POLITECNICO DI MILANO

School of Industrial and Information Engineering
Master of Science in Aeronautical Engineering

An Integrated Model To Optimize HEMS Bases Location and Helicopters Dispatching

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"Non est ad astra mollis e terris via"

Seneca, Herculens Furens, 437

Seneca, in full *Lucius Annaeus Seneca* (born circa 4 BCE, Corduba, Spain and died 65 CE, Rome), was a Roman philosopher, statesman, orator, and tragedian. He was Rome's leading intellectual figure in the mid-1st century CE and he was a virtual ruler of the Roman world between 54 and 62, during the first phase of the emperor Nero's reign.
"Hercules Furens" is his best tragedy, written in or before 54 CE. The play, located in Tebe, chronicles of the Juno's revenge on her stepson Hercules to revenge her husband betrayal. At the end, Hercules, falling to madness due to goddess' influence, kills all his family, wife and children. Antonio Canova realized a marble masterpiece, *Hercules and Lica*, now preserved in National Gallery of Modern Art in Rome.

DEDICATION AND ACKNOWLEDGEMENTS

A lot of people helped me to reach this awesome goal. In the first place, I have to thank my parents and my little sister Lucia, for supporting me during these hard years and always telling me that I could achieve this milestone. Thanks to Professor Maurizio Bruglieri, for working at my side, even on Saturday and Sunday, attending a conference with me, for his help in difficult situations and for his continued presence; but also to Cesare Cardani, for being my co-supervisor, for his suggestions and claims. Thanks to Alessandra who always believed in me and gave me strength also in difficult and stressful periods with an impressive patience. Thanks to all my friends who supported me with their energy, their sympathy, and empathy.
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A special and sincere thanks to all men and women of AREU who, thanks to their work, save thousands of lives risking theirs, every year.

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ACRONYMS

AAMS	Association of Air Medical Services
AAT	Articolazioni Aziendali Territoriali
ALF	Advanced Life Support
AREU	Azienda Regionale Emergenza Urgenza
ARTM	Average Response Time Model
BCAS	British Columbia Air Services
BG	Bergamo province
BLF	Basic Life Support
BLHD	Bases Location and Helicopters Dispatching
BS	Brescia province
CAD	Computer-Aided Dispatch
CDC	Central Dispatch Centre
CGD	Clinical Governance Days
CNSAS	Corpo Nazionale Soccorso Alpino e Speleologico
COEU	Centrali Operative Emergenza Urgenza
CO	Como province
CPR	Cardio-Pulmonary Resuscitation
CR	Crema province
CRELI	Centrale Regionale delle attivita di ELIsoccorso
DMAT	Disaster Medical Assistance Team

DMTE	Dipartimento di Medicina Trasfusionale e di Ematologia
E-HEMS	European Helicopter Emergency Medical Services
ECMO	ExtraCorporeal Membrane Oxygenation
EMS	Emergency Medical Service
EOC	Emergency Operation Centre
GH	Golden Hour
GPS	Global Positioning System
GIS	Geographical Information System
HEMS	Helicopter Emergency Medical Services
HPD	HEMS Paramedic Dispatcher
HQPA	Helicopter Quickest Path Algorithm
IABP	Intra Aortic Balloon Pump
IHA	(Australian) Interior Health Authority
ISS	Injury Severity Scale
KGH	Kelowna General Hospital
KSS	Kent, Surrey and Sussex
KSSAAT	Kent, Surrey and Sussex Air Ambulance Trust
LBS	Location-Based Services
LC	Lecco province
LO	Lodi province
MB	Monza-Brianza province
MCLP	Maximum Coverage Location Problem
MCP	Medical Control Physician
MHLW	(Japanese) Ministry of Health, Labour and Welfare
MI	Milan province

MOI	Mechanism Of Injury
MN	Mantua province
MR-HEMS	MultiRole Helicopter Emergency Medical Services
MTOW	Maximum Take-Off Weight
NCD	Non-Clinical Dispatcher
NVG	Night Vision Goggles
OF	Objective Function
PBN	Performance-Based Navigation
PV	Pavia province
QALY	Quality-Adjusted Life-Year
RIH	Royal Inland Hospital
SAR	Search And Rescue
SDF	Self-Defence Forces
SO	Sondrio province
SOREU	Sale Operative Regionali Emergenza Urgenza
SRC	Struttura Regionale di Coordinamento
TRAMAH	Trauma Resource Allocation Model for Ambulances and Hospitals
UAV	Unmanned Aerial Vehicle
USA	United States of America
VA	Varese province

SOMMARIO

Questa tesi presenta uno studio esplorativo del problema di localizzazione delle basi dell'Helicopter Emergency Medical Service (HEMS) con un metodo integrato di assegnamento degli elicotteri. Per raggiungere questo obiettivo, sono stati sviluppati due modelli Mixed Integer Linear Programming (MILP). Conoscendo *a priori* tutte le richieste in un lasso temporale definito, il problema ha come scopo massimizzare il numero totale di eventi serviti e di minimizzare il tempo totale per servirli. Ogni evento è caratterizzato da un codice di gravità: i codici rossi sono prioritari su quelli verdi. I due modelli differiscono perché nella versione *rigida*, un codice rosso può essere servito solamente da un elicottero immediatamente disponibile, in grado di raggiungerlo entro una soglia temporale predefinita; nella versione *flessibile*, un codice rosso può essere servito anche da un elicottero non immediatamente disponibile purché il vincolo temporale rimanga soddisfatto. I modelli forniscono, inoltre, la possibilità di allocare uno e un solo specifico aeromobile per ciascuna base. Includono intrinsecamente un metodo di assegnamento (chiamato *predittivo*) capace di assegnare gli elicotteri alle missioni. I modelli sono stati testati con esperimenti numerici su dati reali; i risultati sono stati validati per mezzo di un altro metodo di assegnamento (chiamato *online*), più simile alla realtà dal momento che assegna gli elicotteri alle missioni man mano che sorgono, evitando così di sovrastimare le richieste effettivamente servite. È stata eseguita anche un'analisi sui dati per scoprire gli aspetti più importanti da considerare durante le simulazioni. I dati e gli esperimenti sono relativi alla Lombardia nell'anno 2015.

ABSTRACT

This thesis presents an exploring study on Helicopter Emergency Medical Service (HEMS) bases location problem integrated with the helicopter dispatching method. To achieve that, two Mixed Integer Linear Programming (MILP) models have been developed. Knowing *a priori* all requests in a defined time horizon, the problem is aimed at maximizing the total number of served events and at minimizing the total time to serve them. Each event is characterized by an injury-gravity code: red code events take priority over green code events. The two models are different because in the *rigid* version, a red code event can only be served by an immediately available helicopter able to reach it within a desired threshold; in the *flexible* version, a red code event can also be served by a helicopter not immediately available provided that the above time theshold constraint is fulfilled. The models also provide the ability to allocate a single specific aircraft to each base. They intrinsically include a dispatching method (called *predictive*) able to assign helicopters to missions. Models have been tested through numerical experiments on real data; the results have been validated using another dispatching method (called *online*), which is more similar to reality as it assigns helicopters to missions chronologically, as they arise, avoiding to overestimate served requests. A deepening analysis on data has been performed to discover the most important aspects to be considered during simulations. Data and experiments are related to Lombardy region during year 2015.

INTRODUCTION

> Vicar: Mr. Bond, Mr. Bond. I'm so glad I caught you. Your office called. They're sending a helicopter to pick you up. Some sort of emergency.
> Bond: It usually is.
>
> James Bond: For Your Eyes Only, 1981

When dealing with an emergency, no mistakes are admitted: time is the most precious resource and taking action promptly may make the difference between life or death of a human being. With the advent of helicopters, combined with wheeled vehicles, this ability is significantly improved and several additional lives were saved. However, owning a fast, nimble and flexible transportation, able of reaching any location on the territory is no longer sufficient: economic and financial crisis progressing from 2008 taught that the results and the cost to afford them are equally important; in a word, efficiency. Having an adequate number of helicopters, cleverly distributed over a territory, means not only to considerably save taxpayers' money but also to reduce patients' hospitalisation and to make available again the aircraft for a new rescue mission. In this context, the thesis has a double aim: the first is finding the optimal location of Helicopter Emergency Medical Service (HEMS) bases, where helicopters are permanently present, and the type of helicopter each base is equipped of. In the meantime, it decides, for each mission, which helicopter of which base is the most appropriate to be used in order to save both time and money. The problem has been modeled via a Mixed Integer Linear Program (MILP) and, thanks to Azienda Regionale Emergenza Urgenza (AREU), it has been validated with real data concerning Lombardy region.

There exist some other theses works about HEMS, in particular regarding the rendez-vous between the helicopter and ambulance [17],[56] and the optimal path for HEMS helicopter [48]. However, this thesis discusses a completely new objective, i.e. the location of HEMS bases, which was considered given as input in previous works. Now this has become of interest of AREU, since the latter is questioning the current base location and looking for a more efficient and cost-saving solution. In the world, Norwegian researchers treated a similar argument applied to their territory; therefore the thesis represents, to the best of our knowledge, a completely new

argument in the Italian scenario. Moreover, it solves in an integrated way not only the bases location problem but also the helicopter dispatching, which Norwegian work does not include.
Two optimization models have been formulated and coded: the *rigid* one and the *flexible* one. The former works under the hypothesis that a red code event (seriously injured patient), to be considered served, needs an immediately available helicopter, able to reach the incident place within a fixed time threshold. The second model, on the other hand, considers a red code event served if a helicopter, even if not immediately available, can reach the demand point within the above time threshold. Green code (slightly injured patient) events, instead, have a weaker limitation: they are considered served if a helicopter can reach the demand point within three hours from the call receipt, therefore there is no need of immediately available helicopters.
To each injury-severity code is associated with a score which is higher for red code events, average for impervious events and lower for green code events; the score is used to weight the importance of a mission to be served. The objective function of the MILP presents, hierarchically, the maximization of total number of served mission weighted on their score, the minimization of time to serve them and, lastly, the minimization of the take-off delays. The latter are intended as the time lasting between the call receipt and the actual helicopter take-off time, due to its involvement in previous missions.
Both the *rigid* and the *flexible* models assume that to know *a priori* the distribution of all events and therefore the dispatching can exploit this information since there is a prediction of the future requests. But in reality things are different, requests are served chronologically, as they arise. For this reason, downstream of the optimization, another dispatching method (called *online*) activates; this one is able to assign missions to helicopters chronologically, as they arise. In such a way, optimal results are validated and the total number of served missions is not overestimated.
Numerical experiments and data are related to year 2015 in Lombardy Region. However, the methodologies presented are general since they can be applied to whatever year and in whatever region or country. In particular, a Green Field analysis (with no initial bases existing) and Conditioned analysis (with some bases fixed) have been conducted. Also a sensitivity analysis on the adequate number of helicopters (four or five) has been performed.
This thesis work is organized in five chapters as follows.

- **CHAPTER 1: The Helicopter Emergency Medical Service**
  In this chapter history of HEMS is treated (with a statement relative to Lombardy); then, an analysis comparing diversity between wheeled vehicles and rotary wing aircrafts and a cost-benefit analysis of the latter are performed. How HEMS is organized in the world and in Lombardy is explained together with interventions times, their specific definitions, what HEMS on-board staff consists of and a brief deepening on night missions.

- **CHAPTER 2: Literature Analysis**
  This chapter shows what has been done so far in this field, all over the world. In particular,

a deep analysis of a couple of studies on Norwegian territories [62, 63] is performed. Other interesting articles have been written for an Australian HEMS problem [26], for the Iranian province of Lorestan [9] and for Maryland (USA) trauma centers and helicopters location [10]. Finally, a study of some Italian theses performed in Politecnico di Milano.

- **CHAPTER 3: Base Location and Helicopter Dispatching Problem**
  In this chapter a brief introduction of Operations Research is presented, the problem definition is discussed and developed mathematical models are described, with their variables, input data, constraints, and objective functions.

- **CHAPTER 4: Case Study Data Analysis**
  This chapter contains the statistical analyses regarding the real data concerning Lombardy Region provided by AREU related to year 2015. Data were rough, but through a refining work, some interesting results are yet appreciable.

- **CHAPTER 5: Numerical Experiments and Results**
  The chapter is split into three subsections: Green Field scenario, Conditioned scenario, and Fictitious scenario (i.e., a challenging scenario where the rescue requests of two consecutive days are merged into a single day). For each simulation, the mission delays are presented together with a delay times analysis, optimal distribution of bases over the territory with respect to the currently used one, and the total flight-time for each helicopter. A cost analysis and the total number of served missions with both methods (*predictive* and *online*) are also presented. Finally, a couple of discussions regarding models and methods are carried on; a general stable solution proposal closes the chapter.

- **CHAPTER 6: Conclusions and Future Works**
  Main results summary between models and methods and their results are presented. Some technical aspects of the two helicopter models are also presented. A future works brief concludes the thesis work.

The bibliography, an appendix on different types of helicopters used for HEMS worldwide (containing an extract of a study on how to train staff on new helicopters), an appendix displaying the trauma criteria for HEMS utilization and the last appendix on AMPL *rigid* model are presented.

CHAPTER 1

THE HELICOPTER EMERGENCY MEDICAL SERVICE

In Cruce Mea Fides

U.S. 30thArmy Medical Brigade

1.1 History of HEMS

The advent of rotary wing in aeronautical field has been the result of passion, courage, and ingenuity of many men, which worked for a unique great purpose for the entire life-time. Beyond belligerent purposes of the XX century wars, the rotary wing aircraft shows the culmination of its nobility in the Search And Rescue (SAR) and in Medical Evacuation (MedEvac) of people in danger. The first documented MedEvac by helicopter occurred during the World War II. In April 1944 a US Army Air Forces aircraft, with three wounded British soldiers on board, was forced down in the jungle behind Japanese lines near Mawlu in Burma. A new US Army Sikorsky YR-4B helicopter (Figure 1.1), flown by Lt. Carter Harman, could carry only one passenger but, over 25-26 April 1944, four return trips were made [1]. The first dedicated use of helicopters by U.S. armed forces occurred during the Korean War, between 1950 and 1953.

The fact that air ambulance was invented for military purposes should not be a surprise. On the other hand, what can amaze is the very first air intervention, which was not performed by a more-than-air heavy machine; aerostatic balloons were put to use during Paris siege, in 1870 for wounded soldiers evacuation [39]. The first recorded air ambulance flight was during the WWI, in Turkey, when a de Havilland DH9 saved a British Camel pilot after crash [54]. During WW I, air ambulance idea was continually studied, in particular from the United Kingdom and France. Having regard to benefits of development, medical evacuation was used in all following conflicts. Technology, however, evolved parallel to medical skills. During the Vietnam war, for

Figure 1.1: Helicopter MedEvac during the Korean War.

the first time a high-specialized and high-trained team was employed for MedEvac, aboard the helicopters [71]. During the Iraq war, the UH-60 helicopter (also known as Black Hawk, for the homonymous movie) was largely deployed for medical evacuations of US wounded soldiers. It is said that NATO scientists and engineers are currently working to Unmanned Aerial Vehicles (UAVs) capable of evacuations [6]. The lessons learned from military operations in Korea and Vietnam and the emergence of rapid defibrillation as optimal treatment of ventricular fibrillation arrest have fuelled the development of Emergency Medical Service (EMS) systems that can rapidly respond to critically injured patients to provide initial stabilization and rapid transport to a designated receiving facility. In this direction, the first civilian use of air ambulance was recorded in Canada (Saskatchewan Air Ambulance). In a matter of two decades, all industrialized countries had their own air ambulance service. In the US, the first helicopter medical service was funded by J.W. Schaefer, in 1947 (it was also certified by FAA). However, they represented more a medicine courier than a real emergency medical service. Nowadays HEMS service represents the excellence in medical rescue, thanks to ultimate-generation helicopters, equipped with hundreds of thousands of euros of medical machineries and the medical staff is highly-specialized and highly-trained; all of these aspects make EMS helicopters a real mobile operating room, capable to intervene in every region, all day long thanks to new night-vision goggles (NVG) which take advantage of the light intensification.

