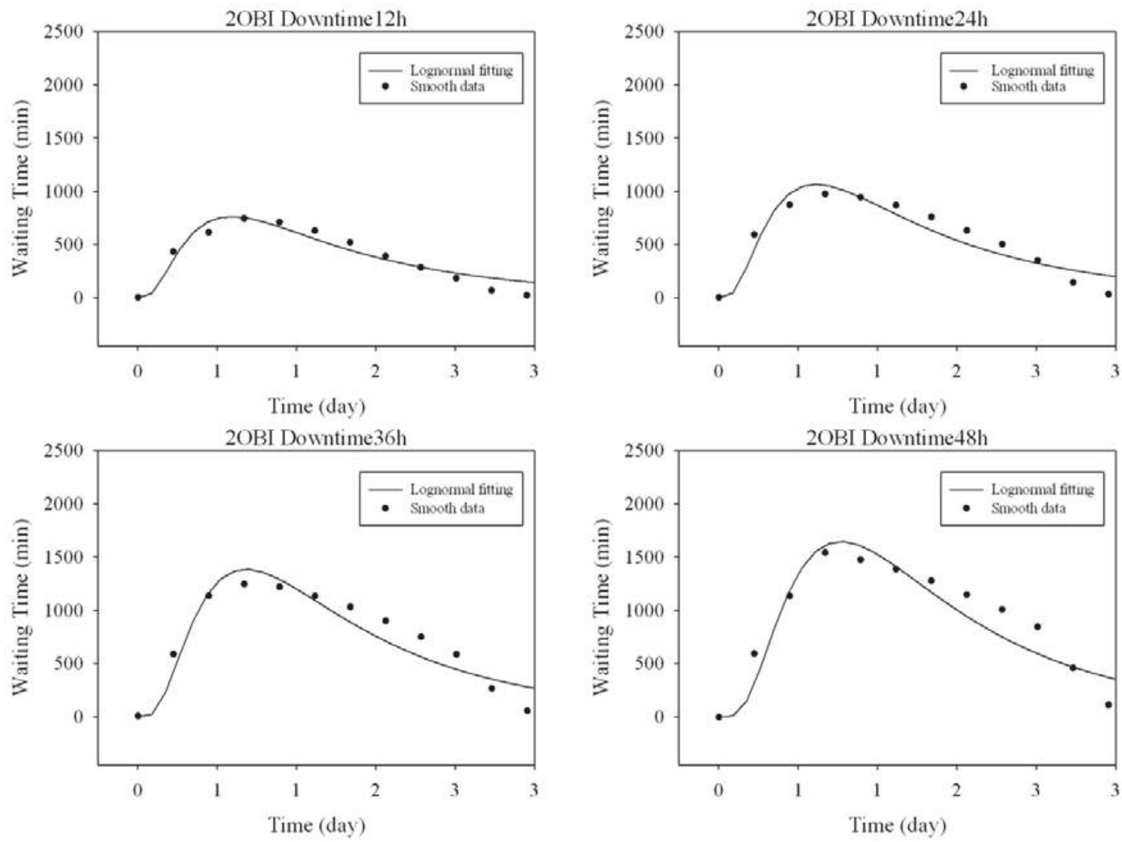


Figure 34 Results from simulations of the organizational model in emergency conditions with two closed rooms (n=2), and increasing the downtime (from 12 hours to 72 hours). Simulations run with three emergency days and 26 normal days. Data clouds (experimental data into legend) from organizational model and smooth analysis with third polynomial degree negative exponential smoother (red medium dash line).Focus on the emergency days.



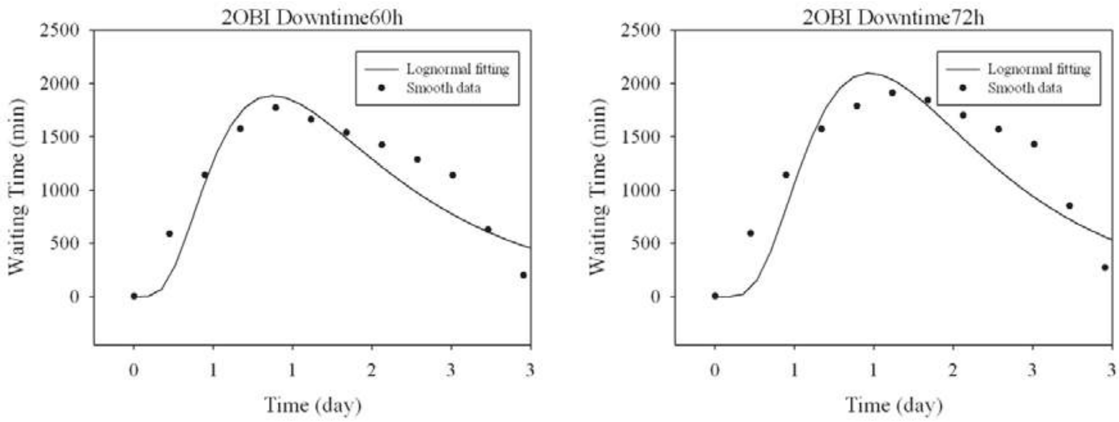
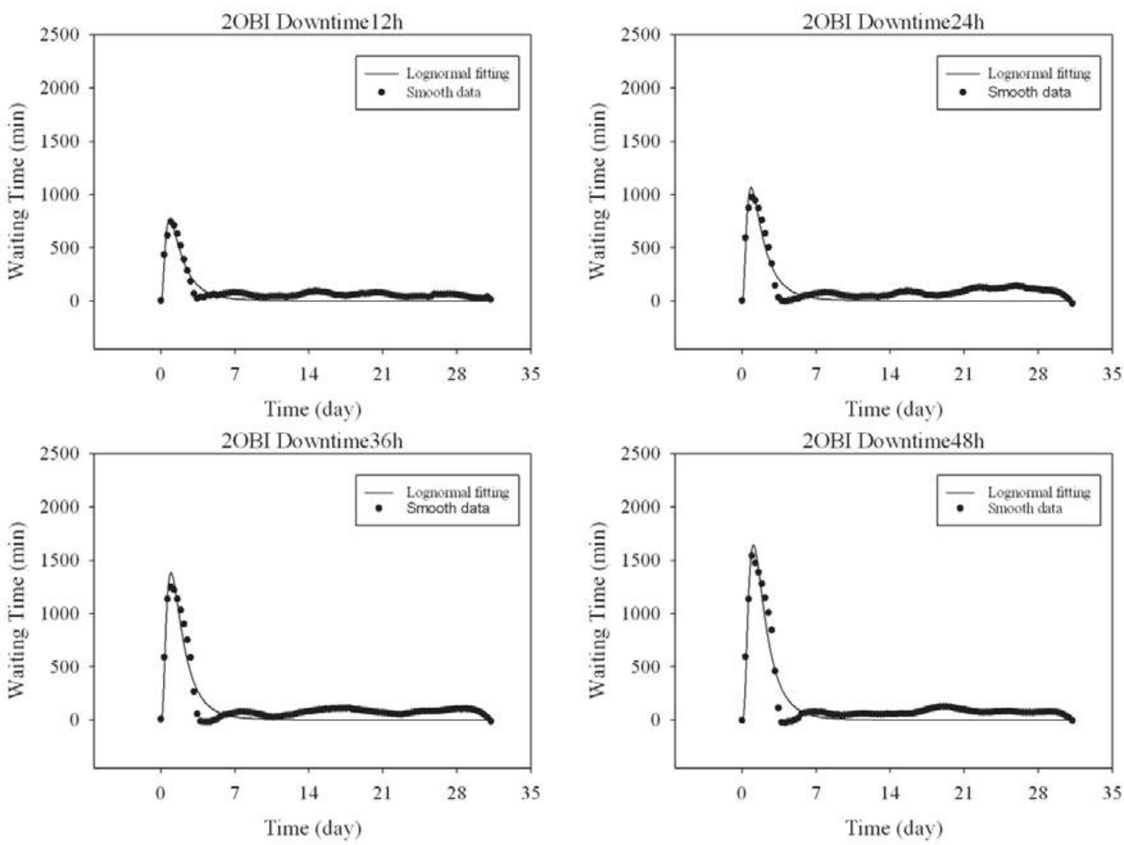


Figure 35 Results from simulations of the organizational model in emergency conditions with two closed rooms (n=2), and increasing downtime (from 12 hours to 72 hours). Simulations run with three emergency days and 26 normal days. Smooth analysis with third polynomial degree negative exponential smoother (black dotted line), and lognormal fitting with three parameters. Focus on the three emergency days.



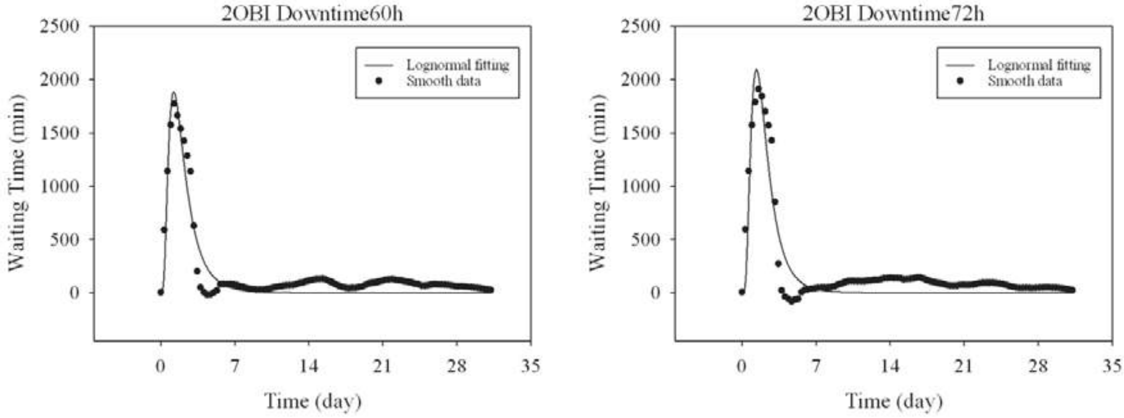
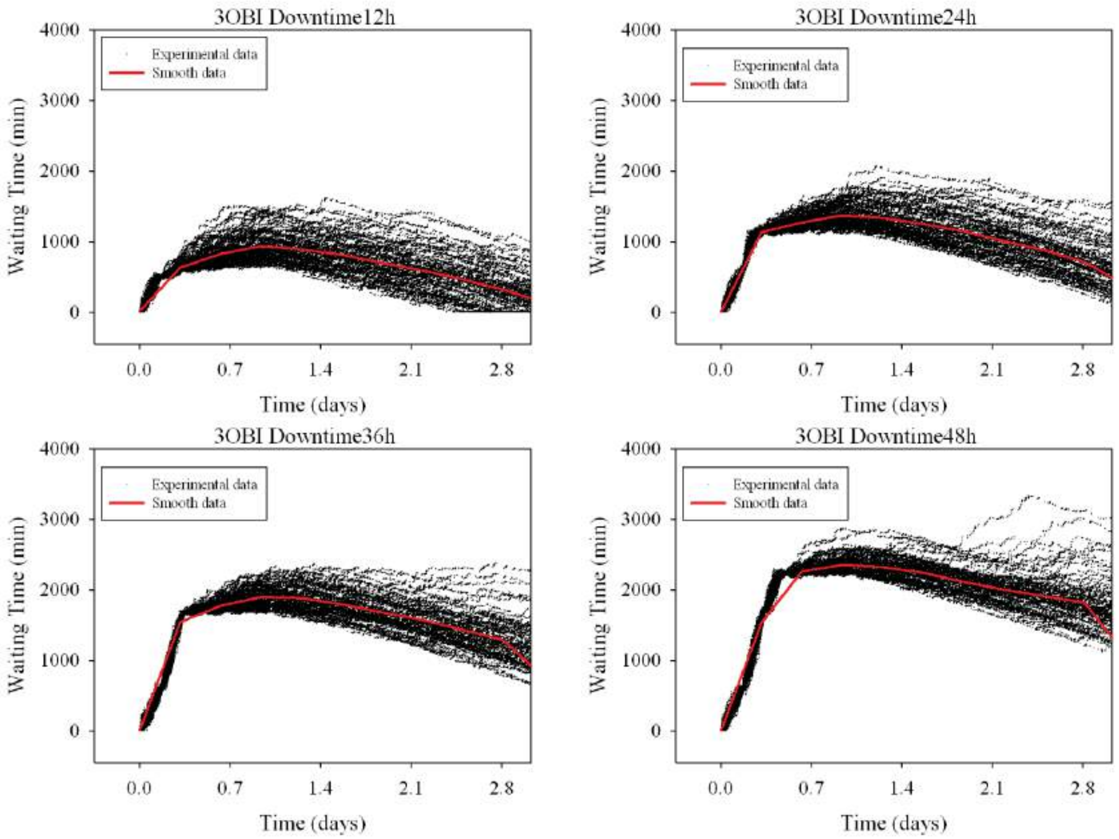


Figure 36 Results from simulations of the organizational model in emergency conditions with two closed rooms (n=2), and increasing downtime (from 12 hours to 72 hours). Simulations run with three emergency days and 26 normal days. Smooth analysis with third polynomial degree negative exponential smoother (black dotted line), and lognormal fitting with three parameters.