1.1.1 Focus on Lombardy region HEMS history

In Lombardy region, the first helicopter rescue was recorded in Sondrio province, in 1986; it was an experimental service with a two-months duration acting on oriental Lombardy (Brescia, Mantua and, Cremona provinces), with was active from 7am to 8.30pm among Desenzano city hospital. This service was managed by the Provincial Administration until 1995; after that, it was taken over by Lombardy Region. Other cities equipped with air ambulance service were Milan, Como, Brescia, and Bergamo. In Milan, there was an Agusta (now Leonardo Helicopters) A109, without a hoist, independently managed; in 2001 the A109 was substituted by a Bell-AgustaWestland AB412 since its Maximum Take-Off Weight (MTOW) was almost the double with respect with the former. In Como, in the first instance, an Agusta A109 was deployed (1986), followed by a Bell AB212 for the same reason but it was not equipped with a hoist; in 1988 a Bell AB412 with hoist took into service. In Bergamo, HEMS service introduction goes back to early 2000s with a last-generation helicopter, the EuroCopter EC-145, now Airbus Helicopters H145 which can count on up-to-date technology and the smaller rotor blades, which can guarantee versatility in mountainous area operations. Nowadays, Bergamo and Brescia can count on two H145, meanwhile cities of Como, Milan, and Sondrio on three AW139. At the beginning of the year 2018, Milan base started an experiment with the new generation Leonardo Helicopters AW169, beside the AW139; the experiment has been shut down few months later. All the five bases are HEMS and SAR (Search And Rescue) operational. Nowadays, night activities are authorized for Como and Brescia HEMS bases, only [47].

1.2 HEMS: why and how?

1.2.1 Air vs. Ground

Minutes not only make the difference between life and death, but they also can determine if a trauma patient will have to spend no time, some time or years in recovery and rehabilitation. Therefore, transportation of the trauma patient to the nearest trauma centre should occur as quickly and efficiently as possible. Since helicopters are faster than ground ambulances and they should not respect traffic lights, they seem to be the optimal solution in all cases. But it is not. An extreme example could be the following: if the location of the injured is one mile off the nearest hospital, it is more convenient to use ground ambulance instead of activating the nearest HEMS base, whose helicopter could take several tenths of minutes before arriving. There is, therefore, a line beyond which the helicopter EMS results to be more convenient with respect to ground ambulances. This fictitious line can be mathematically evaluated by mean of a Linear Integer Problem. Variable taken into account are several, including ground travel time, air travel time (which depends on the helicopter considered), extrication time, distance to the landing zone and lift-off time. Also, possible rendezvous with an ambulance must be taken into account [36] [48] [17]. Results show that helicopter interventions are not justified if the flight does not significantly reduce the interval between injury and patient arrival at an appropriate hospital unless the flight delivers needed medical expertise. Other researches use empirical limits of ground level time of 20 to 30 minutes [36] but it may result in a rough modelling of reality. Of course, it depends on multiple variables which cannot be taken into considerations in a general way: morphology of terrain, tortuous roads, wind. In the study presented by Smith et al.[36], the fictitious line has been placed 66km away the hospital using as helicopter an Aerospatiale Dauphin 365N2.

1.2.2 Costs and Benefits

In an era where healthcare cost savings have a high priority for governments, expensive treatment modalities and health services are monitored carefully. In the United States, a cost-effectiveness study on HEMS vs. ground emergency medical services has been performed for trauma scene transport. Trauma is the leading cause of death for US residents aged 1 to 44 years, it is the most common cause of years of life lost for those younger than 65 years and exacts $406 billion per year in costs, more than heart disease or cancer [12] [37]. In 2010, there were more than 69,700 helicopter transport for trauma to US Level I and II trauma centres. According to the Medicare Fee Schedule, insurance companies reimburse $5,000 to $6,000 per transport more than ground ambulance, which means $200 to $240 million more was spent. The analysis led to the following results: helicopter EMS needs to provide at least a 15% reduction in mortality to be below the threshold of $100,000 per quality-adjusted life-year (QALY) gained. The acceptance of cost per QALY is, however, not an absolute figure. Policy-makers and healthcare economists have proposed that costs varying from €25,000 up to €75,000 per QALY may be considered acceptable [79],[21],[72].

Helicopter EMS would need to reduce mortality by an even larger amount, 30% or save more than 3.3 lives per 100 transports to cost less than $50,000 per quality-adjusted life-year gained. In the region with the lowest overtriage rate (9%), only 11% reduction in mortality would be needed for helicopter EMS to cost less than $100,000 per quality-adjusted life-year. Conversely, in the region with the highest overtriage rate (69%), the threshold is much higher, with a needed mortality reduction of 26%. The cost-effectiveness of helicopter transport decreases as the marginal cost of helicopter transport over ground transport increases from the base-case assumption of $5,700 (see Figure 4.2). However, even if helicopter transport costs $10,000 more per transport than ground transport, as it might in rural areas with low flight volume, it would cost less than $100,000 per quality-adjusted life-year if mortality reductions of more than 25% could be achieved [22].

The use of costs per QALY as an outcome measure is important and allows comparison of the efficiency of different types of healthcare service with one another. It also may support decisions to restrict investment to services with costs per QALY below a predefined acceptance threshold [61]. In Netherlands, a similar study has been performed on the assistance of trauma patients. Depending on conditions, HEMS may be staffed by physicians, flight nurses or paramedics. As these professionals have different levels of certification, they provide different therapeutic

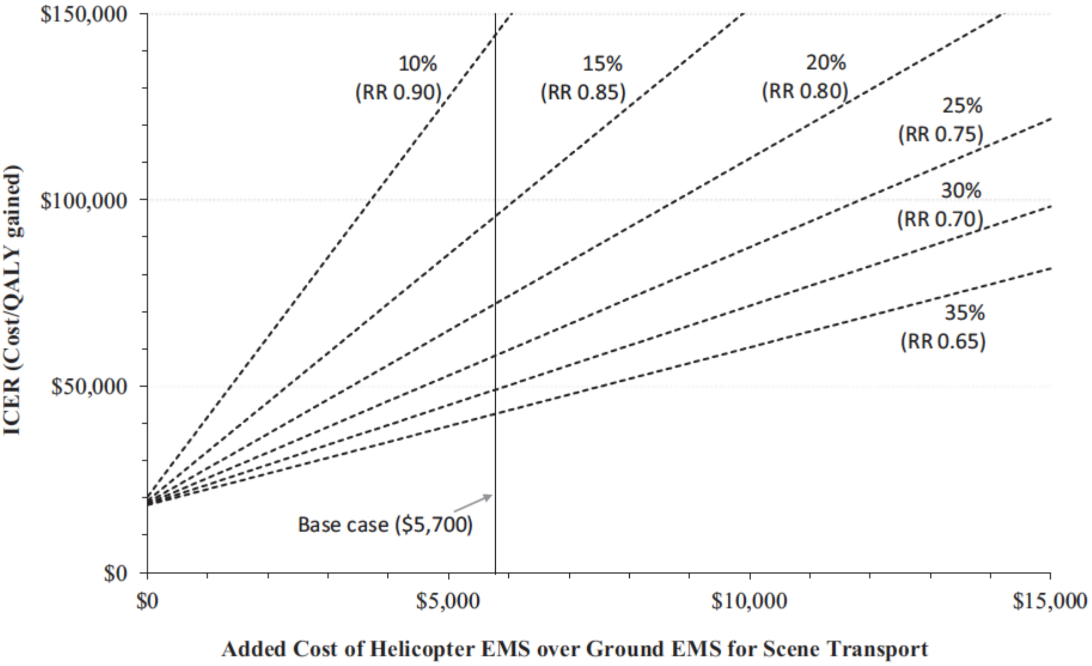
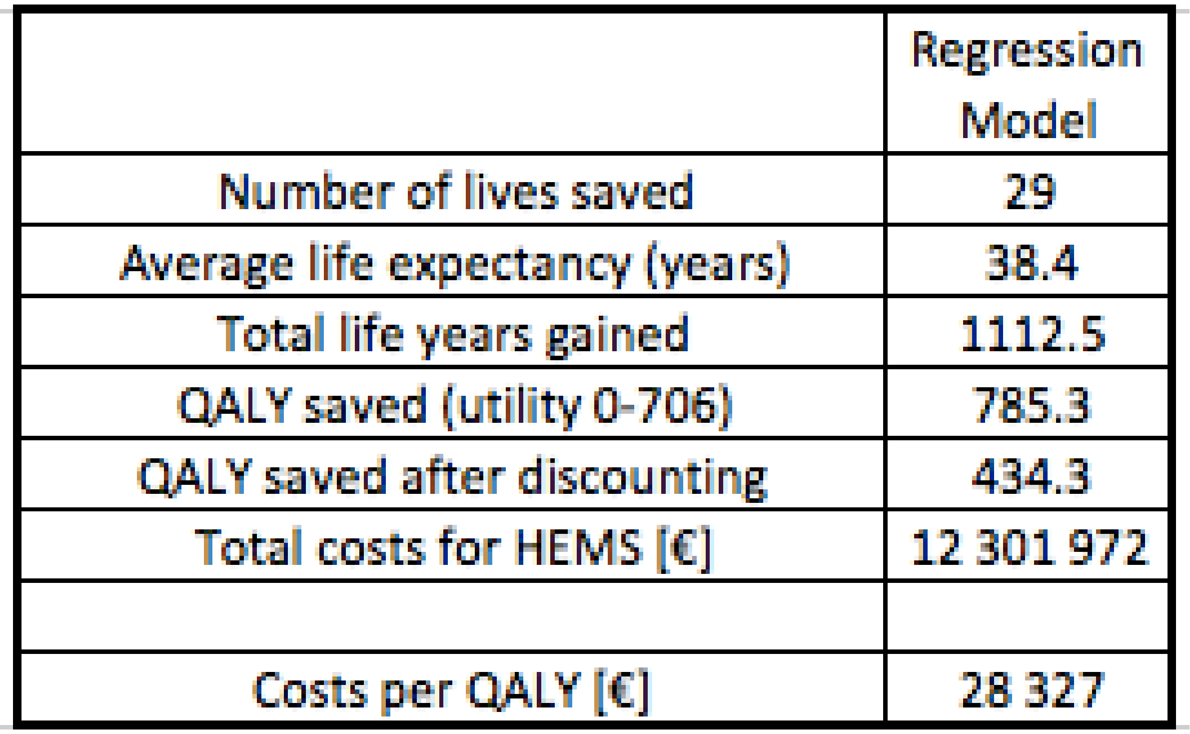


Figure 1.2: Effect of the variation in the added cost of helicopter EMS on the threshold mortality reduction needed to be cost-effective.

options to patients at the accident site. The utilization of HEMS may also differ as a result of topographical and infrastructural diversity costs per QALY for HEMS of between €7,300 and €37,700 [68], [32]. The use of costs per QALY as an outcome measure is important and allows comparison of the efficiency of different types of healthcare service with one another. It also may support decisions to restrict investment to services with costs per QALY below a predefined acceptance threshold. The survival analyses showed that over the study period, HEMS assistance saved a total of 29 additional lives. The mean medical treatment costs for HEMS-assisted patients were €39,200. The main costs relate to the length of hospital admission (€10,300) and intensive care stay (€16,100). The mean costs for an ambulance-assisted patient were significantly lower at €34,500. This difference was due mainly to costs for intensive care and diagnostic modalities, resulting in incremental costs for medical care of €4,700 per HEMS-assisted patient. The costs for the 4 years of HEMS assistance totaled €11,314,972 (€5,574,878 for personnel and €5,740,094 for material costs). The total incremental cost of medical care was €987,000 (€4,700 for each of the 210 surviving HEMS patients over 4 years). The total cost for HEMS assistance was calculated as €12,301,972 (actual HEMS cost of €11,314,972 plus the total incremental cost of €987,000). Based on these calculations, when using the recommended discount rate of 1.5 per cent, the costs for HEMS were €28,327 per QALY (see Figure 1.1). In a sensitivity analysis performed to test the effect of using different discount rates, the costs per QALY for HEMS when using a discount rate of 0.0 or 3.5 per cent were €16,000 and €2,000 respectively.



	Regression Model
Number of lives saved	29
Average life expectancy (years)	38.4
Total life years gained	1112.5
QALY saved (utility 0-706)	785.3
QALY saved after discounting	434.3
Total costs for HEMS [€]	12 301 972
Costs per QALY [€]	28 327

Table 1.1: Characteristics of patients assisted by helicopter emergency medical services or emergency medical services

1.3 HEMS Organization

1.3.1 Emergency Operation Centre

1.3.1.1 Unique Management Centre

Centralizing HEMS organization over a region or a territory would mean to best-manage all resources in terms of efficiency, helicopters and personnel; it means there is one management center, a “big brain” which manage all bases of competence, by ensuring continuous territorial coverage, the best choice of helicopter type and medical staff and granting – in such a way – to minimize costs and to avoid wasting public money. The centre would provide a multipurpose operative, i.e. rational utilization of available infrastructure and technical resources of land, water, and air traffic. The plan to buy, i.e. purchase adequate helicopters has to be made in detail, analysing the needs of the system and economic efficiency of the entire investment. As part of the main coordination centre, the communication and information centre is also organized with a single phone number for the needs of all types of interventions. The main coordination centre manages further coordination of intervention tasks, depending on the location and type of accident, the task is assigned to local coordination centres. Regarding organization, the system has to be unique, efficient, with fast and reliable communication channels and decision-making system. The organization of the system would be such that the call for the helicopter would be sent by the medical staff, ambulance at the accident site or hospital depending on their location, directly to the relevant operative centre for the respective area thus shortening the procedure and the time for reaction. HEMS is usually organized in such a manner that the state territory is covered by a distribution of helicopter bases which cover the entire state, so that the operation radius allows the arrival of helicopters to the accident site within 20 to 30 minutes, and the transport of the injured to the hospital within one hour; the efficiency of emergency operations can be increased by overlapping of the operative areas, thus increasing the effective operative coverage of the area, i.e. reducing the time necessary for intervention. [75].

1.3.1.2 Non-Clinical vs Paramedic Dispatchers

As HEMS is a scarce resource, it is important that they are only tasked to missions with a high likelihood of requiring advanced clinical intervention, beyond the scope of standard land ambulance crews. This also has important consequences for the accurate triage of major trauma patients [15]. In order to make optimum use of a scarce and costly clinical resource, the criteria for dispatching HEMS to trauma scenes should have a high sensitivity and specificity [78] in order to reduce over-triage which may result in high costs and increased risk to crew safety, and under-triage which may result in patients not receiving the assistance of a specialist HEMS team when needed. A common HEMS dispatch model is to have a dedicated person situated within an ambulance service Emergency Operation Centre (EOC) to screen incoming emergency calls and assess them for suitability of requiring a HEMS response. This model is currently used across many UK and international HEMS services [78]. A “HEMS desk” is staffed by a HEMS-trained paramedic who screens incoming emergency calls from the ambulance service Computer-Aided Dispatch system (CAD). An analysis on southern regions of United Kingdom showed that Kent, Surrey and Sussex Air Ambulance Trust (KSSAAT) used HEMS Paramedic Dispatchers (HPD) working on a dedicated dispatch desk in the EOC of the local ambulance service to activate the helicopter and its crew [67]. Since January 2016, due to the scarce availability of HEMS paramedics, it was no longer possible to fully cover the HEMS dispatch desk with a designated HEMS paramedics. Other means of specialist dispatch were therefore explored and the trust began training non-clinically trained dispatchers (NCDs) to work on the HEMS dispatch desk. All NCDs came from an ambulance dispatch background, with all candidates having extensive experience of working an ambulance control room. The NCDs were aided by a bespoke tasking algorithm; this algorithm classifies HEMS dispatch into Grade 1 and Grade 2 dispatches for HEMS, based on mechanism of injury, clinical condition of the patient and geographical location. Whilst listening to the incoming emergency call, dispatchers aim to rapidly identify either one (from Grade 1 criteria list) or two (from Grade 2 criteria list). If these are positively identified, HEMS is dispatched. NCDs receive feedback on individual missions, attending Clinical Governance Days (CGD) and receiving on-going training. A retrospective analysis of collected data from two 12-month periods was performed (period one consisted of data where clinically trained HPDs were responsible for dispatching the HEMS crew, period two was collected from when NCD was responsible) [67]. Results of the study are that the introduction of non-clinical dispatch was associated with a higher proportion of Category 1 dispatches, a lower proportion of Category 2 dispatches and a rise in the number of land ambulance crews requesting HEMS. The results of this study suggest that non-clinically trained dispatchers, assisted by a bespoke HEMS tasking algorithm and fully integrated into a HEMS service, are more effective at accurately dispatching a HEMS team, as a HEMS-trained paramedic; moreover, these results suggest that it may be possible to recruit and train dispatchers, with no prior clinical experience or training, to accurately dispatch HEMS to incidents where HEMS-specific interventions are required. In Kent, Surrey and, Sussex (KSS), there is a performance indicator aiming to keep over triage < 15% and under triage < 5% [67]. This can represent a guideline to optimize Lombardy HEMS dispatch system, since average registered over-triage is about 40%.

1.3.2 Dispatch Criteria

There are many dispatch criteria in HEMS organization within Europe; therefore, the overlap of different criteria may be possible. A study from Wingman et al. [78] highlights different criteria used and compare them in order to reduce overlaps at their minimum. Worldwide HEMS are dispatched for providing on-scene care to severely injured trauma patients based upon a set of dispatch criteria. These criteria should have high specificity and sensitivity in order to adequately identify the trauma patients that would benefit from HEMS assistance. Criteria that fail to identify patients who would benefit from HEMS assistance will lead to either overtriage and subsequently higher costs, or undertriage, which will deprive severely injured patients from getting urgently needed treatment that may potentially be life saving. In 44 of all organisations (Italy comprised) studied by [78] the Central Dispatch Centre (CDC) was primarily responsible for HEMS dispatch. In four of these CDCs, a physician is responsible for the activation of HEMS. In the UK four organisations have a special HEMS desk or a HEMS paramedic that actively screens all emergency calls for the purpose of identifying calls that might meet HEMS dispatch criteria [78],[50]. In Acute Care Region East from the Netherlands, Christoph Hradec Kralov from the Czech Republic, and HEMS Slovenia from Slovenia HEMS are being dispatched by a ground ambulance paramedic or other first responding emergency-care provider. In Alfa Helicopter, Slovakia, and Bomberos de Asturias, Spain, physicians working for the HEMS organisation is responsible for dispatching HEMS via radio communication. In EMI from Portugal and Norwegian Air Ambulance Bergen medical personnel on board of HEMS helicopter are used as dispatchers [78].

1.3.2.1 Trauma-Related Dispatch Criteria

Helicopter Emergency Medical Services (HEMS) dispatch criteria have been identified by a systematic review of the literature by [60]. A total of 50 criteria have been chosen and then divided into four main criteria and can be visible in Appendix B.

In Italy, from a questionnaire study conducted by [78], items *Amputation or near-amputation in case of emergent evaluation for reimplantation* (Patient Characteristics — Anatomy), *Age <5 or >55 years, Known cardiac or respiratory disease / cardiovascular instability, Known pregnancy, Low or high respiratory rate, risk of airway obstruction, or other signs of respiratory distress, Low systolic blood pressure, tachycardia, or pulse character* (in Patient characteristics - physiologic parameters) and *Heavy traffic conditions* (in Others) are not used as dispatch criteria. Some organisations provided additional criteria: for instance, The OAMTC (Austria) uses *Carbon monoxide intoxication with signs of compromised vital signs, suffocation with respiratory compromise, plane crash* and *fall into glacier split and caught on safety lines after a fall*. The Acute Care Region East (Netherlands) also uses additional criteria: *Train accidents, run over by a vehicle* and *paraplegia*. In Slovakia *natural disaster, transport of premature babies* and *perinatal with congenital defects of the heart* are also additional criteria for dispatching the HEMS [78].

1.3.3 Autolaunch and Early Activation

An accident occurs on a dark country road. The emergency center is notified and heads for the accident. The ambulance (Basic Life Support or BLS) also is dispatched. On the way, they get more details of the accident and decide they will need Advanced Life Support (ALS) ambulance. The BLS providers ask the center dispatcher to contact the ALS ambulance dispatch center and request an ALS ambulance for the accident. As the ALS ambulance is en-route and more details of the accident and injuries become available, the paramedics decide that a rapid form of transport or more advanced care may be needed. They notify the dispatch center that the helicopter is needed; the helicopter is dispatched. Precious minutes have passed. A better way for this system to work is to dispatch the helicopter, if certain criteria are met, such as mechanism and severity of injuries— when the ALS ambulance is called. This method of dispatch is called an autolaunch. It also has been well documented that dispatching helicopter crews rapidly to the scene of an accident reduces transport times to the trauma center, decreasing mortality and increasing the chance for survival [8]. Association of Air Medical Services (AAMS) defines "Early Activation" as departing for the requested scene prior to arrival of the first responders, based on a high index of suspicion that specialty services will be necessary, while “Auto Launch” is defined as the simultaneous dispatch of air and ground resources through a 9-1-1 request for EMS based upon pre-designated trauma and/or medical criteria set up by local or regional EMS systems. This is initiated by the request of the first responders [2]. One necessary element to establish an autolaunch program is an integrated dispatch center with defined primary service areas. With this, the dispatch personnel has the ability to hear about an accident in the service area. This connection enables them to dispatch the helicopter simultaneously with the ground ambulance. On-scene personnel still have the ability to cancel the helicopter if the injuries are not severe. The study from Berns et al. [8] shows that in the autolaunch group, 41% of the patients were still being extricated from the vehicle on arrival of the helicopter, and the average extrication time was 21 minutes causing a delay in the helicopter operations. Analysis hospital data revealed the autolaunch patients had a mean hospital stay of 9.38 days and the traditional group had a mean stay of 24.63 days. The mean difference in hospital stay was 15.25 fewer days for the autolaunch group while the risk of mortality when autolaunch was used was not different than when traditional dispatch was used [8].

1.3.4 Is actually autolaunch the most effective system to activate helicopter EMS?

Coats and Newton [18] studied the dispatch system used by four organisations in the UK, where a special "HEMS desk" within a control room staffed by paramedics was created. They found a significant reduction in non-required HEMS missions. A non-required mission was defined as a mission in which HEMS was dispatched but the patient was not treated, because the medical condition of the patient did not require HEMS treatment. Activation of HEMS is not only depending on dispatch criterion protocols, but is also influenced by organisational factors like the education of the dispatcher, the training of the EMS personnel, the familiarity with the dispatch criteria, and the responses of bystanders. Currently, dispatch criteria based on the Mechanism Of Injury (MOI) and physiological parameters seem to be generally accepted as most suitable, with high specificity and intermediate sensitivity.

1.3.5 Lombardy HEMS organization: AREU

AREU (Azienda Regionale Emergenza Urgenza) is a health company born on April 2, 2008; its aim is to evolute emergency/urgency system, developing the integration of intra- and extra-hospital assistance and improving patients treatment. Its mission is to guarantee, to implement and to homogenise, among region territory, extra- hospital medical assistance, also during maxi- emergencies; it has, moreover, the task to coordinate transfusion activities between fifteen departments of Transfusional Medicine (DMTE, Dipartimento di Medicina Trasfusionale e di Ematologia) and medical staff and organs transportation. Actual organization model of AREU is far different with respect to the past: from a 12 off-line COEU (Centrali Operative Emergenza Urgenza) situation, the present situation is characterized by a central structure that consists of AREU Management and some "operational branches", the so-called AAT (Articolazioni Aziendali Territoriali) and the regional operative rooms SOREU (Sale Operative Regionali Emergenza Urgenza), strategically dislocated within regional territory; all of them are online and coordinated. From organization and operational point of view, AREU Management handle human, technological and logistical resources to deal with emergency and urgency of health authorities on

Figure 1.3: AATs distribution in Lombardy. They have a provincial area of expertise

the territory, through a functional-like relation, providing objectives, provisions, and procedures. Trasfusional activities coordination is played through a specific organization corresponding to a coordination center, the SRC (Struttura Regionale di Coordinamento). Organs and specialized surgical staff transportation is granted by metropolitan SOREU.

1.3.5.1 AATs, SOREUs and Macroareas

Having AREU implemented a new organizational model, its own inner structure has been changed; nowadays it comprises of:

1. AAT: 12. They have a quasi- provincial catchment area and have to manage emergency vehicles location. They report to Pavia, Milan, Varese, Monza, Como, Lecco, Sondrio, Bergamo, Brescia, Lodi, Cremona, and Mantua (see Figure 1.3).

2. SOREU: 4. They have to ensure relief beyond every provincial limit, coordinating with the unique management centre located in Bergamo. They are placed in Milan (AAT of Milan

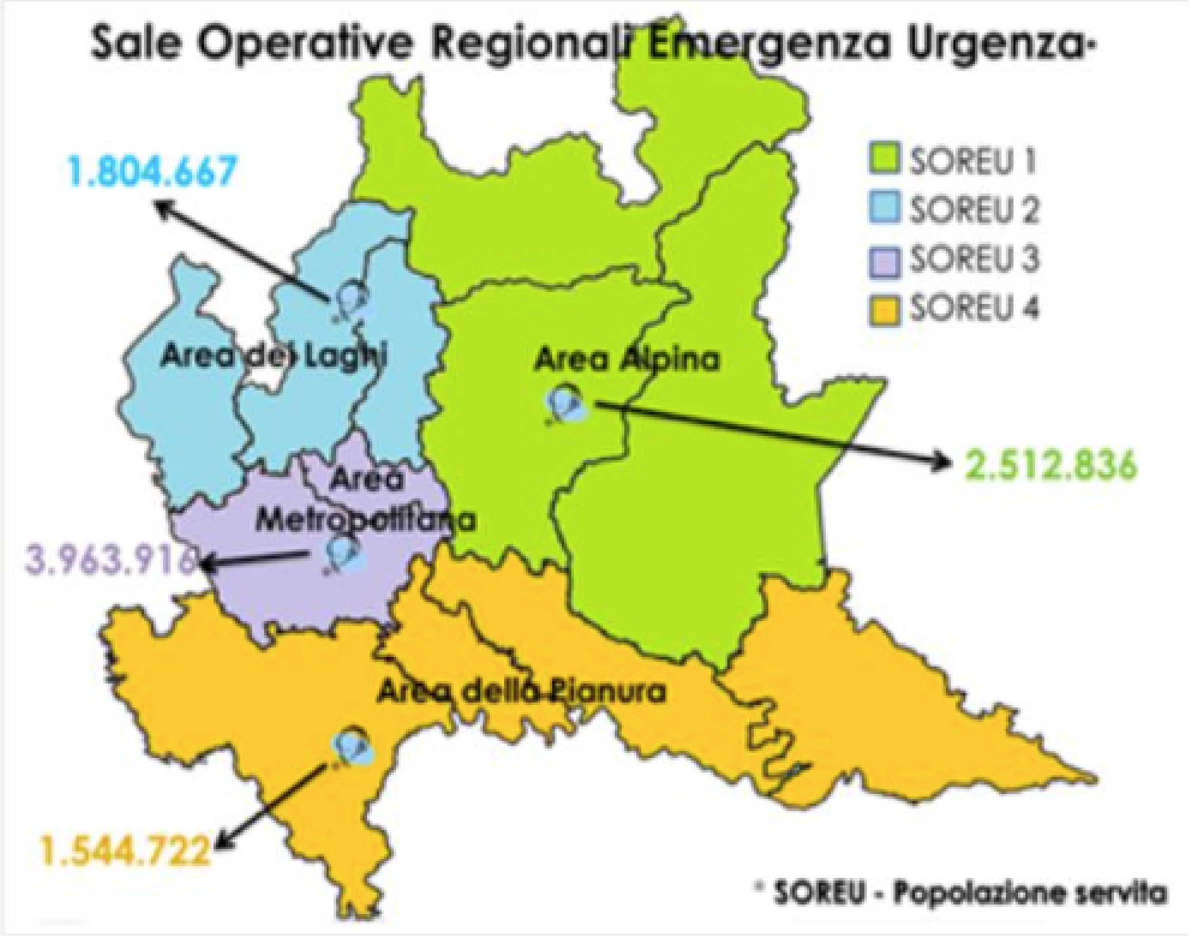


Figure 1.4: SOREU distribution in Lombardy. They have a super- provincial management

and Monza), Bergamo (AAT of Bergamo, Brescia, and Sondrio), Como (Como, Lecco, and Varese), Pavia (AAT of Cremona, Lodi, Mantua, and Pavia) (see figure 1.4);

3. Macroareas: 4. They have a coordination role, concerning the respective SOREU and AATs. They are: Alpine Macroarea (province of Bergamo, Brescia, and Sondrio), Metropolitan Macroarea (province of Milan and Monza), Lake Macroarea (Como, Lecco, and Varese) and Plane Macroarea (Pavia, Cremona, Lodi, and Mantua) (see Figure 1.5);

4. Management centre: 1. General Directorate of financial, health and operational branches.

AREU can count also on institutions, voluntary associations and social cooperatives each of which makes available voluntary staff, vehicles, and equipment. Nowadays, volunteers are about 30,000 [81].