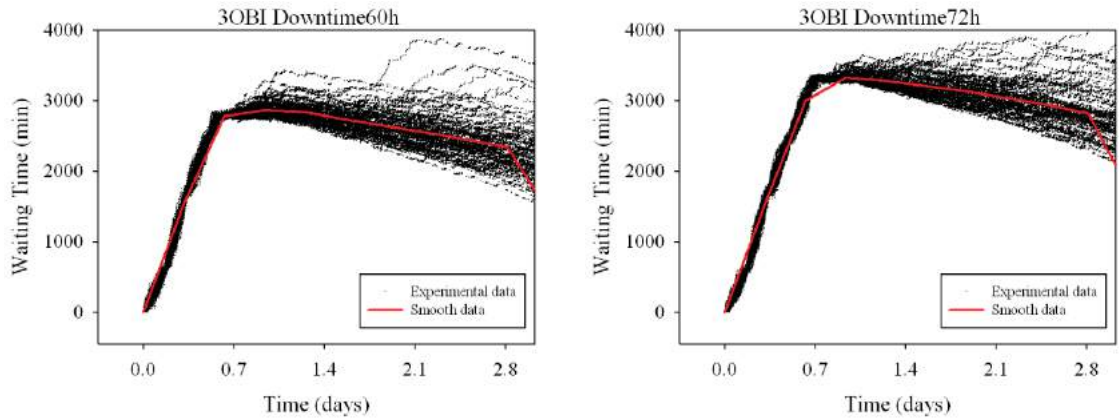
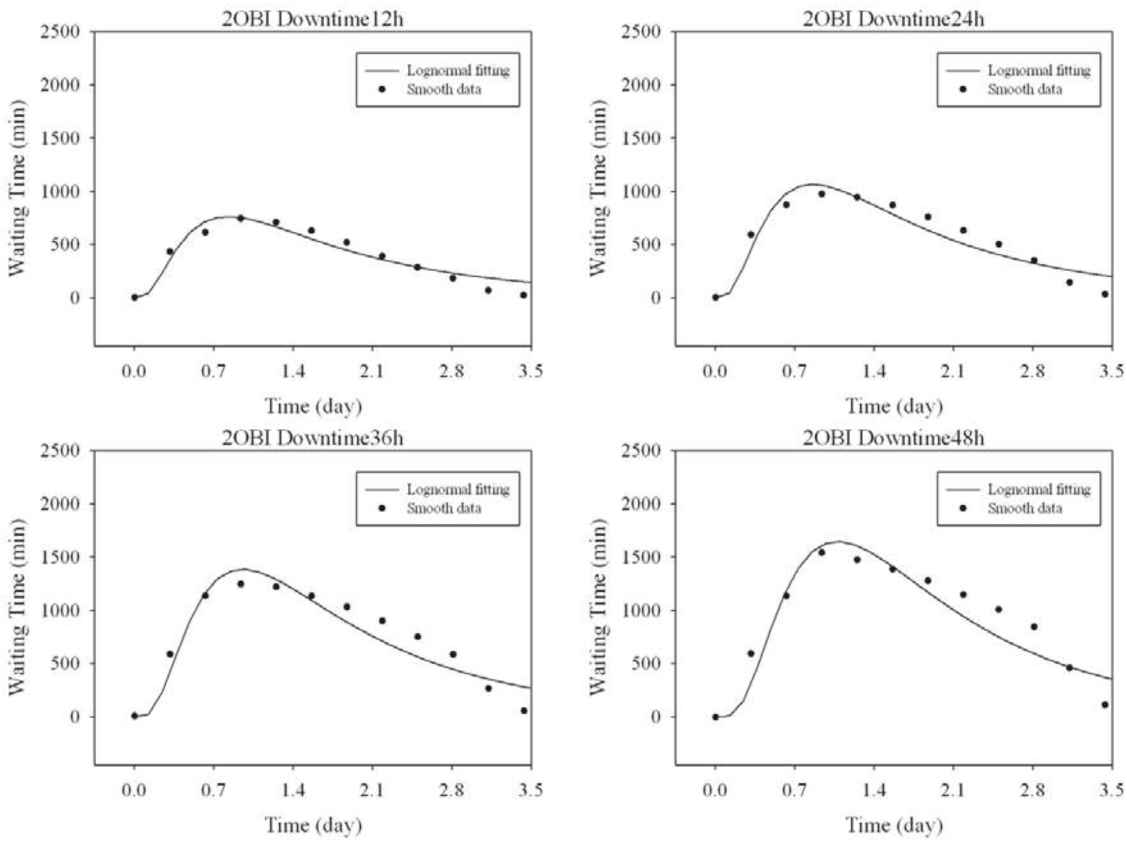


Figure 37 Results from simulations of the organizational model in emergency conditions with three closed rooms (n=3), and increasing the downtime (from 12 hours to 72 hours). Simulations run with three emergency days and 26 normal days. Data clouds (experimental data into legend) from organizational model and smooth analysis with third polynomial degree negative exponential smoother (red medium dash line).Focus on the emergency days.



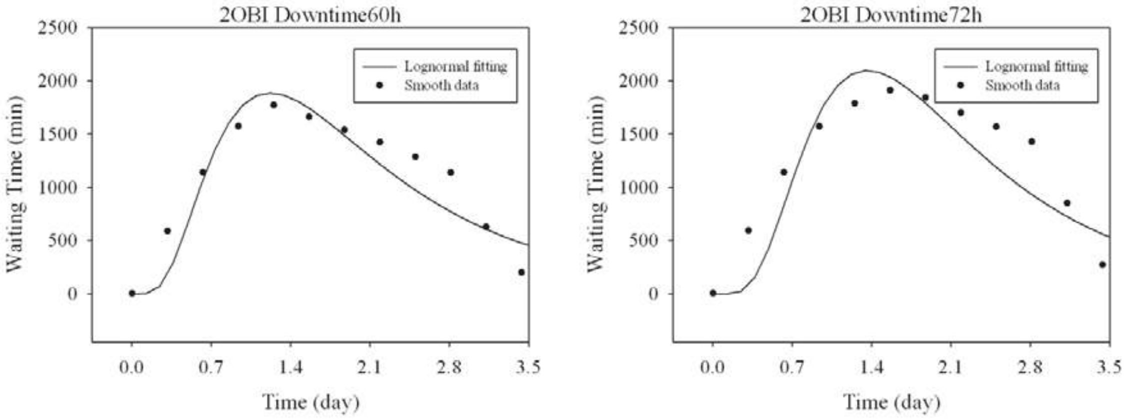
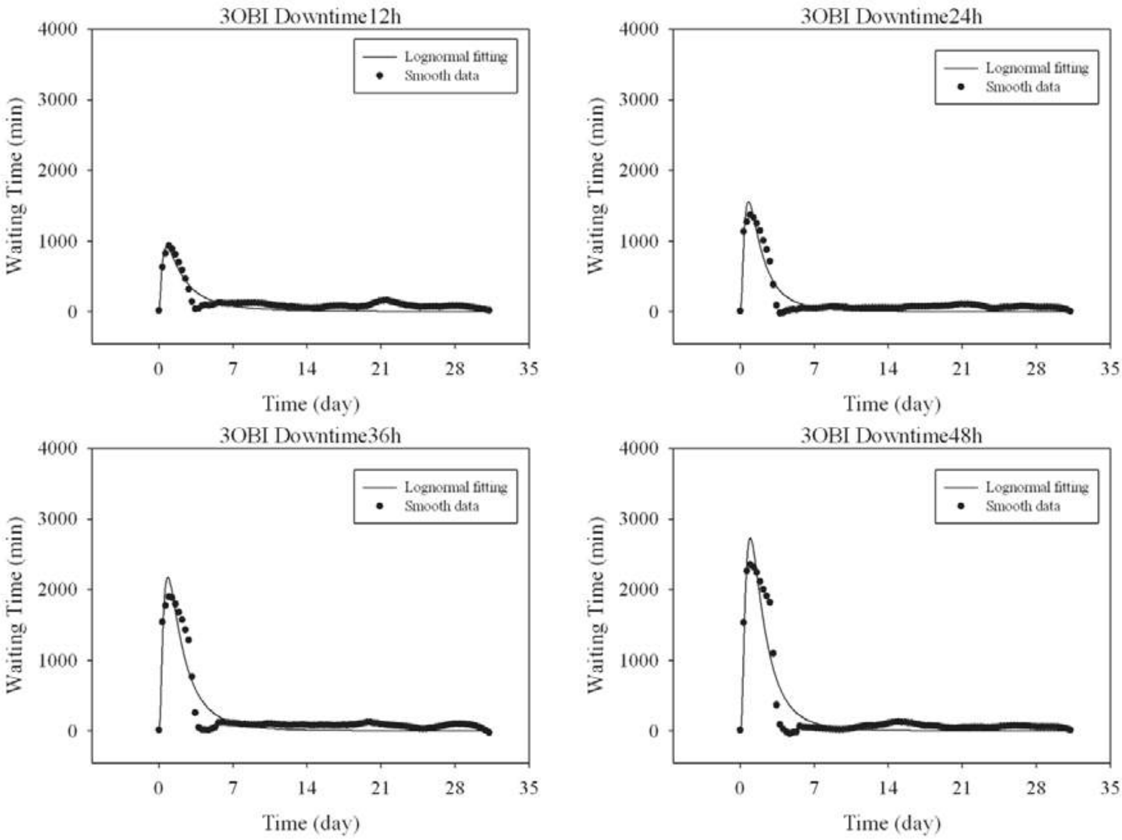


Figure 38 Results from simulations of the organizational model in emergency conditions with three closed rooms (n=3), and increasing downtime (from 12 hours to 72 hours). Simulations run with three emergency days and 26 normal days. Smooth analysis with third polynomial degree negative exponential smoother (black dotted line), and lognormal fitting with three parameters. Focus on the three emergency days.



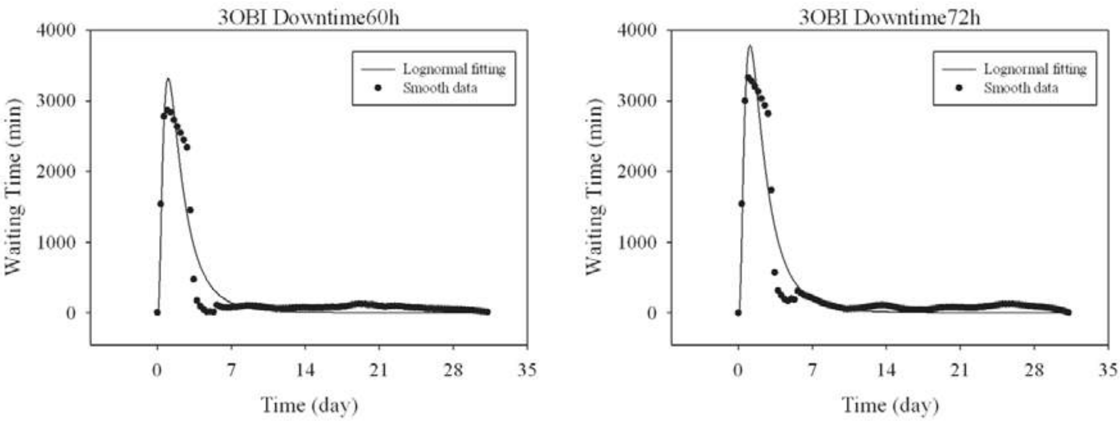


Figure 39 Results from simulations of the organizational model in emergency conditions with three closed rooms (n=3), and increasing downtime (from 12 hours to 72 hours). Simulations run with three emergency days and 26 normal days. Smooth analysis with third polynomial degree negative exponential smoother (black dotted line), and lognormal fitting with three parameters.

Table 24 Coefficient deriving from the dynamic fit-nonlinear regression analysis of the models with n=1.

Model (name)	**Parameters**		
	a	**b**	**c**
Model_OBI1_DT12	877764	0.6954	2049.951
Model_OBI1_DT24	1110638	0.6989	2047.238
Model_OBI1_DT36	1324832	0.6664	2104.993
Model_OBI1_DT48	1560612	0.679	2335.281
Model_OBI1_DT60	1652308	0.7038	2456.303
Model_OBI1_DT72	1719602	0.7704	2759.523

Table 25 Coefficient deriving from the dynamic fit-nonlinear regression analysis of the models with n=2.