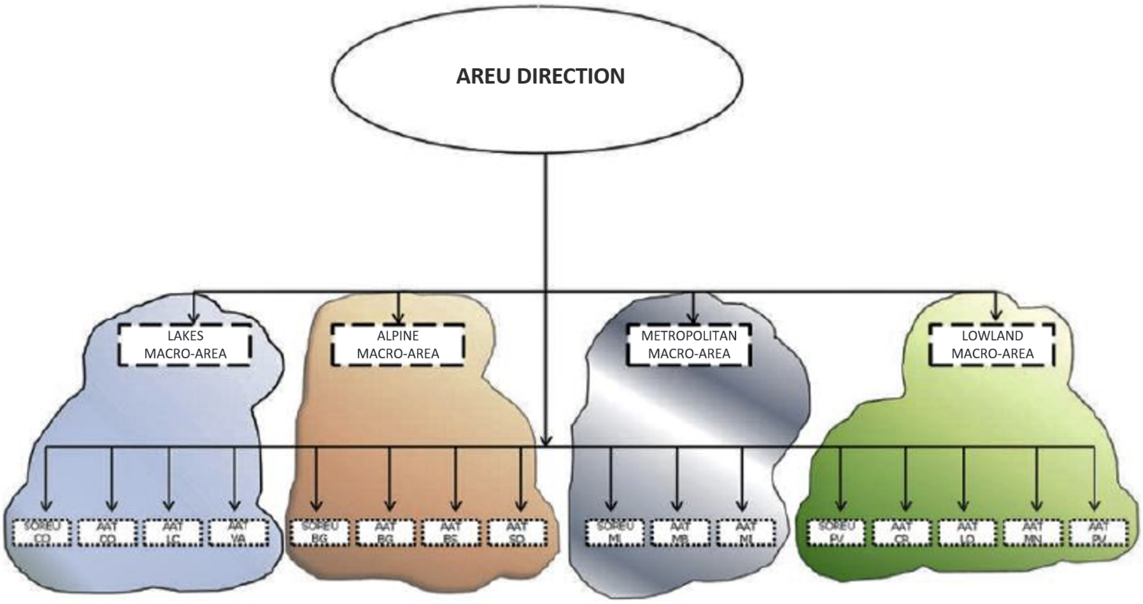
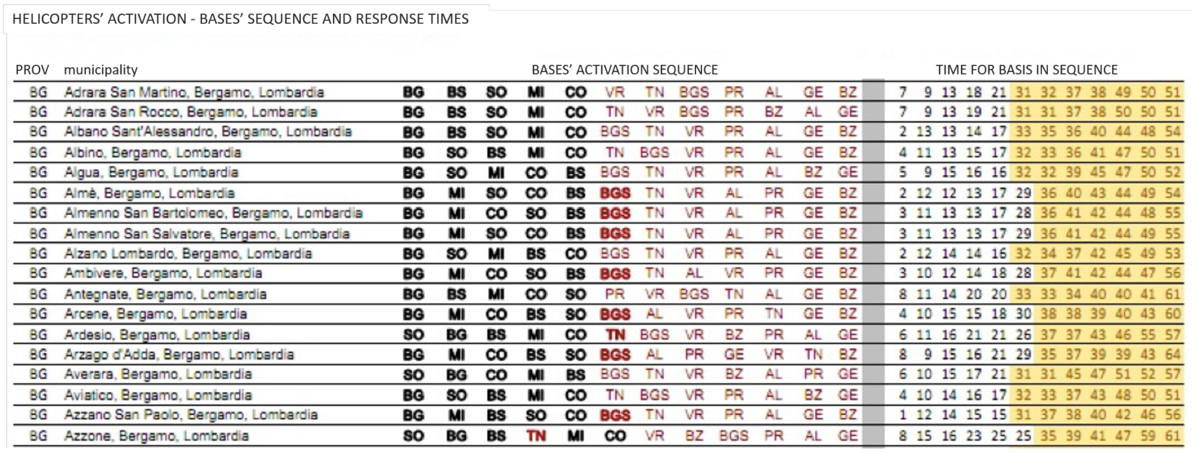


Figure 1.5: Macroarea division and relatives AATs and SOREUs


HELICOPTERS' ACTIVATION - BASES' SEQUENCE AND RESPONSE TIMES

PROV	municipality	BASES' ACTIVATION SEQUENCE												TIME FOR BASIS IN SEQUENCE											
BG	Adrara San Martino, Bergamo, Lombardia	BG	BS	SO	MI	CO	VR	TN	BGS	PR	AL	GE	BZ	7	9	13	18	21	31	32	37	38	49	50	51
BG	Adrara San Rocco, Bergamo, Lombardia	BG	BS	SO	MI	CO	TN	VR	BGS	PR	BZ	AL	GE	7	9	13	19	21	31	31	37	38	50	50	51
BG	Albano Sant'Alessandro, Bergamo, Lombardia	BG	BS	SO	MI	CO	BGS	TN	VR	PR	AL	GE	BZ	2	13	13	14	17	33	35	36	40	44	48	54
BG	Albino, Bergamo, Lombardia	BG	SO	BS	MI	CO	TN	BGS	VR	PR	AL	GE	BZ	4	11	13	15	17	32	33	36	41	47	50	51
BG	Algua, Bergamo, Lombardia	BG	SO	MI	CO	BS	BGS	TN	VR	PR	AL	BZ	GE	5	9	15	16	16	32	32	39	45	47	50	52
BG	Almè, Bergamo, Lombardia	BG	MI	SO	CO	BS	BGS	TN	VR	AL	PR	GE	BZ	2	12	12	13	17	29	36	40	43	44	49	54
BG	Almenno San Bartolomeo, Bergamo, Lombardia	BG	MI	CO	SO	BS	BGS	TN	VR	AL	PR	GE	BZ	3	11	13	13	17	28	36	41	42	44	48	55
BG	Almenno San Salvatore, Bergamo, Lombardia	BG	MI	SO	CO	BS	BGS	TN	VR	AL	PR	GE	BZ	3	11	13	13	17	29	36	41	42	44	49	55
BG	Alzano Lombardo, Bergamo, Lombardia	BG	SO	MI	BS	CO	BGS	TN	VR	PR	AL	GE	BZ	2	12	14	14	16	32	34	37	42	45	49	53
BG	Ambivere, Bergamo, Lombardia	BG	MI	CO	SO	BS	BGS	TN	AL	VR	PR	GE	BZ	3	10	12	14	18	28	37	41	42	44	47	56
BG	Antegnate, Bergamo, Lombardia	BG	BS	MI	CO	SO	PR	VR	BGS	TN	AL	GE	BZ	8	11	14	20	20	33	33	34	40	40	41	61
BG	Arcene, Bergamo, Lombardia	BG	MI	CO	BS	SO	BGS	AL	VR	PR	TN	GE	BZ	4	10	15	15	18	30	38	38	39	40	43	60
BG	Ardesio, Bergamo, Lombardia	SO	BG	BS	MI	CO	TN	BGS	VR	BZ	PR	AL	GE	6	11	16	21	21	26	37	37	43	46	55	57
BG	Arzago d'Adda, Bergamo, Lombardia	BG	MI	CO	BS	SO	BGS	AL	PR	GE	VR	TN	BZ	8	9	15	16	21	29	35	37	39	39	43	64
BG	Averara, Bergamo, Lombardia	SO	BG	CO	MI	BS	BGS	TN	VR	BZ	AL	PR	GE	6	10	15	17	21	31	31	45	47	51	52	57
BG	Aviatico, Bergamo, Lombardia	BG	SO	BS	MI	CO	TN	BGS	VR	PR	AL	BZ	GE	4	10	14	16	17	32	33	37	43	48	50	51
BG	Azzano San Paolo, Bergamo, Lombardia	BG	MI	BS	SO	CO	BGS	TN	VR	PR	AL	GE	BZ	1	12	14	15	15	31	37	38	40	42	46	56
BG	Azzone, Bergamo, Lombardia	SO	BG	BS	TN	MI	CO	VR	BZ	BGS	PR	AL	GE	8	15	16	23	25	25	35	39	41	47	59	61

Table 1.2: Activation times for different helicopters in order of competitiveness

1.3.5.2 Lombardy HEMS

Presently there are 5 helicopters located in Sondrio, Como, Bergamo, Brescia e Milano. The helicopters are coordinated by a unique operative central desk, placed in Bergamo, by the Centrale Regionale delle attività di ELIsoccorso (CRELI) which select, time after time, the most competitive helicopter to be used for the specific mission (see figure 1.2 for an example).

The five helicopters adequately cover the whole regional land both during the day and during the night (Como and Brescia). Once, night flights were allowed only on specific well-defined zones (generally, sport fields); nowadays, thanks to NVG (Night Vision Goggles), the pilot can choose an area wherever he considers to be the closest to the incident and the safest, with no obstacles present (trees, high-voltage lines,...). In the future, Performance-Based Navigation (PBN) routes will allow conducting instrumentally a helicopter from an incident location to a specific hospital, even in low-visibility weather conditions. Bergamo and Brescia adopted an H145 helicopter, while Milan, Como, and Sondrio use an AW139; for more info, see Appendix A. The usual HEMS equipe is constituted by pilot and winchman (they have the task to decide whether or not the mission can be carried out) and health personnel (physician and nurses). There is also rescue mountain personnel or other personnel who can be employed in a specific environment (mountain, under water or other settings). The helicopter transportation is indicated when more competitive as compared to the ambulance:

1. whenever the rescue and transportation from an area that can not be easily reached;
2. whenever the advanced medical car can intervene with longer times as compared to the helicopter;
3. whenever a very limited traumatic assisted transportation is required (such as with spinal cord injuries).

It may concern critically injured patients with life threatening situations whose transportation is time-dependent or the site of the event is very far or patients for whom an ambulance transport may be crucial. There can be interventions out the Region whenever there are diagnostic, therapeutic specialty necessities which cannot be performed within the regional land. There can be interventions out the Region whenever there are therapeutical special necessities which cannot be performed within the regional land. Preparation and assistance of neonatal patients or pregnant women by the helicopter is usually performed with the aid of the specialists, either neonatologist or gynaecologist. The HEMS can be used also for Civil Defence necessities whilst other tasks can be performed when requested by Institutional Organizations (Prefecture, Major, Provincial Government, Regional Civil Defence) [58].

1.4 Intervention Times

1.4.1 On-Scene Time, Dispatch Time, Golden Hour and Platinum 10 minutes

Trauma is time-sensitive: a single minute may mean the difference between life and death of the patient, between a short or long delay rehabilitation, which may vary from weeks to decades up to the entire patient life. One of the fundamental tenets of trauma-care is the so-called "Golden Hour" (GH). This term is used to emphasize the fact that patients receiving advanced care in the first sixty minutes after the incident have a better outcome and a short delay rehabilitation. It represents the first peak in trauma mortality and morbidity in which majority of trauma deaths occur within the first hour after the accident. The vernacular *GH* is widely attributed to R. Adams Cowley, founder of Baltimore's Shock Trauma Institute, who in a 1975 article stated: "[...] The first hour after injury will largely determine a critically injured person's chances for survival" [20]. The actual emergency system is based upon this medical tenet; in the decades following the introduction of the concept of the golden hour, a billion-dollar industry of trauma systems, trauma centres, aeromedical rescue, and advanced pre-hospital life support has emerged [23]. Numerous research projects have been conducted with the intention of finding better ways to deliver patients to trauma centres within the *GH*, although no scientific evidence truly supports this theory [44]. Some studies actually demonstrate its validity: the study treated from Sampalis et al. [65] shows that more than sixty minutes prehospital time is associated with higher mortality; six years later the same group demonstrated the same in another research [64]. Additionally, reduced prehospital time has been found to be beneficial in specific patient populations, including rural trauma patients with long EMS transport times [27]. Figure 1.6 shows effectively the trend of mortality with respect to on-scene time, defined as the total time for the emergency provider takes to leave with the patient onboard once it arrives at the scene of injury: the higher the amount of time spent *in-situ*, the higher the mortality.

Despite the above-mentioned studies, others show that the *GH* is not a representative method to rely on. Studies in this direction are several, including one of the most comprehensive investigations of time to definitive care in trauma. A 2010 prospective cohort study by Newgard et al. [16] of 146 EMS agencies transporting patients to 51 trauma centres in North America, identified no relationship between EMS intervals and inhospital mortality among injured patients with physiologic abnormality. A 2012 German study by Kleber et al. [38] found similar results. Other studies have been conducted also in Canada [69], in United States [43]) and in Italy [5]. The issue the *GH* presents is to be respected for incidents in rural areas, as transportation time to a larger hospital for rural patients can greatly surpass the hour. So, what to do if demand location is further than one-hour travel time, even with faster transport, as a helicopter? Different studies asked if prehospital interventions have to be considered as wasted-time or saved-time. As already mentioned, EMS helicopters are able to offer the highest quality staff and equipment available; therefore, can physicians try to stabilize the patient both on-scene and when airborne? Or have they to hurry up to the hospital? The study from [74] shows that, although preclinical actions in the primary assessment of victims of blunt trauma may prolong the time to definitive clinical care, HEMS practice more prehospital intervention with respect to EMS and, although this leads to a lower number of in-hospital intervention, no reduction in time in hospital may be expected from the interventions performed before hospital admission. Another study from [59] shows that for patients residing distant (>20 miles) from a Trauma Center, increasing distance from an airbase is associated with an increased risk of death; for each mile, the risk of mortality increases by approximately 1%. Moreover, there is no additional benefit to living close (<25 miles) to more

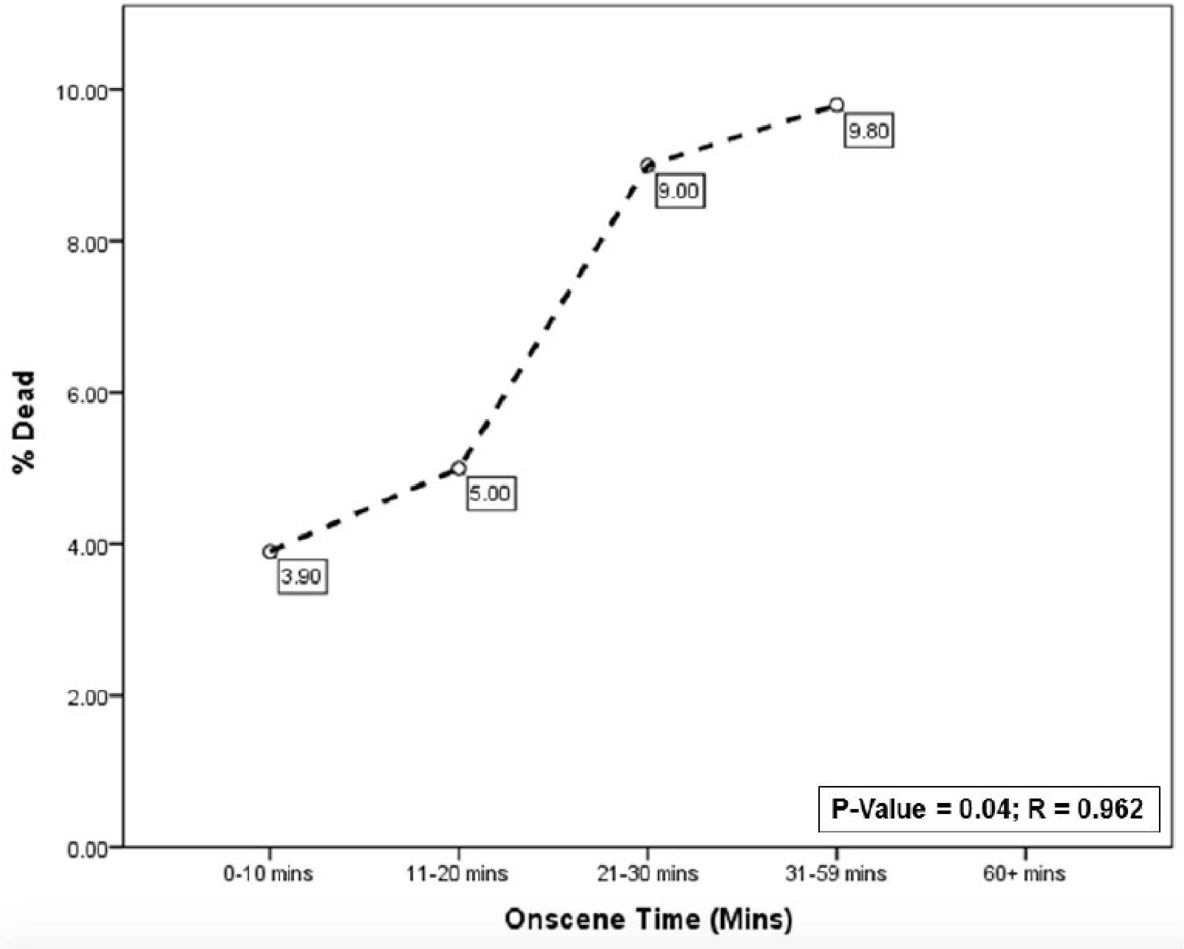
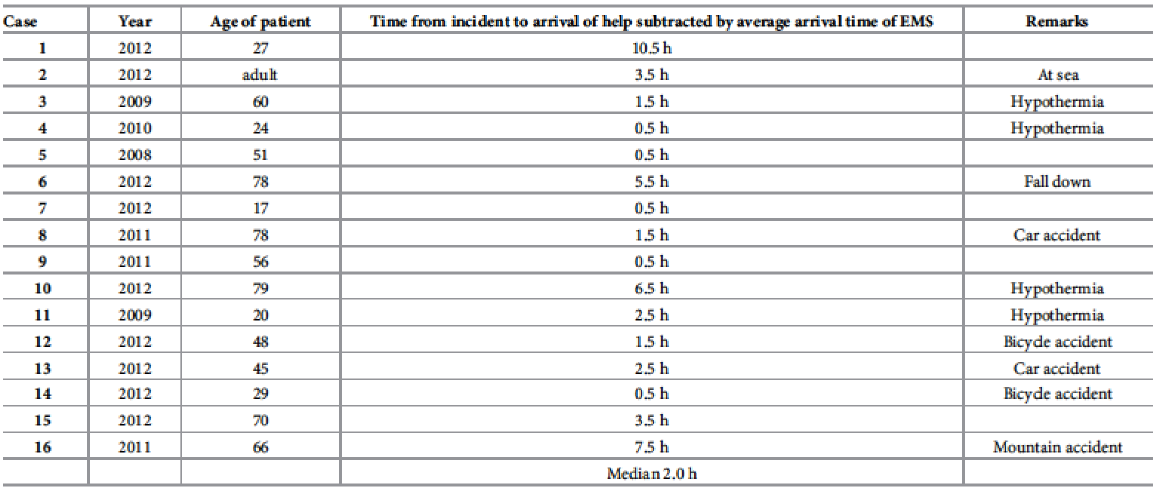


Figure 1.6: Trauma patient mortality correlation with on-scene time

than 1 airbase. Rogers et al. mentioned firstly, about the "Platinum 10 minutes". "Like the golden hour, the platinum 10 minutes places a time constraint on the pre-hospital care of seriously injured patients, stating no patient should have more than 10 min of scene-time stabilization by emergency medical personnel prior to being transported to definitive care at a trauma centre" [23]. This dogma likely arose from the military, as many battlefield fatalities occur within the first minutes post-injury [73]. Dispatch time, defined as the amount of time it takes for the emergency provider to reach the patient, and on-scene time can greatly influence how quickly the patient will reach definitive care, but also imply different processes. The study from [55] shows that Injury Severity Score (ISS) is a major factor in patients outcome. Those patients with higher ISS may require longer scene times due to the need for urgent interventions such as extrication from a vehicle or more advanced life-saving on-site procedures, increasing mortality. Regardless, efforts should focus on reducing on-scene and dispatch times. Wald's criterion (non-probabilistic decision-making model in decision and game theory) demonstrates that only ISS made a signifi-



Case	Year	Age of patient	Time from incident to arrival of help subtracted by average arrival time of EMS	Remarks
1	2012	27	10.5 h	
2	2012	adult	3.5 h	At sea
3	2009	60	1.5 h	Hypothermia
4	2010	24	0.5 h	Hypothermia
5	2008	51	0.5 h	
6	2012	78	5.5 h	Fall down
7	2012	17	0.5 h	
8	2011	78	1.5 h	Car accident
9	2011	56	0.5 h	
10	2012	79	6.5 h	Hypothermia
11	2009	20	2.5 h	Hypothermia
12	2012	48	1.5 h	Bicycle accident
13	2012	45	2.5 h	Car accident
14	2012	29	0.5 h	Bicycle accident
15	2012	70	3.5 h	
16	2011	66	7.5 h	Mountain accident
			Median 2.0 h	

Table 1.3: Emergencies with failed emergency calls due to disorientation and language barriers.

cant contribution to prediction. Those with higher ISS may require longer scene times due to the need for urgent interventions such as extrication from a vehicle or more advanced life-saving on-site procedures, increasing mortality ,[11, 41, 55].

1.4.2 An Easier Geolocation using Smartphone GPS

In paper [77] a discussion about the using of smartphone geolocation for decreasing the time of arrival is discussed. All studies regarding activation of emergency response systems start their measurements when the call is received at the alarm center [51, 53]. Any time delay between the triggering event and the successful activation of the emergency response system is difficult to measure. The time necessary to make an emergency call is considered to be very short [42]. Nowadays mobile networks guarantee availability almost everywhere and provide communication in emergency situations to initiate an emergency call by the patient. The use of foreign mobile networks is possible when dialling emergency numbers, like 911 or 112, which allows access to call service without being locked into a specific mobile network. When dealing with remote or internationally travelling patients, the time to activate the emergency response system abroad becomes relevant when patients are disorientated or experiencing language barriers. As soon as the call reaches the alarm center, the dispatchers are confronted with the inability of the caller to express the appropriate location: even with excellent location knowledge of the dispatcher, it might take long to overcome the location unfamiliarity of the caller. This phenomenon of disorientation in reporting emergencies is a known problem for EMS. Figure 1.3 shows an example of what language barriers or disorientation can lead in terms of on-scene time of arrival.

Several studies reveal communication problems in emergency situations [49]. Since the introduction of smartphones, a wide range of applications have become available to support emergency

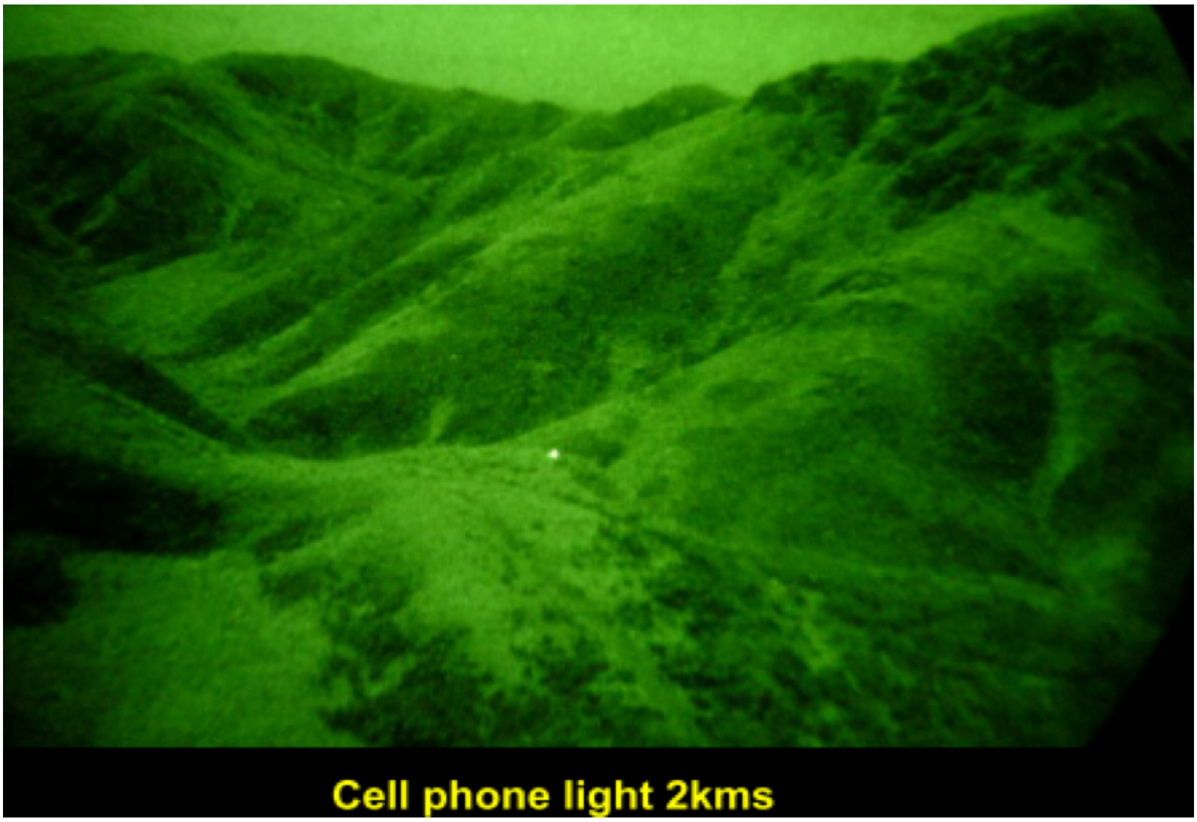


Figure 1.7: How a mobile phone torchlight appears from 2Km distance using NVG.

calls; in 1996 the "Enhanced 911 (E911)" system was started in the United States, providing coordinates of intersections to the alarm center. In Europe, the "eCall" system has been initiated to inform alarm centers about car accidents including geolocation information. A 4% reduction in mortality was calculated due to the reduction of time to inform the alarm center and provision of geolocation data. The study from Weinlich et al. demonstrated that, even if a patient is disoriented or experiences language barriers, it is possible to activate the local EMS within a short time, not exceeding one hour. Using the different tracking options, Global Positioning System (GPS), wireless LAN (Wi-Fi) and Location Based Services (LBS) of the patient, the geolocation data should quickly and reliably be forwarded via an international network to the local alarm center in the country of the patient. In eleven countries on different continents GPS accuracy was below 10 m almost everywhere, Wi-Fi had a similar range, but was not as accurate, with diversions up to 100 m. LBS divergence even exceeded 1 km with a maximum error in distance of up to 2.5Km. During the night, also light intensification Night Vision Googles (NVG) usage will lead to great benefits: NVG allows distinguishing a mobile phone torchlight from many kilometres away (see Figure 1.7). For a more specific usage of NVG, see Night Ops (1.4).

1.4.3 Mission Activation Criteria and Intervention Typology in Lombardy

Every country, every HEMS organization define their own "Mission Activation Criteria (MAC)" and "Intervention Typology (IT)", based on what everyone considers the best-management. Lombardy region MAC are discussed in the following.

1.4.3.1 Mission Activation Criteria

Utilization criteria of medical helicopters must:

1. Guarantee an efficient application of "helicopter resource" in clinical terms;
2. Optimize helicopter usage and guarantee territory coverage;
3. Guarantee safety standards.

Normally, HEMS equipe cannot refuse an intervention except for non-fulfilment of the General Regulation[40], technical issues (failures, maintenance, etc) or operational issues (meteorological, sun-light, etc). Unforeseen events which prevent destination to be reached or helicopter landing to a helipad (adverse meteorological conditions, lights-off on helipad, insufficient visibility, etc) can be the reason for the mission abort if not-solvable in real-time[40].

1.4.3.2 Intervention Typology

The underlying principle on how the decision is made is that the aviation risk should be proportionate to the task. To provide a road ambulance analogy[46]:

1. if called to an emergency: an ambulance would proceed at great speed, sounding its siren and proceeding against traffic lights - thus matching the risk of operation to the risk of a potential death;
2. for a transfer of a patient (or equipment) where life and death (or consequential injury of ground transport) is not an issue: the journey would be conducted without sirens and within normal rules of motoring - once again matching the risk to the task.

Intervention typologies, therefore, differ in the kind of mission: emergency mission, inter-hospital patient transportation or transport of organs. Not all countries adopt the same differentiation. Lombardy Region ITs are discussed in the following.

Primary Intervention Primary interventions are those who require an immediate dispatch of the helicopter due to an emergency situation (normally, red code). Transportation choice, in this case, is driven by clinical criteria, situational criteria (less-traumatic possible transportation e.g. spin injury or impervious place not reachable by wheeled-ambulance). Primary interventions can be performed in two different ways:

1. Direct transport: the helicopter, once taken-off from HEMS base, is capable to land on-scene and - after patient stabilization - take-off from it in a safe manner and, thus, to fly directly to the best hospital in accordance with patient's injury.
2. Indirect transport (or Rendez-Vous): in case the helicopter cannot land safely on-scene, ground ambulance carries the patient to the nearest already located HEMS site (such as sport fields) or to the nearest free-obstacle area. Then helicopter flies directly to the most appropriate hospital.

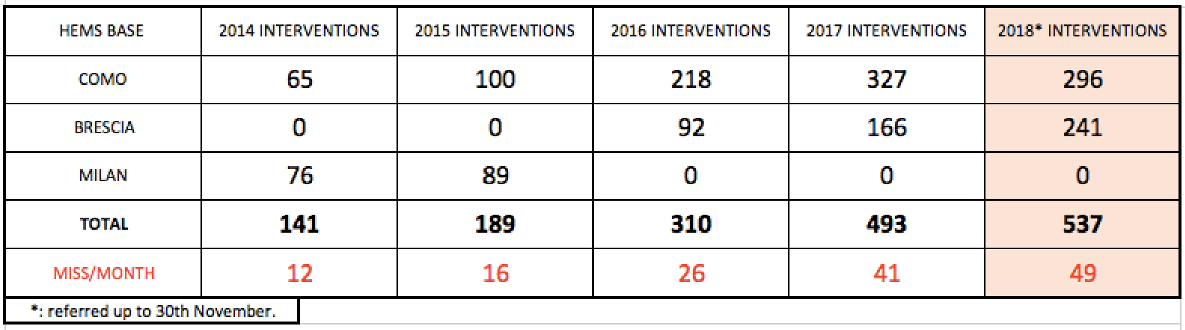
Secondary Intervention Secondary interventions involve patient inter- hospital transportations due to the fact that some analyses cannot be performed in the actual hospital and require advanced medical equipment available in a further medical centre. Helicopter transportation is preferable when patient treatments are urgent.

Tertiary Intervention Tertiary interventions consider all cases in which medical staff has to be re-assigned to another hospital or HEMS base, or the cases in which organs/blood are required urgently in a hospital, for surgery purposes or after a local disaster. Also, international organs transportations are covered by this typology of intervention.
Moreover, regional HEMS must fulfill the following missions:

1. SAR requests;
2. SAR mission during mass emergencies;
3. Rare drugs and blood deliveries in urgent emergency situations;
4. Medical and non-medical staff exercises and training activities;
5. Patrolling national territory for operational situations.

1.5 HEMS Equipe

The staff aboard the EMS helicopters are divided into two groups: the medical personnel and the navigation personnel. A third category can be considered, the Corpo Nazionale Soccorso Alpino e Speleologico (CNSAS) personnel, trained to operate in mountains and cave SAR. The former can count on a Cardio-Pulmonary Resuscitation (CPR) anaesthesiologist and on an expert nurse trained to helicopter environment which has experience on advanced rescue transportations (MSA). The physician has the health responsibility, while the nurse has to control onboard equipment efficiency, functioning restoration and mission data recording. The navigation personnel shall consist of a pilot or a pilot and a copilot. The role of the copilot is extremely controversial. His presence can reduce the work-load on the pilot, especially in bad-weather conditions or during night ops; on the other hand, for normal-weather daylight missions, copilot seems



HEMS BASE	2014 INTERVENTIONS	2015 INTERVENTIONS	2016 INTERVENTIONS	2017 INTERVENTIONS	2018* INTERVENTIONS
COMO	65	100	218	327	296
BRESCIA	0	0	92	166	241
MILAN	76	89	0	0	0
TOTAL	**141**	**189**	**310**	**493**	**537**
MISS/MONTH	12	16	26	41	49

*: referred up to 30th November.