Model (name)	**Parameters**		
	a	**b**	**c**
Model_OBI2_DT12	1233159	0.7923	2209.246
Model_OBI2_DT24	1751188	0.7708	2212.085
Model_OBI2_DT36	2440071	0.7186	2279.949
Model_OBI2_DT48	3169909	0.672	2413.966
Model_OBI2_DT60	3990307	0.6254	2572.643
Model_OBI2_DT72	4795560	0.5704	2690.156

Table 26 Coefficient deriving from the dynamic fit-nonlinear regression analysis of the models with n=3.

Model (name)	**Parameters**		
	a	**b**	**c**
Model_OBI3_DT12	1606621	1.0332	2985.176
Model_OBI3_DT24	2530779	0.8647	2354.487
Model_OBI3_DT36	3823951	0.8817	2585.468
Model_OBI3_DT48	5071096	0.7948	2540.925
Model_OBI3_DT60	6503694	0.7709	2631.671
Model_OBI3_DT72	7900675	0.7632	2789.055

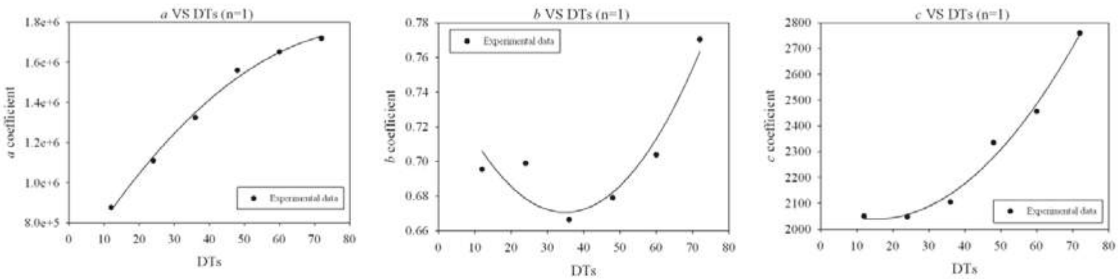


Figure 40 a, b, c parameters variation for n=1.

Table 27 a0, a1, a2, b0, b1, b2, c0, c1, and c2 parameters value for n=1.

a parameter	**value**	**b parameter**	**value**	**c parameter**	**value**
$\mathbf{a_0}$	547646.1	$\mathbf{b_0}$	0.7529	$\mathbf{c_0}$	2088.803
$\mathbf{a_1}$	28180.38	$\mathbf{b_1}$	-0.0047	$\mathbf{c_1}$	-6.6526
$\mathbf{a_2}$	-163.429	$\mathbf{b_2}$	6.75E-05	$\mathbf{c_2}$	0.2211

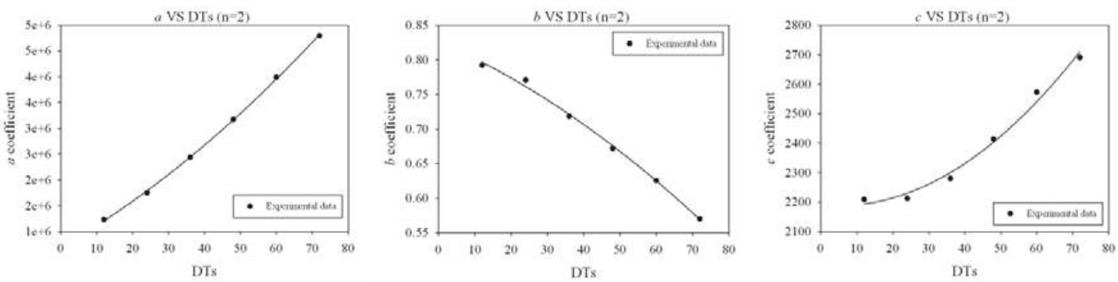


Figure 41 a, b, c parameters variation for n=2.

Table 28 a0, a1, a2, b0, b1, b2, c0, c1, and c2 parameters value for n=2.

a parameter	value	b parameter	value	c parameter	value
a_0	697808.5	b_0	0.8266	c_0	2190.421
a_1	39701.59	b_1	-0.0023	c_1	-1.1369
a_2	243.3258	b_2	-1.80E-05	c_2	0.1161

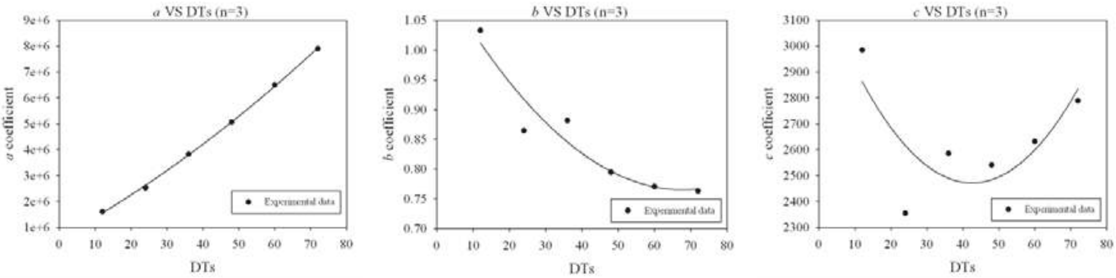


Figure 42 a, b, c parameters variation for n=3.

Table 29 a0, a1, a2, b0, b1, b2, c0, c1, and c2 parameters value for n=3.

a parameter	value	b parameter	value	c parameter	value
a_0	596156.7	b_0	1.13	c_0	3230.393
a_1	75840.97	b_1	-0.0108	c_1	-35.6633
a_2	362.3285	b_2	7.94E-05	c_2	0.4191

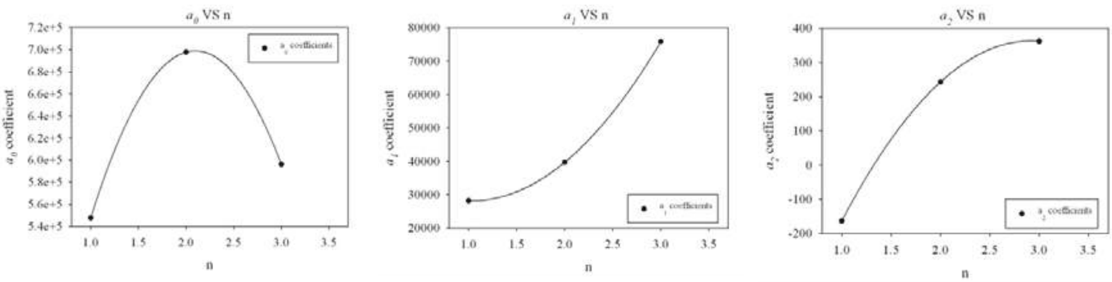


Figure 43 a_0, a_1, a_2 parameters for the variation of n.

Table 30 a_0, a_1, a_2 values of parameters for the variation of n.

a_0 parameter	value	a_1 parameter	value	a_2 parameter	value
a_{00}	145669.5	a_{10}	41277.34	a_{20}	-857.936
a_{01}	527883.7	a_{11}	-25406	a_{21}	838.3832
a_{02}	-125907	a_{12}	12309.08	a_{22}	-143.876

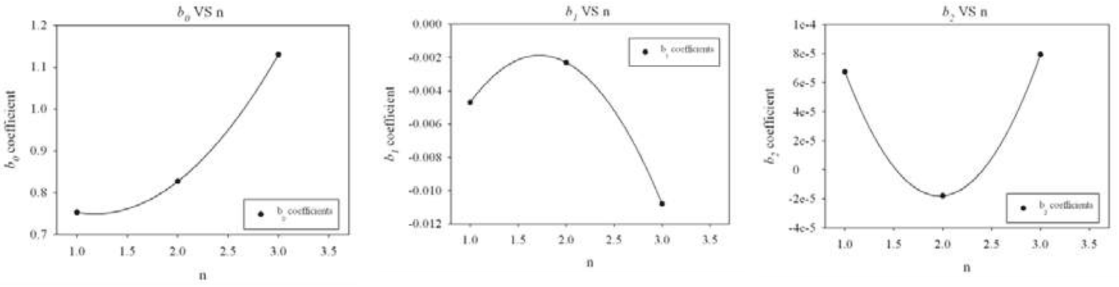


Figure 44 a_0, a_1, a_2 parameters for the variation of n.

Table 31 b_0, b_1, b_2 values of parameters for the variation of n.

b_0 parameter	value	b_1 parameter	value	b_2 parameter	value
b_{00}	0.9089	b_{10}	-0.018	b_{20}	0.000300
b_{01}	-0.2708	b_{11}	0.0188	b_{21}	-0.000400
b_{02}	0.1148	b_{12}	-0.0055	b_{22}	0.000091

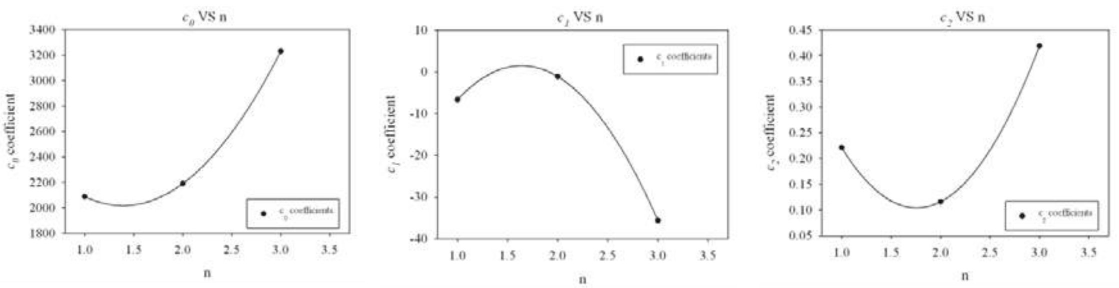


Figure 45 b_0, b_1, b_2 parameters for the variation of n.

Table 32 c_0, c_1, c_2 values of parameters for the variation of n.

c_0 parameter	value	c_1 parameter	value	c_2 parameter	value
c_{00}	2925.539	c_{10}	-52.2104	c_{20}	0.7341
c_{01}	-1305.91	c_{11}	65.5789	c_{21}	-0.717
c_{02}	469.1773	c_{12}	-20.0211	c_{22}	0.204

Appendix e): Results of the case study

In this Appendix are presented the results from the application of the methodology on the case study. In particular are shown the fragility curves derived with the MLE procedure and the parameters values comparison with the traditional approach.

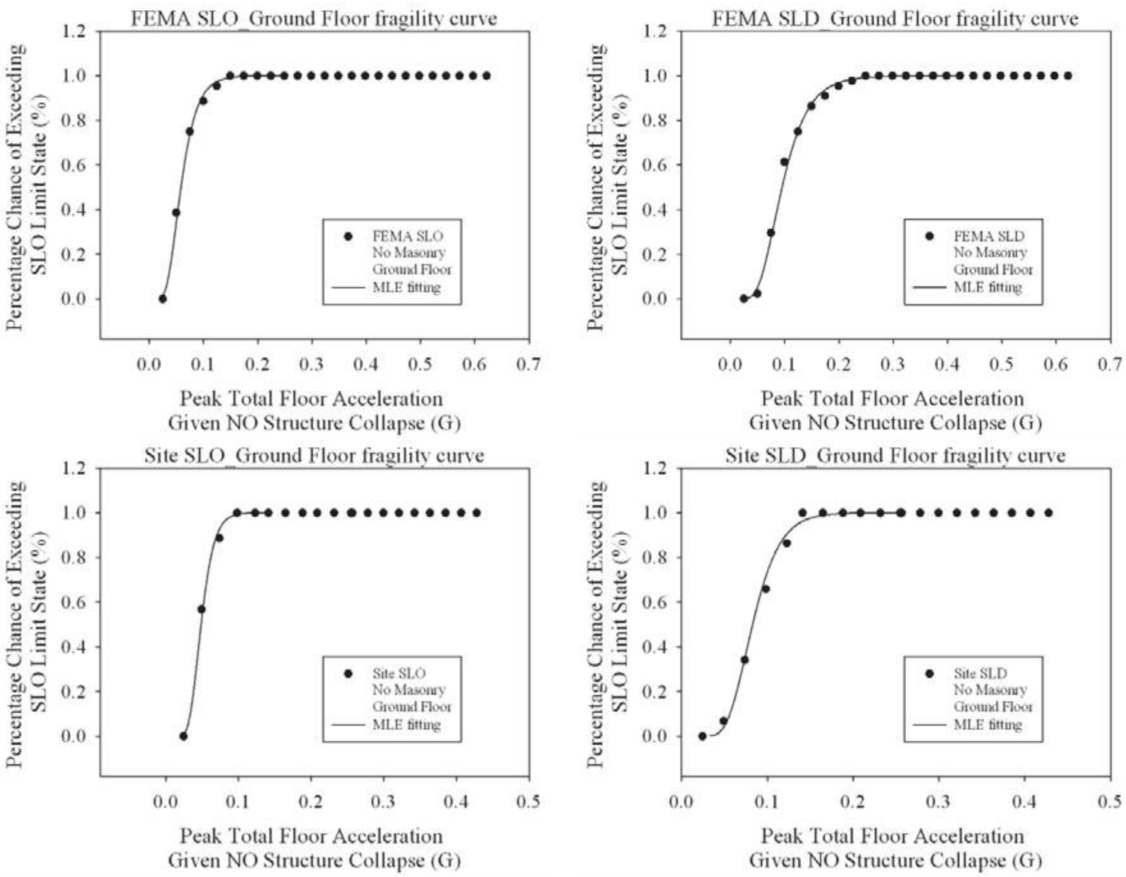


Figure 46 Derived fragility curves for both the two ground motion sets (FEMA and Site Specific), for the Serviceability Limit State (indicated as SLO) and the Damage Limit State (indicated with SLD),associated with the ground level.