Table 1.4: Lombardy night operations during years

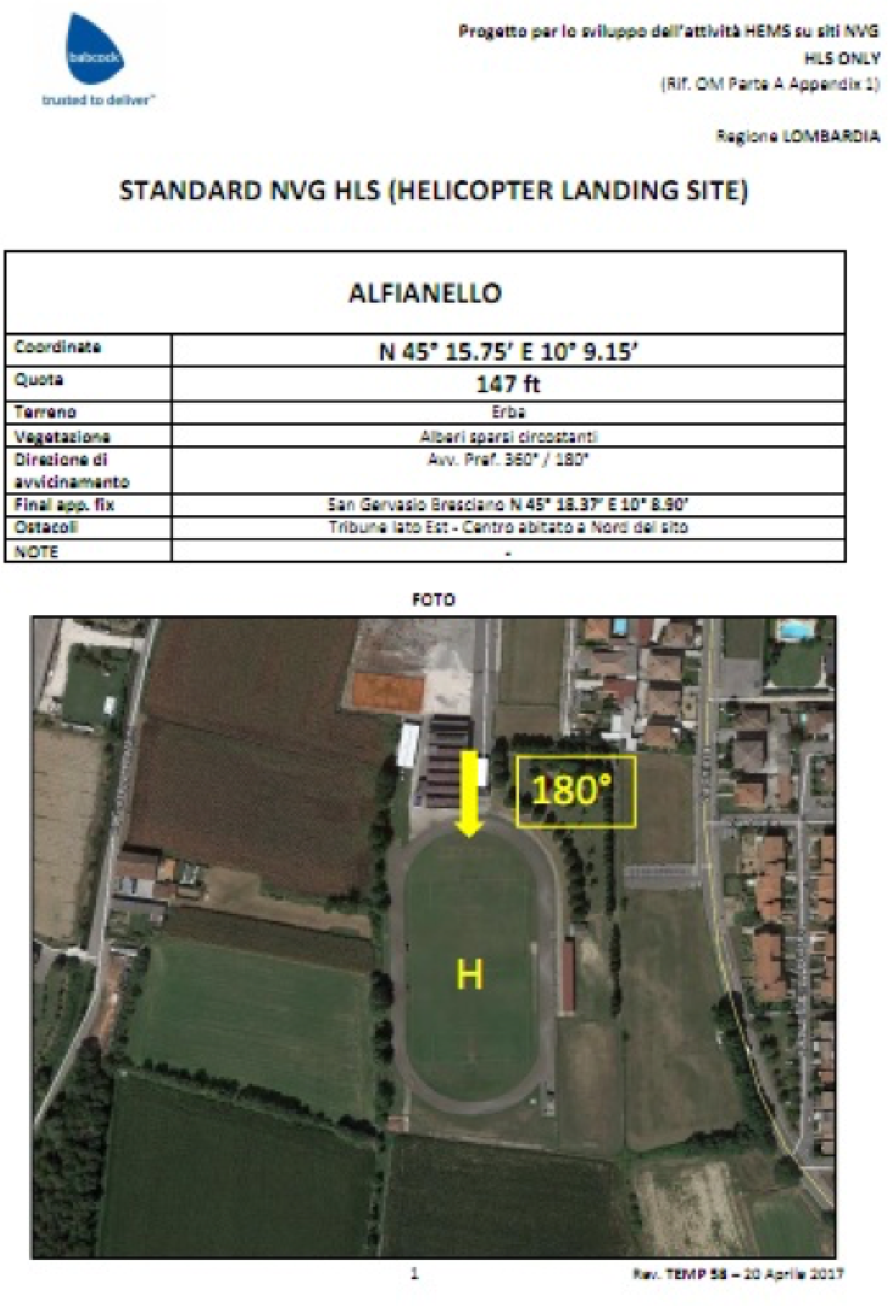
a wasted resource keeping in mind also he can greatly influence the MTOW of the helicopter and therefore its manoeuvrability and performances. Someone also proposes to give the pilots a medical train [34]; but also this argument is greatly controversial: is it wasted time that can lead to navigation errors with fatal results or an added value which can improve patients outcome, lightening nurse's workload? The third category is formed by CNSAS personnel which provides an added technician and dog squad, when necessary. Typical scenarios in which CNSAS personnel is requested are mountainous environment, both in summer and in winter [40].

1.6 Night Operations

Night operation happens from half an hour after the sunset to half an hour before the sunrise. Night ops are allowed for airports/night heliports and helipads authorized by the aeronautical legislation and for areas corresponding to European legislation EU 965/2012 [19]. Such an activity has begun in 2014 and it is still evolving. To land in sports field is now possible, as long as they are lighted and respondents to constraints of Aeronautical Authority[56]. From July 2016 in Como HEMS base (Villaguardia) an experimental project has been started for night flight with NVG; this technology was born in the military field, about 1950s but it is still very expensive. Also Brescia HEMS base is performing night ops using NVG. The usage of NVG allows the pilot to land in non-lighted area and leading the helicopter as a day-like mission (see Figure 1.9) without being forced to land on certified sport fields. The latter are, of course, still used but not every field is allowable for the helicopter to land: it has to be specific requirements, such as free space with no obstacles for a range of eight times the rotor diameter and must be registered. For each site, there is a specific route to be used both in day-time and night-time (see figure 1.8).

Complex areas (in a tight valley, for instance) must be flown by every pilot to be tested.

Table 1.4 shows night ops during years; it can be seen how night requests are increasing and how Milan HEMS base does not perform night missions any longer.



Progetto per lo sviluppo dell'attività HEMS su siti NVG
HLS ONLY
(Rif. OM Parte A Appendix 1)

Regione LOMBARDIA

STANDARD NVG HLS (HELICOPTER LANDING SITE)

ALFIANELLO	
Coordinate	N 45° 15.75' E 10° 9.15'
Quota	147 ft
Terreno	Erba
Vegetazione	Alberi sparsi circostanti
Direzione di avvicinamento	Avv. Pref. 360° / 180°
Final app. fix	San Gervasio Bresciano N 45° 18.37' E 10° 8.90'
Ostacoli	Tribune lato Est - Centro abitato a Nord del sito
NOTE	-

FOTO

1 Rev. TEMP 58 – 20 Aprile 2017

Figure 1.8: Example of sport field authorized for helicopter ops

Figure 1.9: Comparison between a ramp visual without and with NVG

CHAPTER 2

LITERATURE ANALYSIS

> "What we have done for ourselves alone dies with us; what we have done for others and the world remains and is immortal."
>
> Gen. Albert Pike

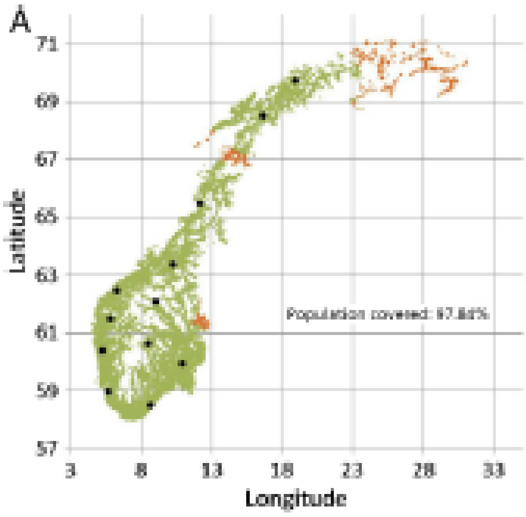
In this chapter, literature has been investigate in order to analyze already-existent knowledge in this field: this has been the base knowhow on which the present thesis has been built. This chapter is divided into five sections, each of which presents briefly and exhaustively the study conducted to improve HEMS service in different countries. A final conclusion, summarizing analyzed articles and showing differences between them and this thesis work, closes the chapter. As previously said, the first hour after the trauma is the so-called "golden hour"; and this because the majority of trauma patients die after this amount of time. In this scenario, helicopter intervention must be as fast as possible. Different time frames and total intervention time have been discussed in Section 1.4; as already said, the second parameter by importance, to reach the patient within one hour, is the base locations. This topic has been partially studied in a research of mine ("Bibliographic Research on Optimization Problem for Helicopter Emergency Medical Service (HEMS)") based on a study of [9, 10, 26, 63, 66]. The following studies are conducted in the same way: the first optimization is based on the so-called "Green Field" analysis, in which no-base assumption is made; the next step is the "Conditioned" analysis, in which relocation or construction/disposal of new bases are taken into account since reallocation of all bases may have high costs. In general, the issue is to reach rural area population, which live far from hospitals and HEMS bases; this is reflected in a greater amount of trauma related deaths. This excess rural mortality suggests that, even within streamlined inclusive trauma systems, patients with life threatening injuries may not have adequate access to high level trauma care.

2.1 HEMS Bases Location in Norway

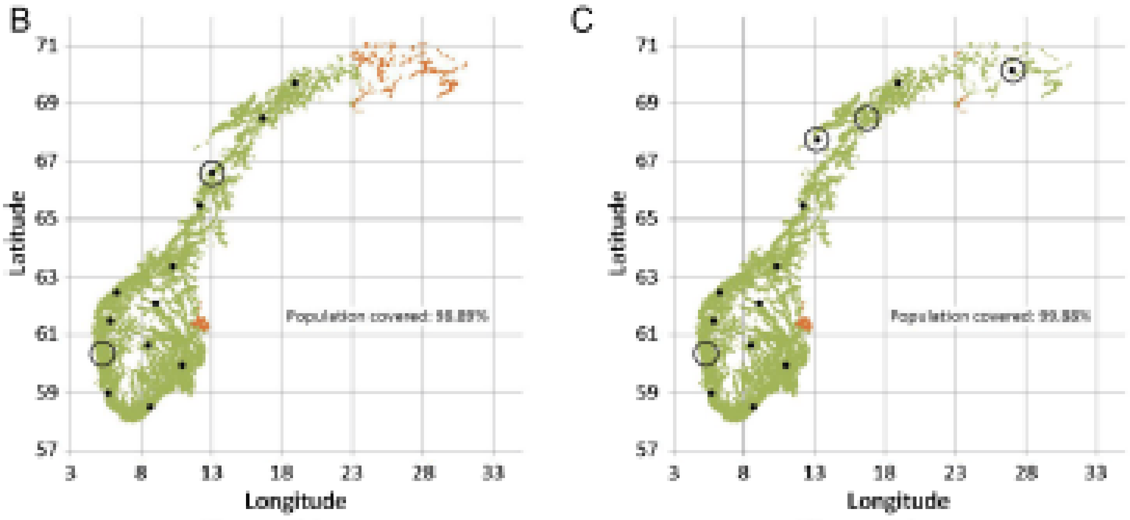
Norway government requirements state that 90% of the population should be reached by a physician staffed ambulance service within 45 min. With 12 helicopters available, a team studied how to better allocate bases and vehicles [63]. The team used the Maximal Covering Location Problem (MCLP) which maximises the population covered within a desired service distance from a facility, by allocating a fixed number of facilities. Conversely, the model can be used to determine the least number of bases needed in order to guarantee a certain coverage of the population. The MCLP model places one ambulance at each base location, assuming that each ambulance is always available. While in practice, this might be overly optimistic, the model was chosen as it represents a best-case scenario. Results were that with a threshold of 45 min, 90% of the population could be covered using four bases. The 12 existing bases cover an estimated 97.84% of the population. The base which contributes less is in the city of Bergen; moving this base from its current location to south of the city Bodo in Northern Norway, would increase population coverage from 97.84% to 98.89%. Moving two bases, the Bergen and Evenes bases, would increase coverage further to 99.88%. Adding one base to the existing 12 results in adding a base close to where the Bergen base should optimally be moved, increasing coverage from 97.84% to 98.89%. Adding two bases would further increase coverage to 99.88%. Results are shown in Figure 2.1.
However, the study has been repeated since the former did take into account the population distribution but not the incidents locations; from this new study [62] of 2018 both population and incidents distributions have been taken into account. Using again the MCLP model, results showed that if taking into account population only, bases are allocated near big cities; if taking into account number of incidents location only, bases are allocated in scarcely-populated areas.

2.2 Locating HEMS Bases in Australia

Similar studies have been conducted also by Australia[26]; the goal was duplex: either maximize population coverage or minimize intervention time. As study looked for two different Objective Functions (*OFs*), two different algorithms were used; these are the already-used MCLP and the Average Response-Time Model (ARTM). An additional hybrid model has been proposed, too. Another difference was presented: in many high density European countries HEMS (*E-HEMS*) roles are specialised with separate services conducting scene response, interfacility transfer and, search, rescue and hoisting (*SAR*) roles. The Australian HEMS model utilises multirole retrieval HEMS (*MR-HEMS*) services that have a broad scope of operations including offshore and mountain hoist rescue, specialised interfacility transports such as ECMO (ExtraCorporeal Membrane Oxygenation), IABP (Intra Aortic Balloon Pump) and neonatal transfers as well as scene response. Both Green field analyses, assuming a hypothetical situation with no current

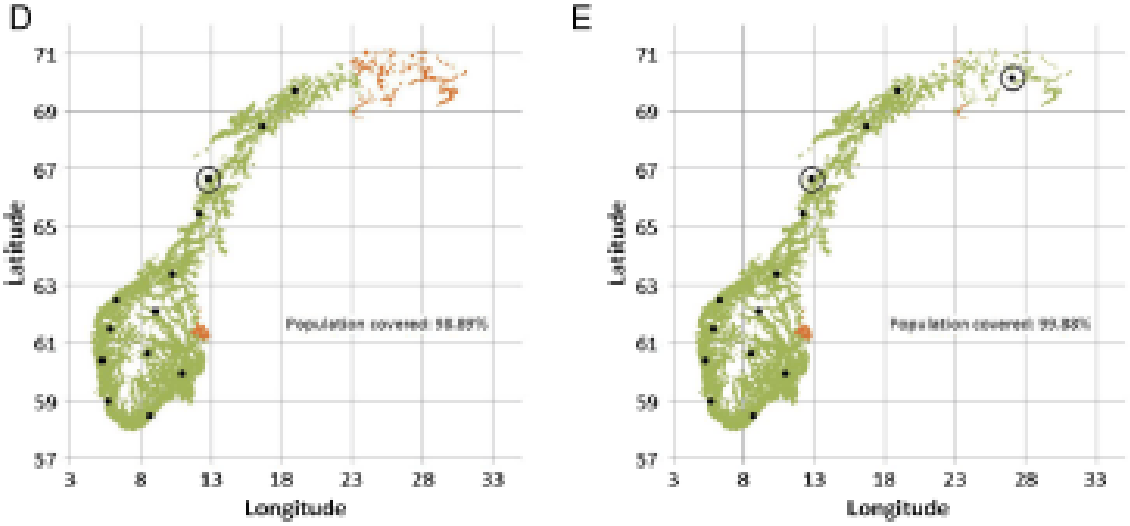


Current situation



Change 1 base

Change 2 bases



Add 1 base

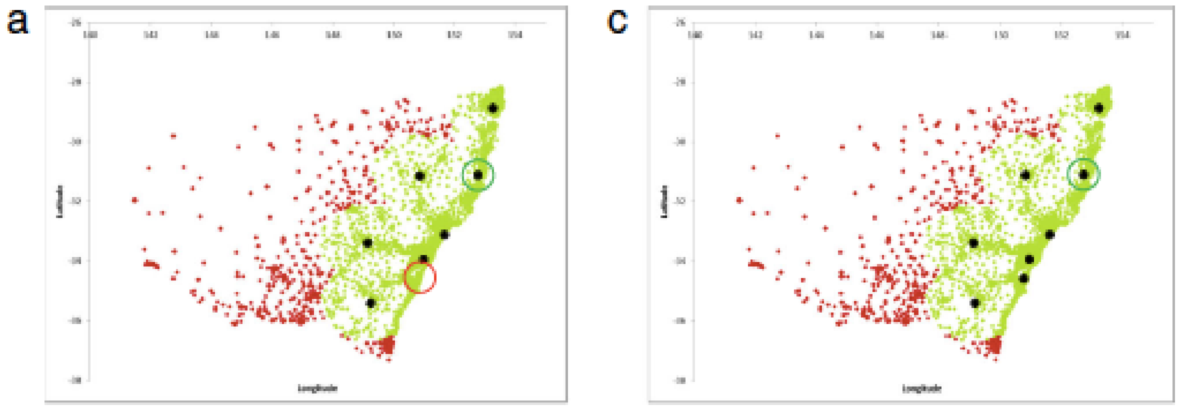
Add 2 bases

Figure 2.1: Coverage of existing base structure using fine grid population data and a 45 min threshold (A); moving one (B) or two (C) existing bases; adding one (D) or two (E) new bases.