Table 33Values of Θ and β, with the traditional procedure and the Maximum Likelihood Estimation procedure

CONDITION	*VALUES*	MLE	TRADITIONAL
FEMA record set, SLO	***Θ***	0.122655115	0.360931399
	β	0.366248563	0.11881654
Site Specific record set, SLO	***Θ***	0.193784866	0.360530943
	β	0.307485506	0.118297566
FEMA record set, SLD	***Θ***	0.128863885	0.423552357
	β	0.282647358	0.151952079
Site Specific record set, SLD	***Θ***	0.215713687	0.423052357
	β	0.274722551	0.151425733

Appendix f): Redundant and not redundant organizational model simulations

In this Appendix are presented the results from the organizational model simulated with and without redundant elements. The results are grouped according to the steps described into Chapter5: the first group show the data clouds, then are presented the fitted curves. This order is followed for each varied variable. The second part of the appendix shows the coefficient deriving from the dynamic fit-nonlinear regression analysis, grouped according to the varied variable.

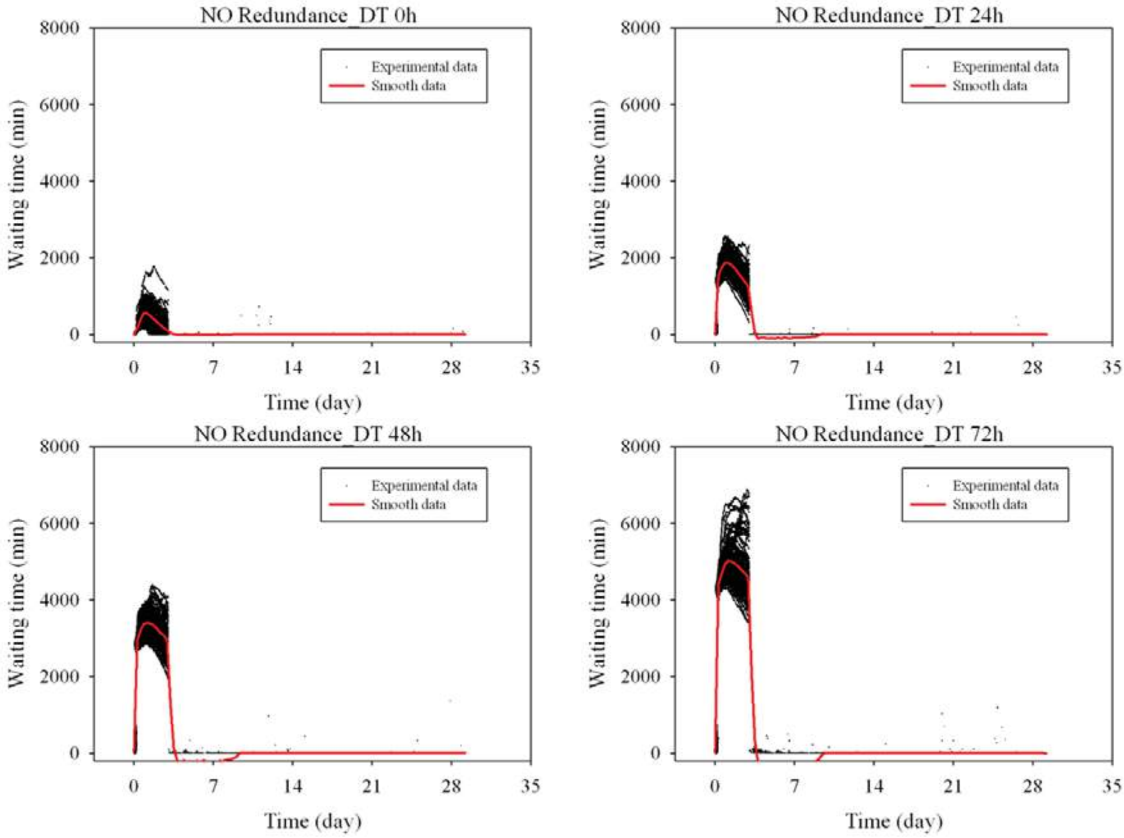


Figure 47 Results from simulations of the organizational model in emergency conditions without redundant element (elevator), and variation of several downtimes (from DT=0 hours to DT=72 hours). Simulations run with three emergency days and 26 normal days. Data clouds (experimental data into legend) from organizational model and smooth analysis with third polynomial degree negative exponential smoother (red medium dash line).

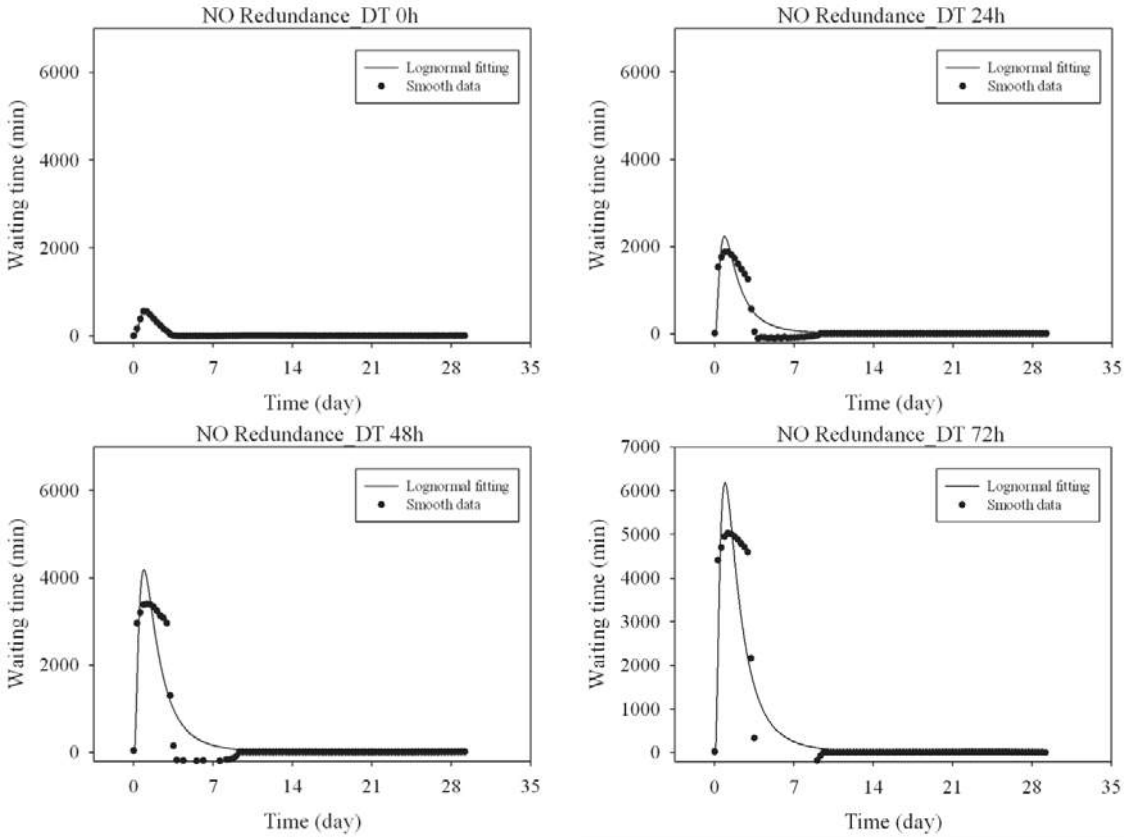
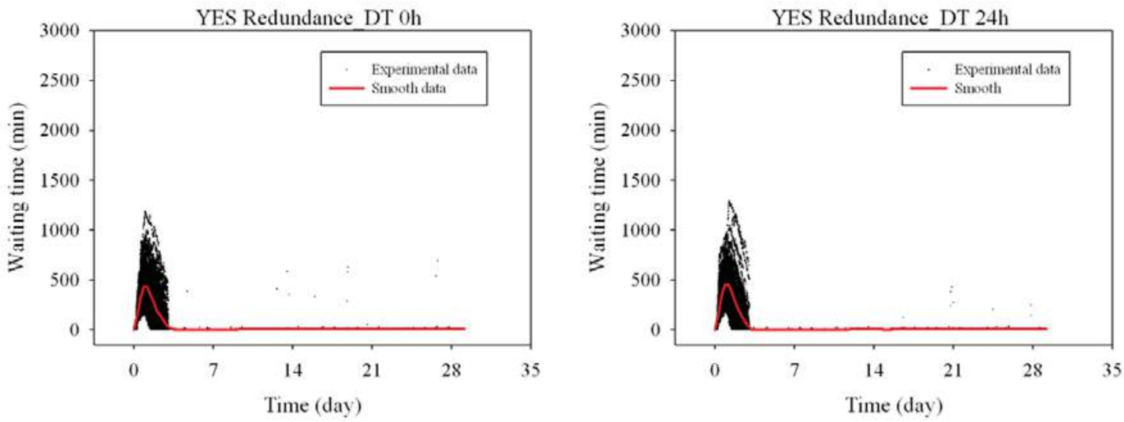


Figure 48 Results from simulations of the organizational model in emergency conditions without redundant element (elevator), and variation of several downtimes (from DT=0 hours to DT=72 hours). Simulations run with three emergency days and 26 normal days. Smooth analysis with third polynomial degree negative exponential smoother (black dotted line), and lognormal fitting with three parameters.



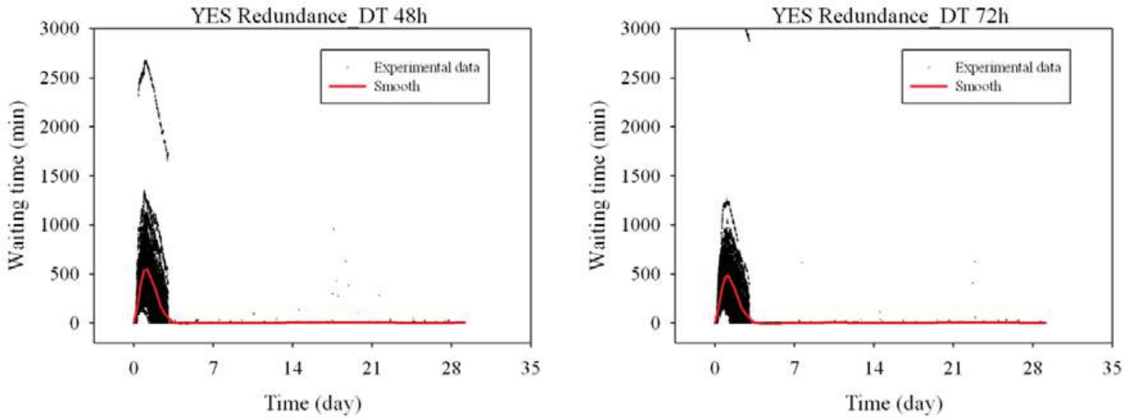


Figure 49 Results from simulations of the organizational model in emergency conditions with a redundant element (elevator), and variation of several downtimes (from DT=0 hours to DT=72 hours). Simulations run with three emergency days and 26 normal days. Data clouds (experimental data into legend) from organizational model and smooth analysis with third polynomial degree negative exponential smoother (red medium dash line).

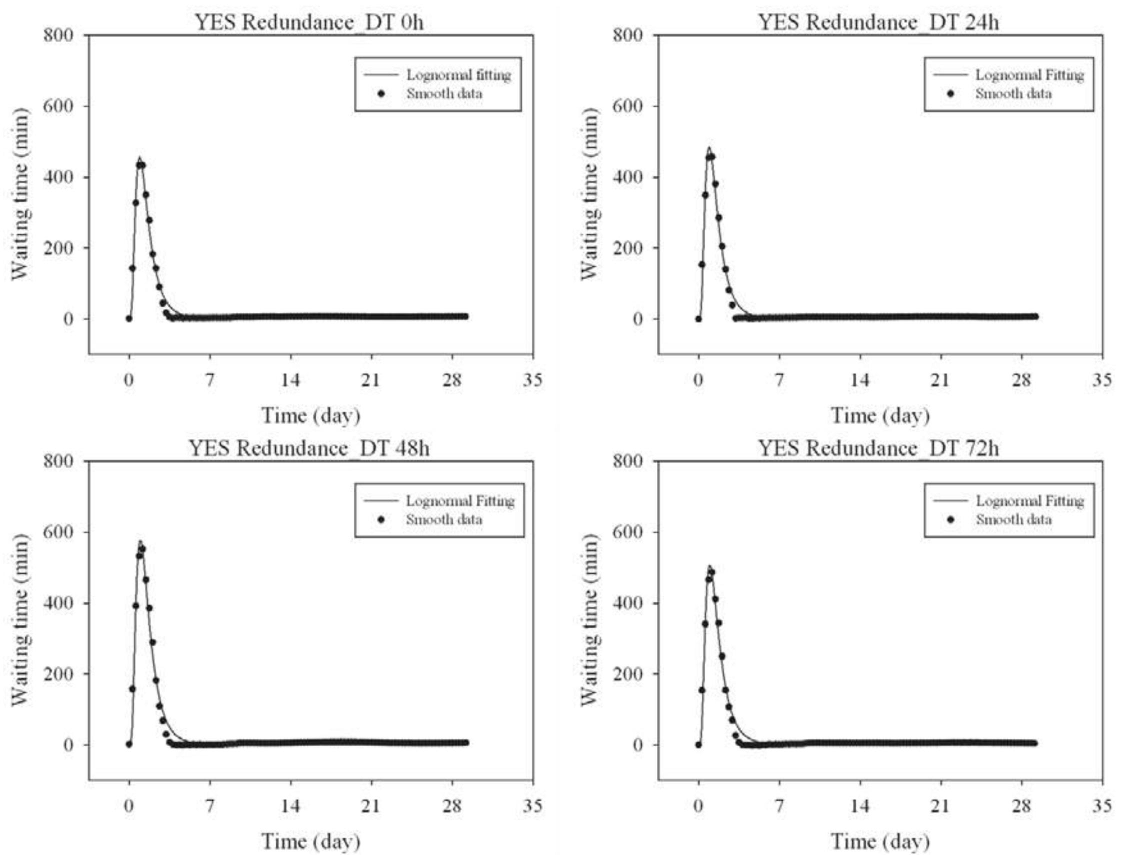


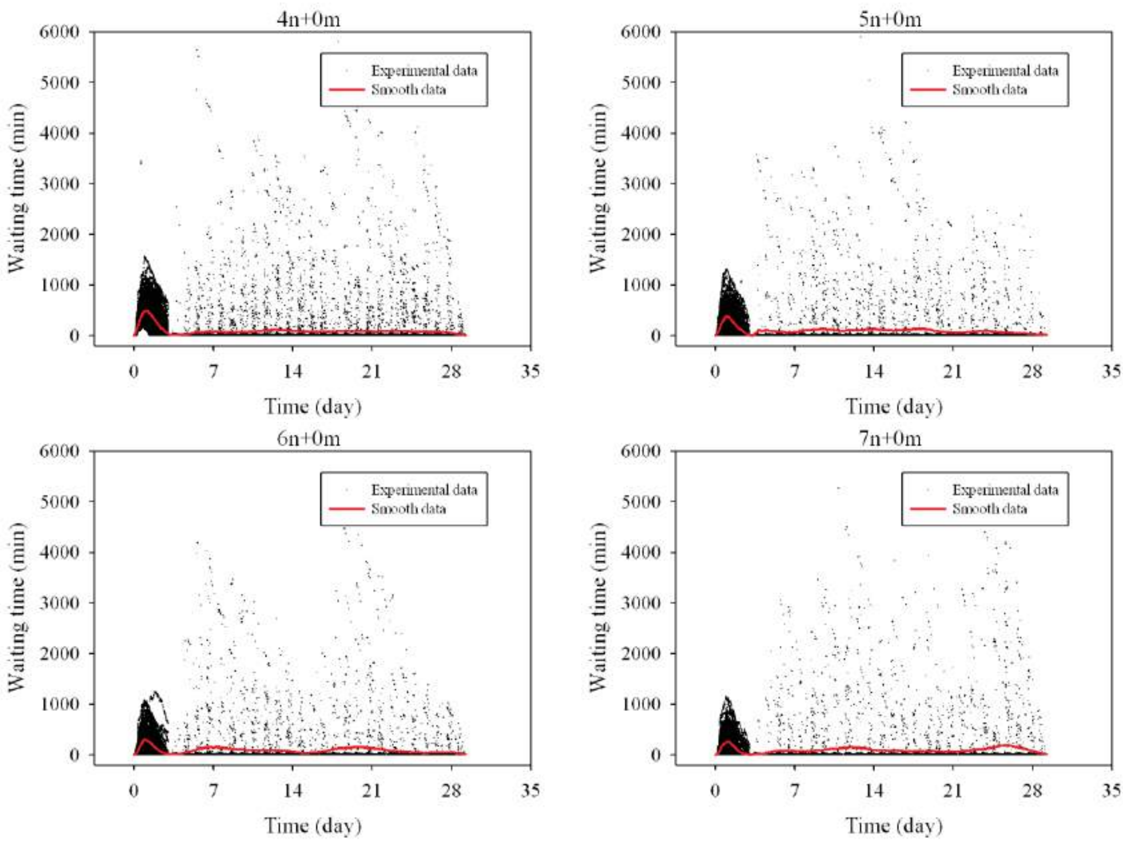
Figure 50 Results from simulations of the organizational model in emergency conditions with a redundant element (elevator), and variation of several downtimes (from DT=0 hours to DT=72 hours). Simulations run with three emergency days and 26 normal days. Smooth analysis with third polynomial degree negative exponential smoother (black dotted line), and lognormal fitting with three parameters.

Table 34 Coefficient deriving from the dynamic fit-nonlinear regression analysis of the models with several redundance.

Model (name)	**Parameters**		
	a	**b**	**c**
Model_NOredund_NODT	988223.6898	0.6012	2014.6146
Model_NOredund_DT24h	3737265637	0.8067	2312.5064
Model_NOredund_DT48h	7392824.86	0.8043	2439.4505
Model_NOredund_DT72h	11129913.1871	0.8042	2484.4952
Model_YESredund_NODT	707410.9730	0.6011	1855.7629
Model_YESredund_DT24h	825985.2742	0.5894	1936.8207
Model_YESredund_DT48h	945402.0640	0.5820	1932.8797
Model_YESredund_DT72h	749854.8807	0.5931	1839.9637

Appendix g): Sensitive parameters organizational model simulations

In this Appendix are presented the results from the case 2- organizational model. The results are grouped according to the steps described into Chapter5: the first group show the data clouds, then are presented the fitted curves. This order is followed for each varied variable. The second part of the appendix shows the coefficient deriving from the dynamic fit-nonlinear regression analysis, grouped according to the varied variable.



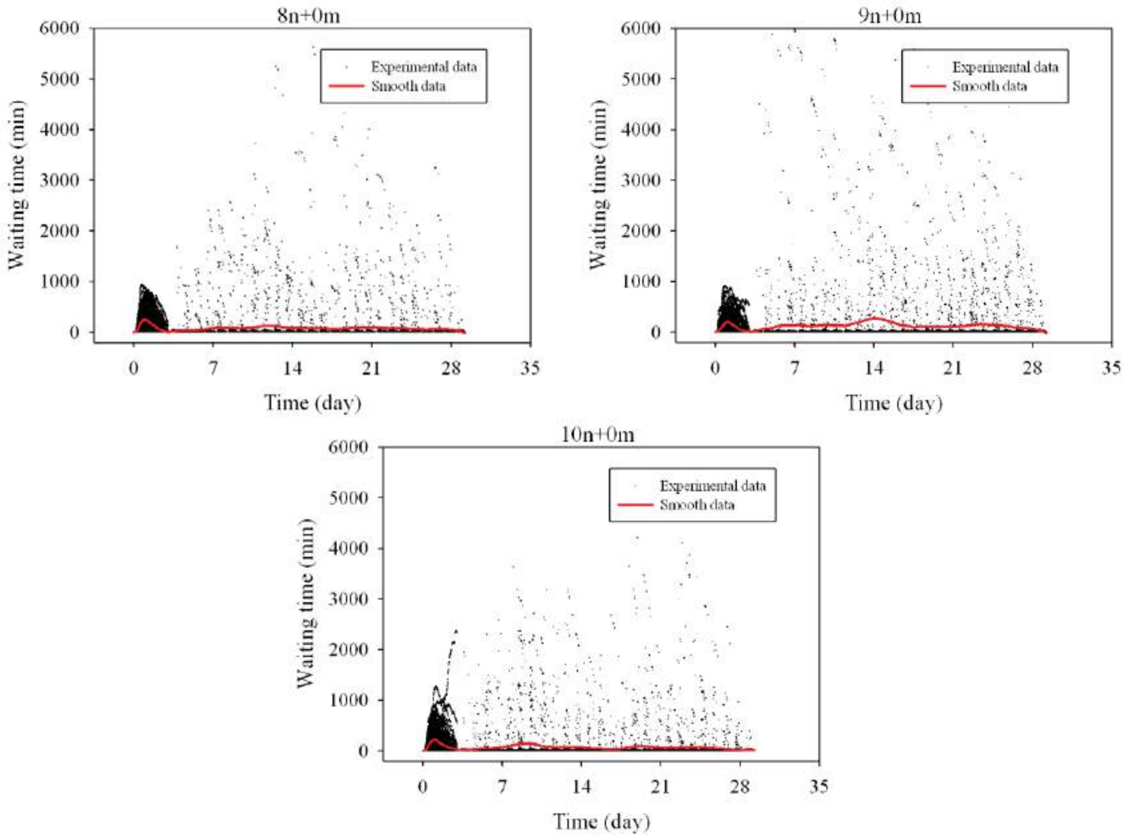
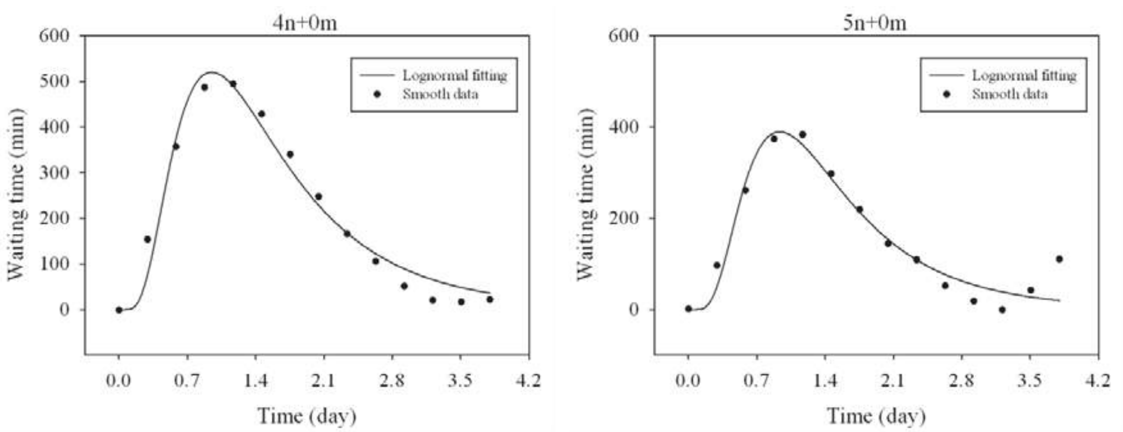


Figure 51 Results from simulations of the organizational model in emergency conditions with added variable rooms (from n=4 to n=10), and current staff resources (m=0). Simulations run with three emergency days and 26 normal days. Data clouds (experimental data into legend) from organizational model and smooth analysis with third polynomial degree negative exponential smoother (red medium dash line).