MR-HEMS bases, and optimisation conditioned on the current bases have been carried on (as in Norway analysis), in order to explore whether improvements to the existing base structure could be achieved by moving or adding a few select bases. NSW currently has a system of nine MR-HEMS services operating from seven bases 24 h a day to cover a population distributed over more than 809,000 $\Bbbk$. Results for green field analysis highlights the difference on which model has been used: for *MCLP* model, the average response time increases as base locations move away from the densely populated coastal strip although nine bases are able to cover 99.15% of the population; using *ARTM* model, the moving from seven to nine bases decreases the average state wide response time by 1.27 min although population coverage also increases by more than 3% to 97.62%. Concerning the conditioned analysis referring to *MCLP* model, the first base to be replaced is Wollongong which moved to Kempsey on the mid north coast. If two bases were moved, Tamworth moves east far enough to cover the Mid North Coast whilst Wollongong moved to Wagga Wagga. If bases were added the first base was at Kempsey and the second was at Wagga Wagga (see Figure 2.2). If looking at *ARTM* model, the first base relocated is Canberra which moved to Wagga Wagga and the second relocation is Tamworth to Kempsey. If bases were added, the first was at Narrandera and the second was at Port Macquarie (see Figure 2.3). A hybrid greenfield model for seven HEMS bases including the CRRH base as a potential base location was constructed for a range of coverage percentages between 95.94% and 98.03%. There is an increase of nearly 8 minutes (30%) in the average response time due mostly to movement of the Sydney base away from the CRRH base location when the minimum population coverage moves from 97.75% to 98%. The optimal trade-off between population coverage and response time with seven bases is, therefore, a model covering just under 98% of the population in less than 45 min with an average response time to all inhabitants of the state in under 18 min. This consists of six MR-HEMS bases providing population coverage whilst benefiting from the addition of the E-HEMS base in Sydney.

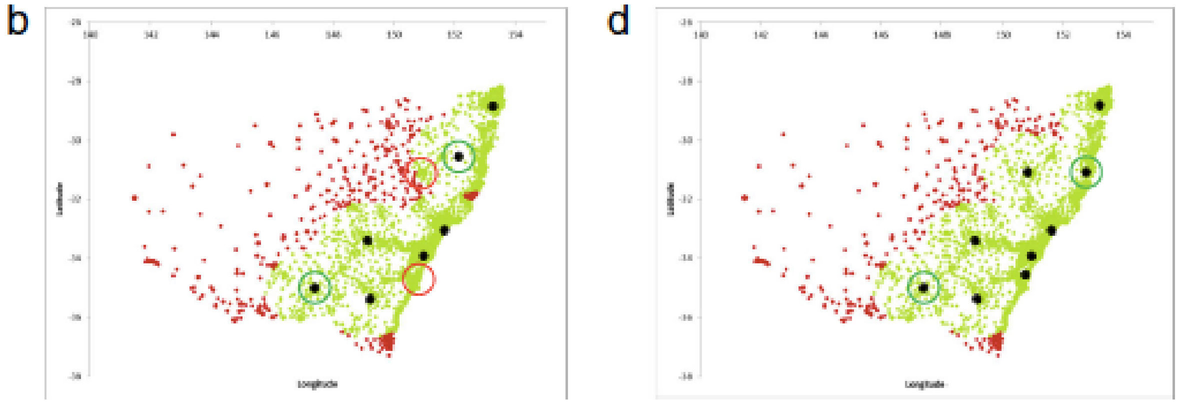
2.3 Locating of HEMS Bases and Helipads in Iran Under Demand Location Uncertainty

In a study from Iran[9], an integer nonlinear programming model is presented for the integrated locating of helicopter stations and helipads by considering uncertainty in demand points. Some points were geographically located in mountainous areas or those with high population density, which could make helicopter landing procedure difficult. Thus, it seemed necessary to establish helipads. There were three modes to transfer injuries to the hospital; the first mode was to transfer injuries directly to the hospital by an ambulance, the second was to transfer them to the helicopter station by an ambulance and, then, to the hospital by a helicopter and the third was to transfer them to helipad by an ambulance and, then, to the hospital by a helicopter. The model objective function attempted to minimize the sum of transfer times from demand areas to



MCLP replace 1 base

MCLP add 1 base



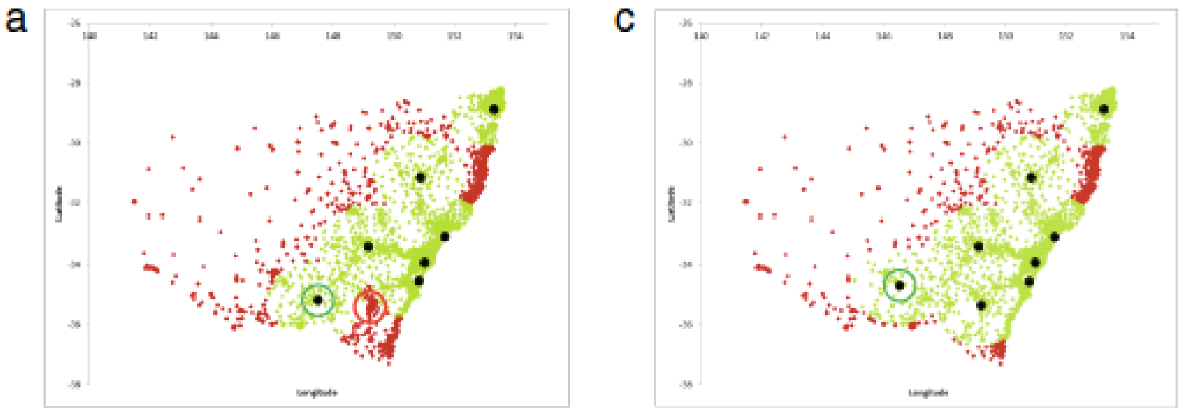
MCLP replace 2 bases

MCLP add 2 bases

Figure 2.2: MCLP fixed MR-HEMS base solutions. **a** and **b** are the replace one base and replace 2 base solutions respectively whereas **c** and **d** are the add one base and add two base solutions respectively

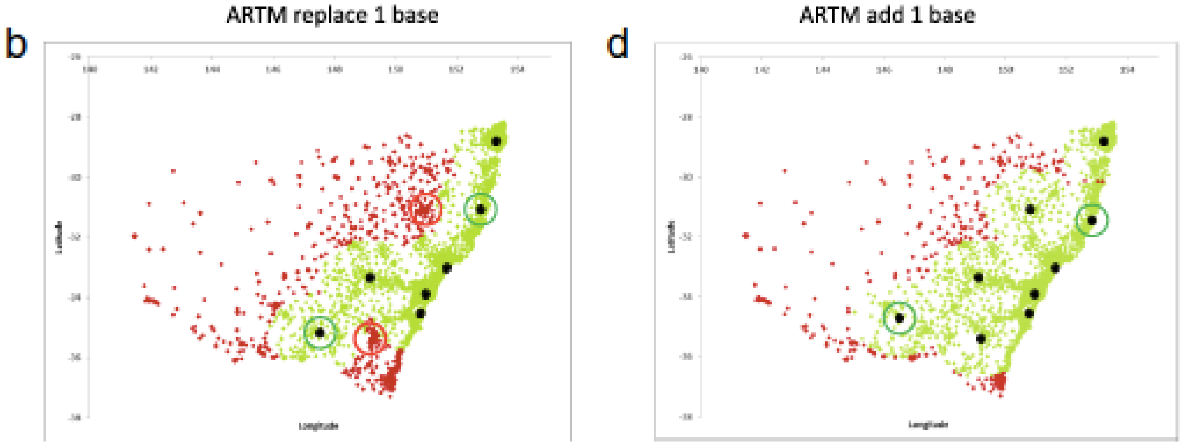
the hospital. To evaluate the model, a simple numerical example was set on Lorestan province. Lorestan province is one of the western provinces in Iran, with the area of 28294 𝕜 and population of more than 1,700,000. According to the evidence, there are too many accidents happening on the roads of this province. In the mathematical model, the objective function was equal to 32.4 min. Researchers also assume that demands occur in a square-shaped area, in which each side follows a uniform distribution. The purpose of the model is to minimize the transfer time from demand points to the hospital by considering different modes. The proposed model is examined in terms of validity and applicability in Lorestan Province and a sensitivity analysis is also conducted on the total allocated budget.

The model activated two helicopter stations and five helipads (see Figure 2.4)



ARTM replace 1 base

ARTM add 1 base



ARTM replace 2 bases

ARTM add 2 bases

Figure 2.3: ARTM fixed MR-HEMS base solutions. **a** and **b** are the replace one base and replace 2 base solutions respectively whereas **c** and **d** are the add one base and add two base solutions respectively

2.4 Locating Trauma Centers and Helicopters in Maryland: the USA case

A US team wondered how to best-allocate statal resource in order to optimize trauma organization [10]. The development of trauma systems has been shaped by historical patterns, competition between local service providers and politics. Consequently, some States have unnecessary duplication of trauma care services or lack adequate coverage for rural areas. The question of how many trauma centers are needed for the population remains unanswered. The American College of Surgeons estimates that one trauma center per million people is sufficient to handle the typical volume of severely injured patients and to maintain the expertise of medical providers. Traditionally, trauma systems planners have tried to maximize coverage of land area, a strategy that has led them to locate many trauma centers and helicopters at the same sites. But this may not lead to maximal coverage of people who need trauma services. To improve resource

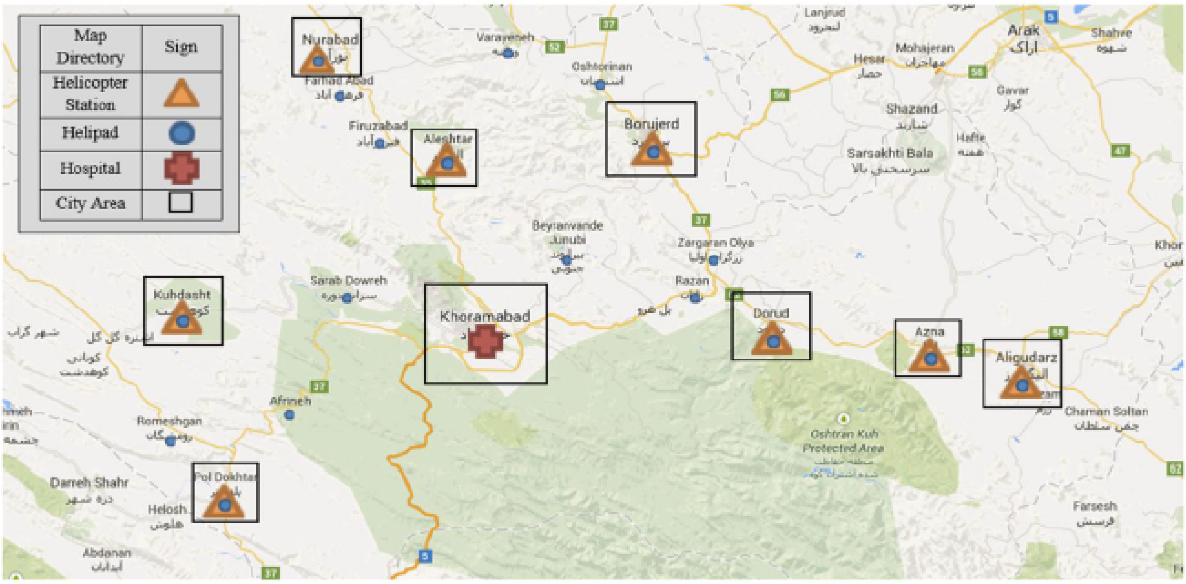


Figure 2.4: Lorestan Province's helicopter stations and helipad candidate points

allocation, Branas and colleagues developed and tested a new mathematical model to optimize the location of trauma centers and related resources. The Trauma Resource Allocation Model for Ambulances and Hospitals (*TRAMAH*) simultaneously locates trauma centers and helicopter depots and measures success by the number of severely injured people having timely access to a trauma center by either ground or air. In contrast to a strategy of maximizing land area covered, TRAMAH can maximize coverage based on the demonstrated need for trauma services. Because of its flexibility, it can be used to build a relatively new regional trauma system from a "clean slate" or to accommodate partially developed or well-developed systems that need only incremental improvements. Results were that Using the clean slate approach, TRAMAH repositioned the existing 9 trauma centers and 8 helicopter depots and covered more than 99% of the severely injured population within 30 minutes. This translates into an additional 461 severely injured people covered each year. Helicopter depots are often logistically and politically easier to relocate than trauma centers. Assuming that no trauma center would be moved, and using a 15-minute time standard, TRAMAH achieved the same level of coverage as that of the existing system by optimally locating only two helicopter depots. By optimally relocating all 8 existing helicopter depots, the model estimated an increase in coverage from 70% to 85% within 15 minutes, or an additional 1,348 people each year. By repositioning just one trauma center, and leaving all helicopter depots unchanged, TRAMAH improved 15-minute coverage by 4%, or an additional 371 people. Repositioning two trauma centers increased coverage by nearly 7%.

2.5 HEMS studies in Lombardy: an Analysis on Previous Theses

From 2014, a new study area has been developed in Politecnico di Milano; these studies were aimed at re-organizing the Helicopter Emergency Medical Service in Lombardy. Among these, the first thesis (Putzu, [56]) represents a pioneering study on the location of HEMS bases and sites through use of Geographical Information System (GIS). The second thesis (Monai, [48]) objective was to study rendez-vous between helicopter and ambulance in an optimal manner, while the third (Miele and Lozupone, [4]) was aimed at minimizing the helicopter path from origin to destination.
The first pioneering study in the HEMS service was carried out by Putzu in his Master thesis [56], together with Bruglieri and Cardani[14] in 2014. The work was aimed at locating the HEMS bases and sites. The location of the bases and the sites have been performed with the aid of GIS tools. A preliminary study on candidate sites for HEMS bases and sites has been carried out, before optimizer had been run. The incident data were not known, therefore a statistical analysis of the number of incidents has been used; the latter locates more incidents in areas where there are more inhabitants. The results show that, with the current base locations, few are the points not reached within a fixed flight time by helicopter. However, results basing on population data are not affordable, as the study from Roislien et al. [62] demonstrates. Also a study on helicopter landing sites has been performed, only for SOREU of lakes area; results were that some thousands of sites were appropriate for a HEMS helicopter to land on. However, no dispatching problem is present in the model but, as said, this was the pioneering study in the HEMS in Lombardy.