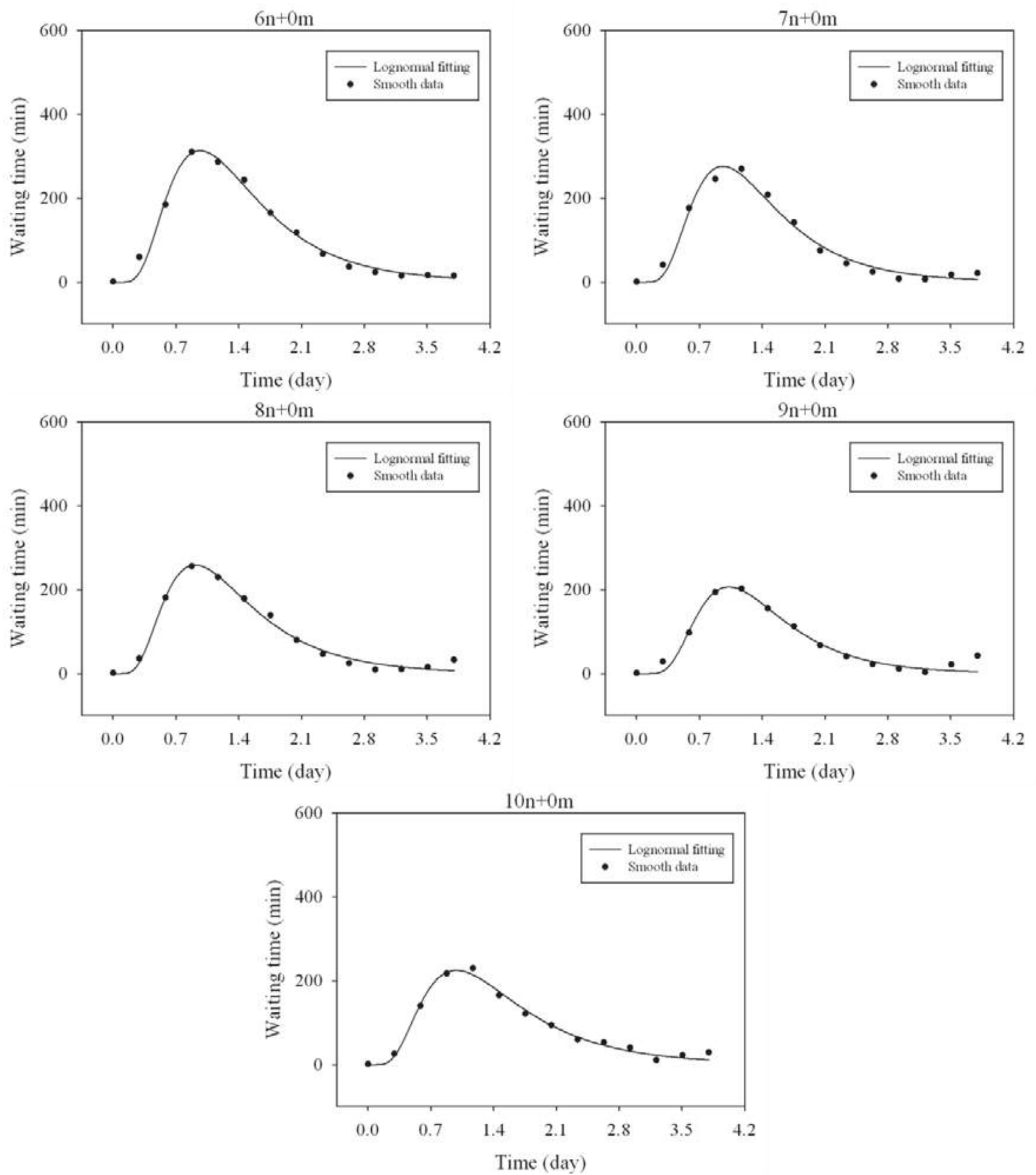
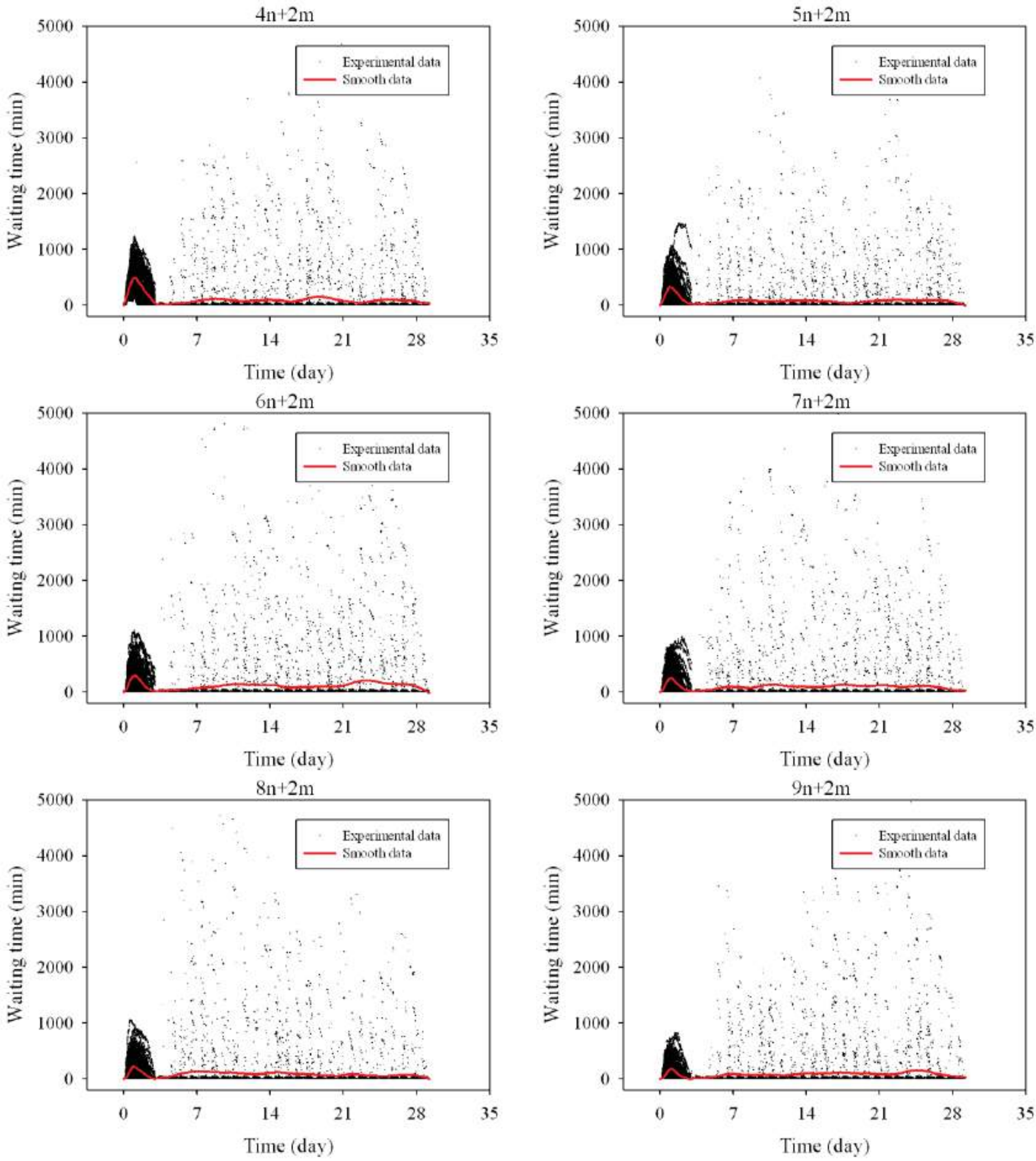


Figure 52 Results from simulations of the organizational model in emergency conditions with added variable rooms (from n=4 to n=10), and current staff resources (m=0). Simulations run with three emergency days and 26 normal days. Smooth analysis with third polynomial degree negative exponential smoother (black dotted line), and lognormal fitting with three parameters.


4n+2m
5n+2m
6n+2m
7n+2m
8n+2m
9n+2m
Experimental data
Smooth data
Waiting time (min)
Time (day)
0
1000
2000
3000
4000
5000
0
7
14
21
28
35

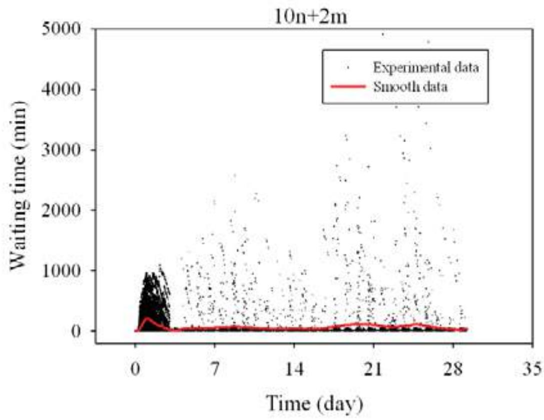
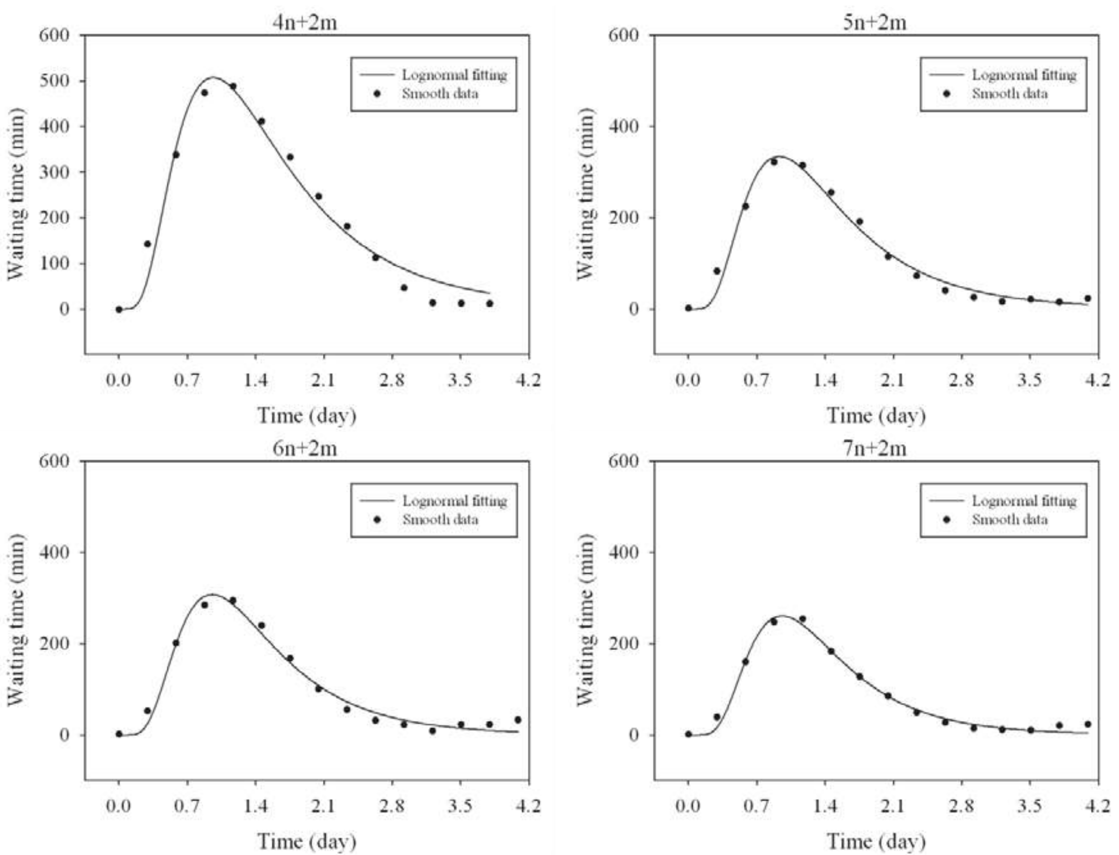


Figure 53 Results from simulations of the organizational model in emergency conditions with added variable rooms (from n=4 to n=10), and added doctors to the current staff resources (m=+2). Simulations run with three emergency days and 26 normal days. Data clouds (experimental data into legend) from organizational model and smooth analysis with third polynomial degree negative exponential smoother (red medium dash line).



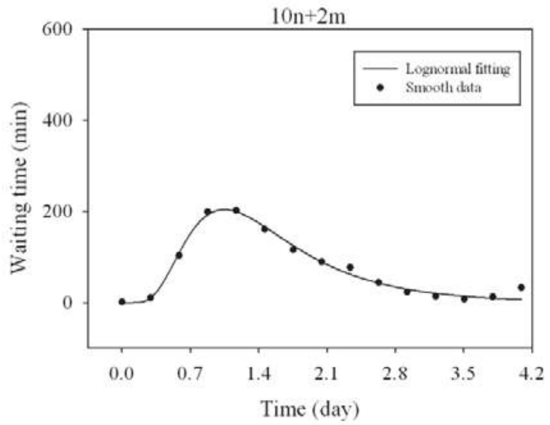
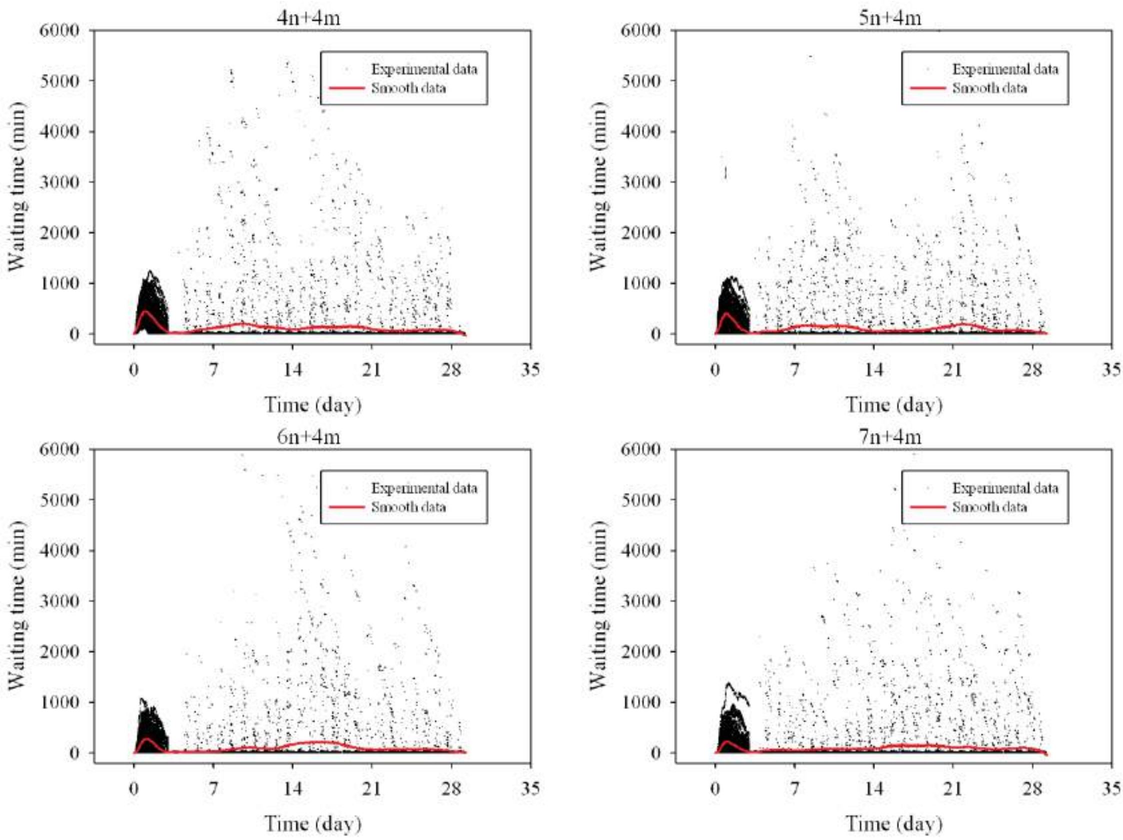


Figure 54 Results from simulations of the organizational model in emergency conditions with added variable rooms (from n=4 to n=10), and added doctors to the current staff resources (m=+2). Simulations run with three emergency days and 26 normal days. Smooth analysis with third polynomial degree negative exponential smoother (black dotted line), and lognormal fitting with three parameters.



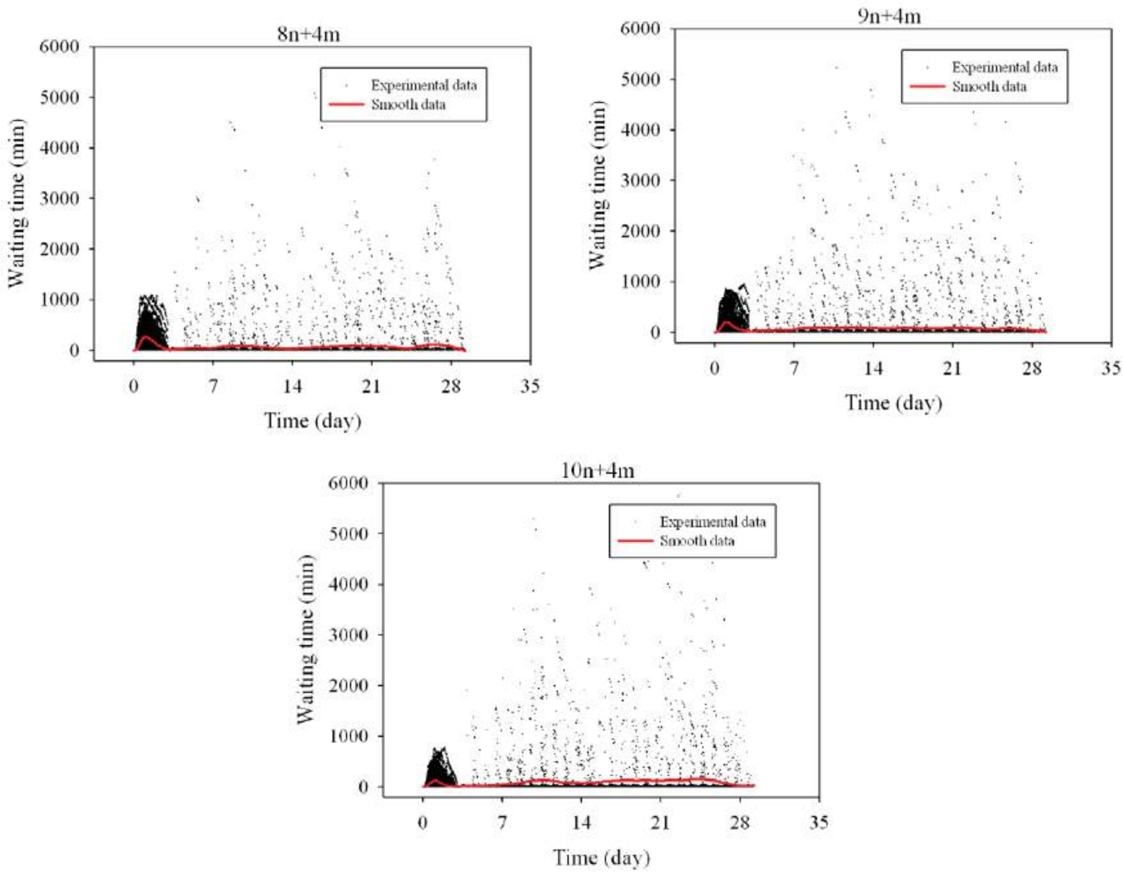
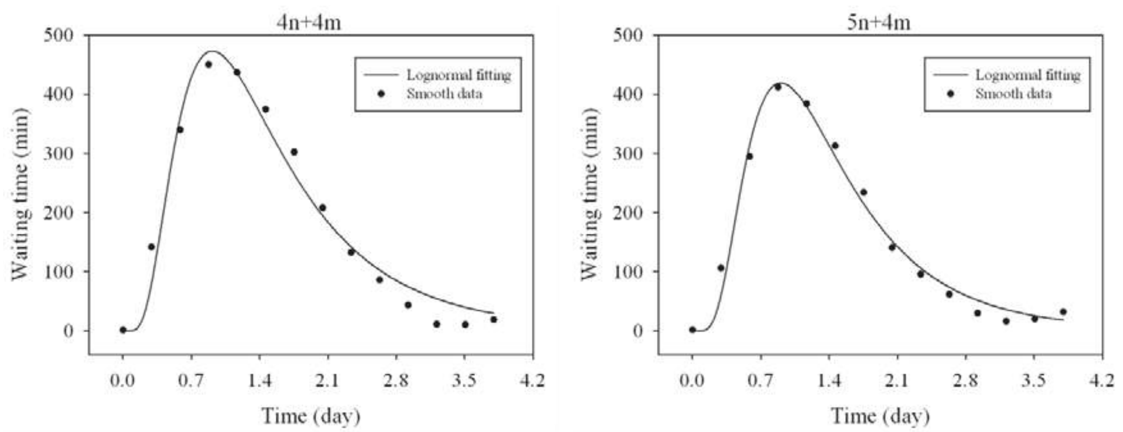


Figure 55 Results from simulations of the organizational model in emergency conditions with added variable rooms (from n=4 to n=10), and added doctors to the current staff resources (m=+4). Simulations run with three emergency days and 26 normal days. Data clouds (experimental data into legend) from organizational model and smooth analysis with third polynomial degree negative exponential smoother (red medium dash line).



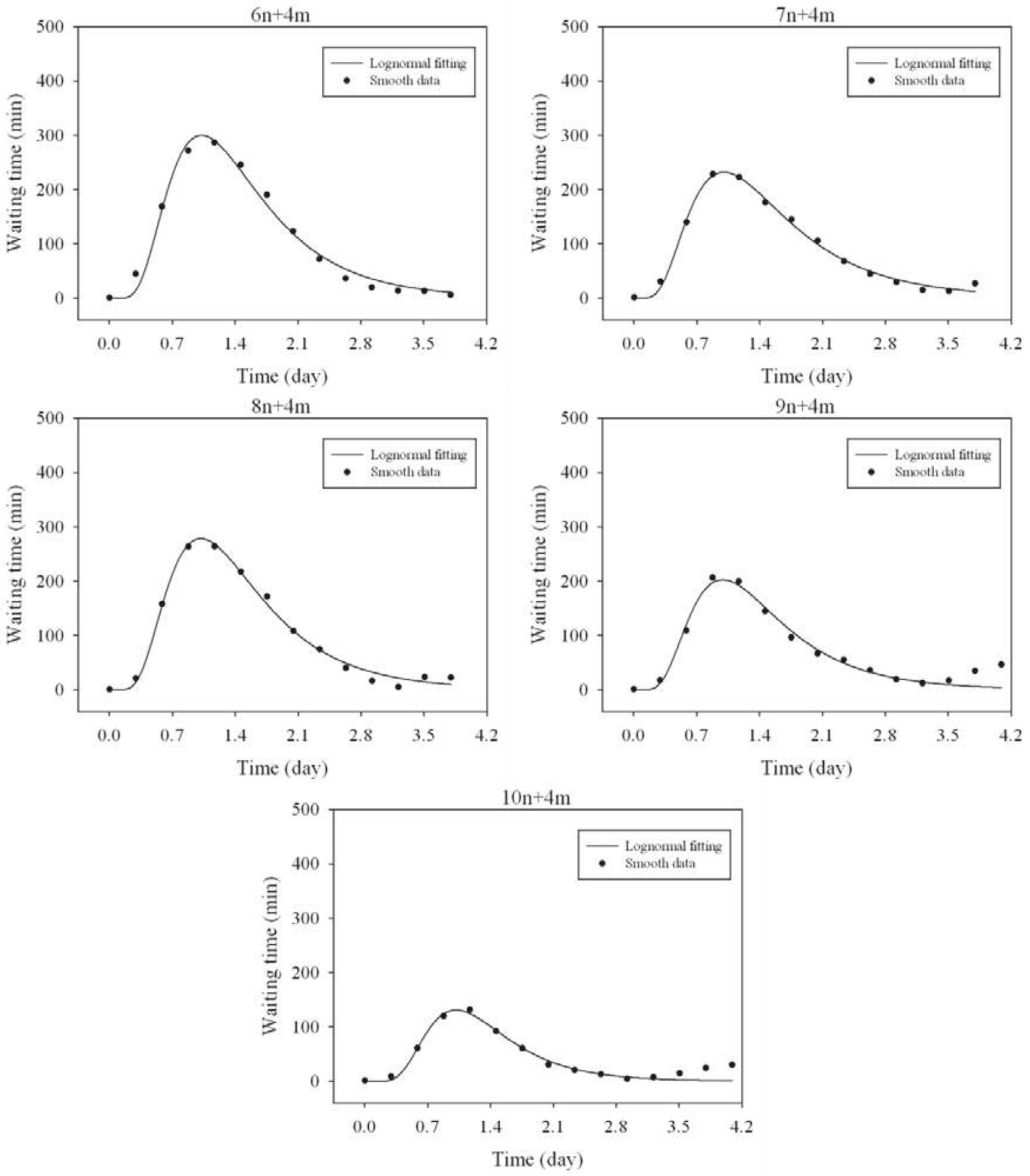


Figure 56 Results from simulations of the organizational model in emergency conditions with added variable rooms (from n=4 to n=10), and added doctors to the current staff resources (m=+4). Simulations run with three emergency days and 26 normal days. Smooth analysis with third polynomial degree negative exponential smoother (black dotted line), and lognormal fitting with three parameters.

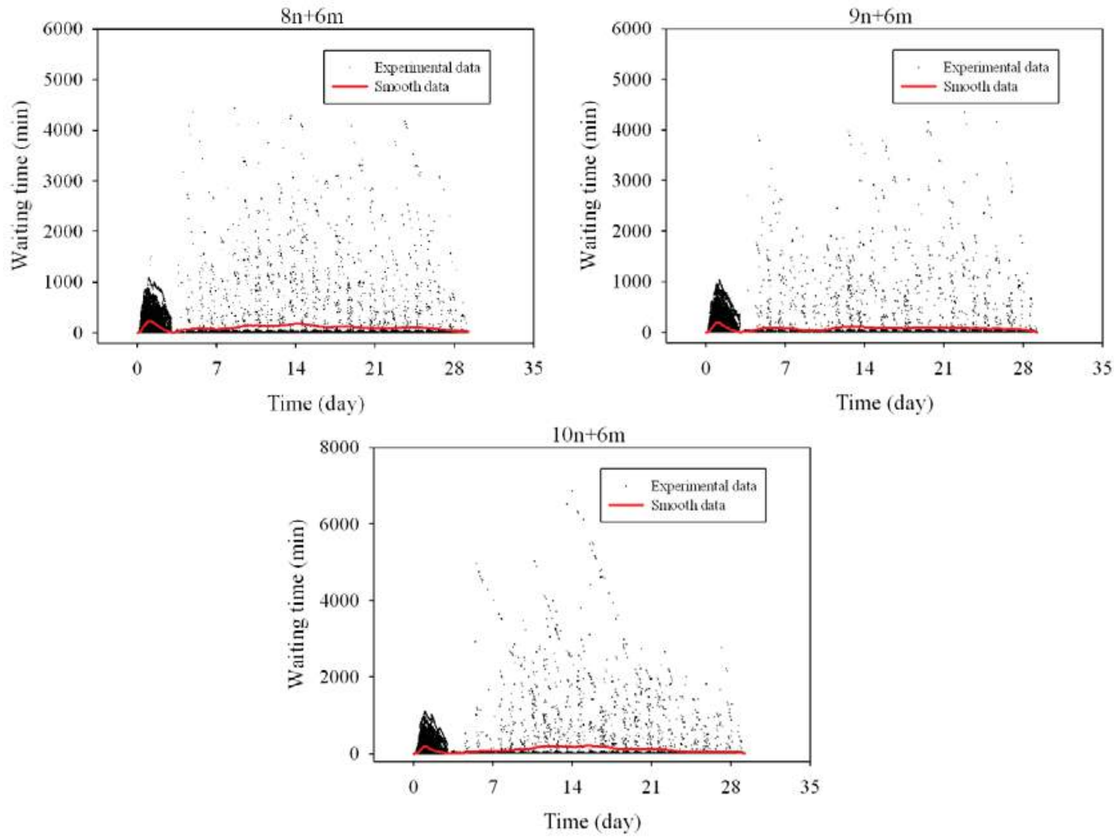
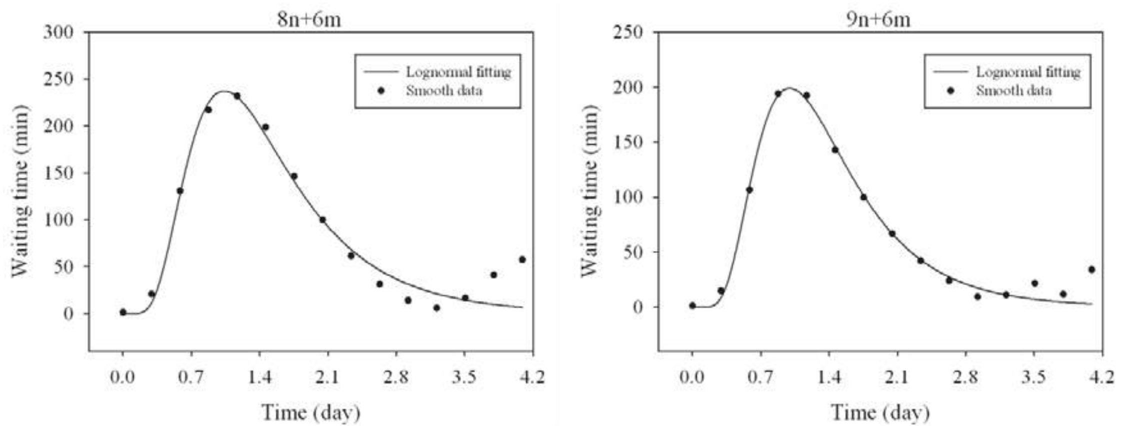


Figure 57 Results from simulations of the organizational model in emergency conditions with added variable rooms (from n=8 to n=10), and added doctors to the current staff resources (m=+6). Simulations run with three emergency days and 26 normal days. Data clouds (experimental data into legend) from organizational model and smooth analysis with third polynomial degree negative exponential smoother (red medium dash line).



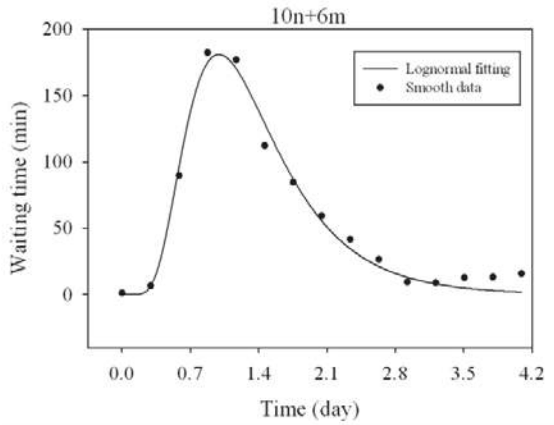


Figure 58 Results from simulations of the organizational model in emergency conditions with added variable rooms (from n=8 to n=10), and added doctors to the current staff resources (m=+6). Simulations run with three emergency days and 26 normal days. Smooth analysis with third polynomial degree negative exponential smoother (black dotted line), and lognormal fitting with three parameters.

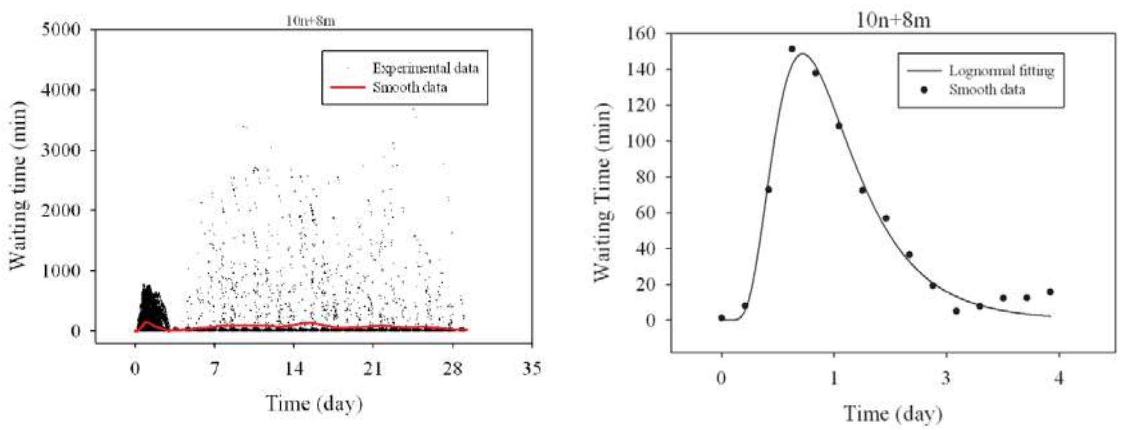


Figure 59 Results from simulations of the organizational model in emergency conditions with added rooms (n=10), and added doctors to the current staff resources (m=+8). Simulations run with three emergency days and 26 normal days. Data clouds (experimental data into legend) from organizational model and smooth analysis with third polynomial degree negative exponential smoother (red medium dash line) on the left; smooth analysis with third polynomial degree negative exponential smoother (black dotted line), and lognormal fitting with three parameters, on the right side.

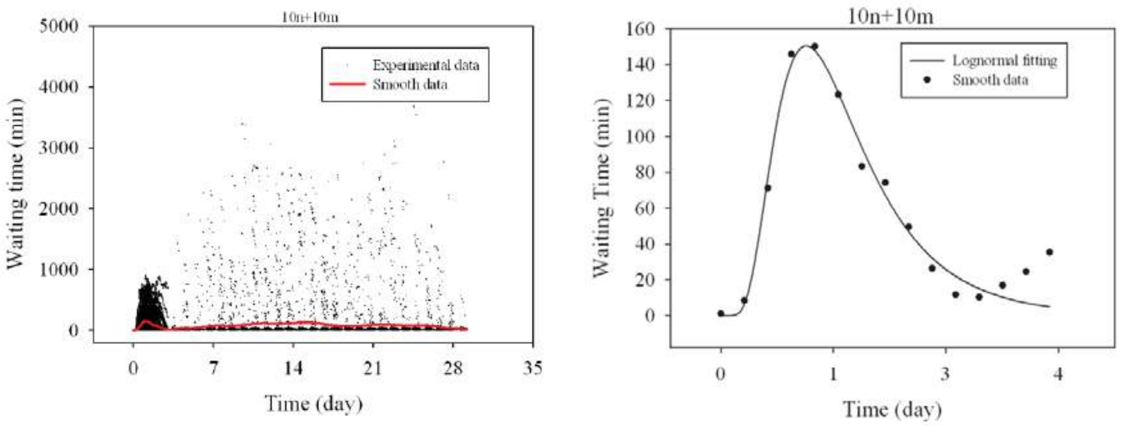


Figure 60 Results from simulations of the organizational model in emergency conditions with added rooms (n=10), and added doctors to the current staff resources (m=+10). Simulations run with three emergency days and 26 normal days. Data clouds (experimental data into legend) from organizational model and smooth analysis with third polynomial degree negative exponential smoother (red medium dash line) on the left; smooth analysis with third polynomial degree negative exponential smoother (black dotted line), and lognormal fitting with three parameters, on the right side.

Table 35 Coefficient deriving from the dynamic fit-nonlinear regression analysis of the models with no added resources and variable n parameter.

Model (name)	**Parameters**		
	a	**b**	**c**
M_n4+0m	843120.9104	0.5987	1939.3751
M_n5+0m	612355.0456	0.5733	1854.5782
M_n6+0m	497272.3405	0.5207	1816.0836
M_n7+0m	429044.0747	0.4993	1761.6146
M_n8+0m	389735.1823	0.5332	1735.7617
M_n9+0m	338511.6766	0.4723	1834.6718
M_n10+0m	368274.6166	0.5518	1906.7290

Table 36 Coefficient deriving from the dynamic fit-nonlinear regression analysis of the models with added resources (m=+2), and variable n parameter.

Model (name)	**Parameters**		
	a	**b**	**c**
M_n4+2m	832712.6983	0.5898	1954.1657
M_n5+2m	517599.1598	0.5597	1809.8346
M_n6+2m	481812.9846	0.5266	1798.9821
M_n7+2m	405322.1273	0.5058	1766.5394
M_n8+2m	352920.1932	0.4985	1770.6030
M_n9+2m	292196.8861	0.4263	1737.6020
M_n10+2m	349253.8971	0.5205	1962.2569

Table 37 Coefficient deriving from the dynamic fit-nonlinear regression analysis of the models with added resources (m=+4), and variable n parameter.

Model (name)	Parameters		
	a	**b**	**c**
M_n4+4m	741698.9015	0.6041	1882.5122
M_n5+4m	637953.7836	0.5725	1739.7489
M_n6+4m	499925.8945	0.5069	1894.1601
M_n7+4m	385018.9811	0.55	1930.6213
M_n8+4m	460840.2695	0.5098	1883.1450
M_n9+4m	326439.4519	0.5112	1834.2628
M_n10+4m	209551.7561	0.4434	1765.3829

Table 38 Coefficient deriving from the dynamic fit-nonlinear regression analysis of the models with added resources (m=+6), and variable n parameter.

Model (name)	Parameters		
	a	**b**	**c**
M_n8+6m	286416.3013	0.4708	1768.5762
M_n9+6m	318661.2349	0.4876	1802.8411
M_n10+6m	401307.3237	0.5141	1930.2542

Table 39 Coefficient deriving from the dynamic fit-nonlinear regression analysis of the models with added resources (m=+2), and variable n=10.

Model (name)	Parameters		
	a	**b**	**C**
M_n10+8m	240639.3250	0.4831	1819.6506

Table 40 Coefficient deriving from the dynamic fit-nonlinear regression analysis of the models with added resources (m=+2), and variable n=10.

Model (name)	Parameters		
	a	**b**	**c**
M_n10+10m	260752.6464	0.5166	1982.0952