Monai's thesis [48] together with Bruglieri and Cardani [13]. This second study was aimed at improving the previous one, through the optimization of the randez-vous between helicopter and ambulance, in terms of effectiveness and efficiency. Indeed, in that year the European Commission entered in force allowing night landings of helicopters for emergency medical service in dedicated spaces called HEMS operating site, where the transfer of the patient from the ambulance to the helicopter takes place (the so-called Rendez-vous). The problem is double: one version maximize coverage, locating a fixed number of them and maximizing the total number of the accident points that can be reached within a given threshold time; in the second version, the problem is aimed at seeking the minimum number of HEMS operating sites that minimizes the average or maximum mission time, guaranteeing a certain coverage. Such problems are formulated as Mixed Integer Linear Programs (MILP) and solved both in heuristic way through the Geographic Information Systems software and in exact way, by solver Gurobi. This allowed to compare solutions from the GIS tools with the ones coming from optimization model, to test the goodness of GIS solver. In this thesis, real data on incident provided by AREU are used. Moreover, in the model a refining of the helicopter path is carried out: the helicopter does not fly directly from point to point but chooses either the latter way or to fly through valleys, depending on which way is the faster.

Results show that the GIS solutor always provides the optimal solutions, although it cannot be guaranteed to find them. Moreover, the computational time is far lower than that of Gurobi, thus showing that ArcGIS is an efficient and an effective tool to solve the HEMS location problems.

The last and more recent thesis, developed in Politecnico di Milano, is written by Miele and Lozupone, under the supervision of Bruglieri [4]. This work is aimed at minimizing the flight time during the mission, through looking for the quickest path. The problem of the quickest path is defined in order to model the helicopter flight in a manner that is as realistic as possible: differently from the previous thesis, in the current work several path are considered (not just flying point to point or through valleys). To solve this problem, an appropriate algorithm is implemented: the Helicopter Quickest Path Algorithm (HQPA), based on Dijkstra algorithm and its variant A*. The results obtained are then compared with the exact solution of linear programming formulation, performed by the Gurobi solver. Found results are the same, but concerning computational time the HQPA is more favourable than Gurobi-AMPL. Through this work it has been demonstrated that the AREU approach of sending the nearest helicopter is greedy; flight times show how a more distant base is more suitable for a rescue mission if orographic and helicopter characteristics are favourable.

With the work presented in this thesis not only the base locations, but also the dispatching choice problem is aimed at maximizing the total number of requests served.

2.6 Final Considerations

From this literature analysis, some differences have been spotted between them and this thesis work. In particular, compared to other Politecnico di Milano theses [4, 48, 56], this work is intended to develop in a wider area (Lombardy region) and to be solved with the tools of the mathematical optimization. Besides the difference between locating HEMS sites and bases, problem has been *ad-hoc* modelled and optimally solved considering also incident places known for every day of the year; in this way, the bases can be located by relying on real events. Moreover, in the present thesis, an integrated dispatching method is also present together with the choice of helicopter types to be allocated to each base. The dispatching method and the choice of the best type of helicopter are, to the best of our knowledge, completely new aspects in HEMS studies; they represent, therefore, a novelty with respect to all papers and thesis analyzed. Also the Australian study [26] presents two different models, one to maximize the coverage and the other to minimize the average response time and their differences are highlighted in the results. Outcomes from the first model show that the average response time increases as base locations move away from the highly populated coastal strip, but coverage is maximized; the second model suggests to increase the total number of bases to decrease the average response time but population coverage is less satisfactory. Therefore, a hybrid model has been developed to catch the optimal solution between the maximum coverage and the minimum average response time. Iran case has also been studied; in this case, an integer nonlinear programming model has been implemented for locating helicopter bases and HEMS sites. The mathematical model activated two helicopter stations and five helipads. The purpose of the model is to minimize the transfer time from demand points to the hospital by considering three different modes. A sensitivity analysis has been also conducted on the total budget. The differences, in this case, are that the problem from [9] is solved by a nonlinear analysis and that the objective function is to minimize hospitalization (no data on events were known). Therefore, the results guarantee the minimum time from each cell of a grid to the nearest hospital but no information is given about the time the helicopter takes to reach the incident place. In this thesis work, the aim is to maximize served events (which rarely are close to big cities) by minimizing the on-scene arrival time and hospitalization. The USA study does involve trauma centers locations. The article is, however, present in this literature analysis since the model developed simultaneously locates trauma centers and HEMS bases and measures success by the number of severely injured people having timely access to trauma center by either ground or air. Contrary to models that maximize coverage, the proposed model maximizes coverage basing on the demonstrated need for trauma services. The difference between this model and the one in this thesis is, again, in the objective function. The Norwegian studies are the ones that more approach the problem proposed in this thesis. The objective function of their first study was to maximize the coverage of the territory; the second paper modified the objective function since they recognize that high population density does not imply high HEMS demand. As in this work, the model places one vehicle at each base location, but it considers it always available; the model was chosen as it represents a best-case scenario. Moreover, the problem has been formulated to have a duplex function: to allocate a fixed number of facilities or to determine the least number of bases needed to guarantee a certain coverage. Differences are several compared to this thesis work. The objective function is to maximize the number of served events and, secondly, to minimize the total time to serve them; each helicopter is not considered always available for a mission. Also, this problem is duplex, to allocate a fixed number of bases minimizing costs or to allocate the maximum number of bases within a certain budget. Moreover, as said at the beginning, the model proposed counts on an integrated dispatching method, which can assign each helicopter to each event and it is able to choose the best type of helicopter to be allocated in each base. One interesting result is, however, remarkable: Norwegian studies show that, if taking in account population only, bases are located near big cities; if taking into account number of incidents location only, bases are allocated in scarcely-populated areas.

CHAPTER 3

BASE LOCATION AND HELICOPTER DISPATCHING PROBLEM

> “If you are in trouble anywhere in the world, an airplane can fly over and drop flowers, but a helicopter can land and save your life.”
>
> Igor Sikorsky

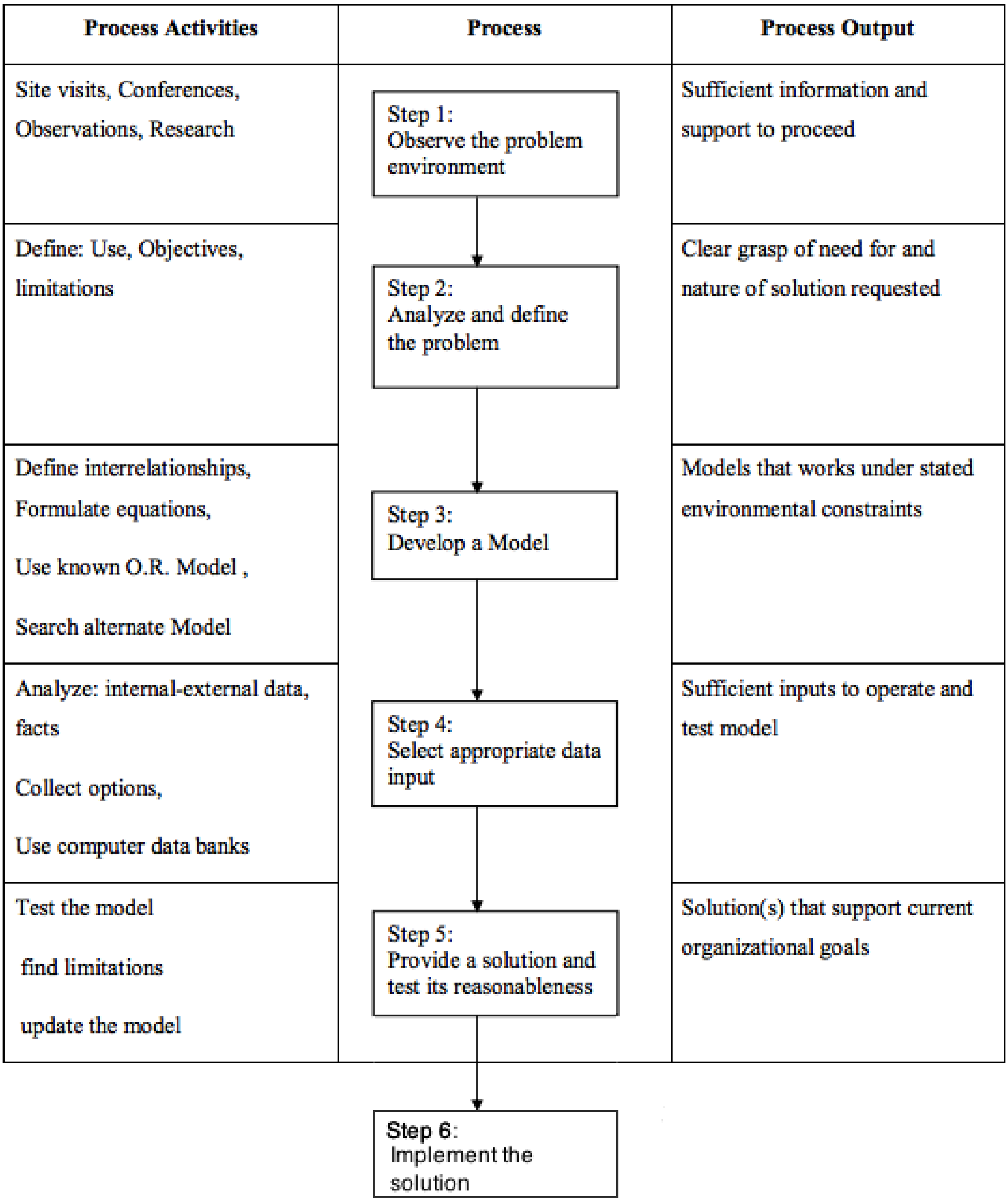
3.1 Operations Research: a Quick Introductive Brief

Operation Research (OR) is a relatively new discipline and its contents and boundaries are not yet fixed. Therefore, to give a formal definition of the term Operations Research is a difficult task. According to the Operational Research Society of Great Britain [52], Operational Research is "the attack of modern science on complex problems arising in the direction and management of large systems of men, machines, materials and money in industry, business, government, and defense". The OR starts when mathematical and quantitative techniques are used to substantiate the decision being taken. In our daily life, we make decisions even without taking care. They are taken simply by common sense, judgment, and expertise without using any mathematical or any other models. Operations Research takes tools from different disciplines such as mathematics, statistics, economics, psychology, engineering, etc. and combines these tools to make a new set of knowledge for decision making. The main purpose of O.R. is to provide a rational basis for decisions making in the absence of complete information because the systems are composed by human, machines, and procedures. Operations Research can also be treated as science in the sense it describes, understands and predicts the systems’ behaviour, especially man-machine system. The stages of development of O.R. are also known as *phases and process* of O.R, which have six important steps. These six steps are shown in Figure 3.1.

OR uses any suitable tools or techniques available. The common frequently used tools/techniques are mathematical procedures, cost analysis, and electronic computation. However, OR gave special importance to the development and the use of techniques like linear programming, game theory, decision theory, queuing theory, inventory models and simulations. In addition to the above techniques, some other common tools are non-linear programming, integer programming, dynamic programming, sequencing theory, Markov process, network scheduling (PERT/CPM), symbolic model, information theory, and value theory. Many other Operations Research tools/techniques also exist. Operations Research has a great number of applications; similarly, it also has certain limitations. These limitations are mostly related to the model building and money and time factors problems involved in its application. Some of them are: distance between O.R. specialist and Manager, magnitude of calculations, money and time costs, non-quantifiable factors (emotional or qualitative) and implementation (must take into account human relations and psychological factors) [7],[35], [45],[70],[76].

3.2 Problem Definition

HEMS represents an added resource to healthcare service provided by the country since it allows to bring advanced medical staff on the incident place within the Golden Hour (see Chapter 1). In order to ensure widespread coverage, the base location study is central. In general, bases location does not derive from optimization analysis but from historical reasons and experience, therefore optimal location may be expected to be different compared to the currently used. The base location must keep into account locations of historical requests, their occurrence time, injury-gravity code, helicopter types, and their own characteristics - both technical and economical; all of this within a prescribed budget. Knowing *a priori* all events which require HEMS intervention, the Base Location, and Helicopter Dispatching (BLHD) problem is aimed at placing HEMS bases over the territory in order to maximize the number of served requests, weighting them according to their injury-gravity code (red code vs green code) and, secondly, to minimize the total intervention time. In this context, two versions of the problem can be defined. In the *rigid* version, a red code event can only be served by an immediately available helicopter able to reach the incident place within a time threshold (e.g. 30 minutes); while, in the *flexible* version, a red code event can also be served by a helicopter not immediately available provided that it can reach the incident place within the threshold. The problem also includes an integrated dispatching method (called *predictive*) to assign one and one only specific helicopter to each base. Downstream of optimization, another dispatching method is used, the so-called *online* method. This has been created for validating results with a dispatching method more similar to reality. It does not assume to know all events *a priori*, but assigns the more suitable helicopter to each event, as they chronologically arise.



Process Activities	Process	Process Output
Site visits, Conferences, Observations, Research	Step 1: Observe the problem environment	Sufficient information and support to proceed
Define: Use, Objectives, limitations	Step 2: Analyze and define the problem	Clear grasp of need for and nature of solution requested
Define interrelationships, Formulate equations, Use known O.R. Model , Search alternate Model	Step 3: Develop a Model	Models that works under stated environmental constraints
Analyze: internal-external data, facts Collect options, Use computer data banks	Step 4: Select appropriate data input	Sufficient inputs to operate and test model
Test the model find limitations update the model	Step 5: Provide a solution and test its reasonableness	Solution(s) that support current organizational goals

Step 6:
Implement the solution

Figure 3.1: Phases and processes of a Operations Research study

3.3 Mixed Integer Linear Programming Formulation

As previously affirmed, there exist two versions of the problem: the first, called *rigid* BLHD and the second, called *flexible* BLHD. Both versions consider the real events of a certain period of time and categorize each of them into different characteristics, such as injury-severity code, occurrence hour and day and morphological characteristics of the incident place. The latter is important in order to choose the type of helicopter. A score is assigned to each code in order to establish a ranking of priorities: higher score for red code events, intermediate for impervious green code events and lower for non-impervious green code event. The problem is aimed at finding a solution in order to maximize the number of served events minimizing the missions total time. The total time of a single mission takes into account delay mission start time, ignition time, take-off time, flight time (based on distance of the event with respect to the base), the descent and landing time, shut-off time, time for the medical team to medically stabilize the patient, the ignition time and the time for the helicopter to fly to the nearest appropriate trauma-center. What is different between the two versions of BLHD problem is how red code events are managed. In *rigid* BLHD problem, red code event needs an immediately available helicopter able to reach the incident place within a desired threshold to be considered served. That is the reason of its name: if no helicopter is available at call receipt, the mission is considered rejected. The *flexible* BLHD problem allows the helicopter not to start immediately at the call receipt provided that the incident place can be reached within the threshold. The time threshold depends on the injury-severity code of the event: a red code event has a lower time threshold than a green code one. Since BLHD problem is designed for trying to reduce times as possible, this means that also costs are reduced accordingly. Costs are divided into leasing cost (which depends on leasing period and type of helicopter) and operational costs (which depends on how much the helicopter actually has its engines on); costs of building new bases have not been considered since they depend on several factors whose study is not of interest to this thesis. For this reason, constraint on budget could be bypassed considering a constraint that limits the number of bases that can be opened. To temporally separate two consecutive take-offs of the same helicopter, a fixed time has been considered. This guarantees the model does not superimpose two consecutive missions for the same helicopter. To determine where bases can be opened, the region area has been divided by mean of a grid into cells, as also successfully made in [63]. The centres of each cell represent the possible base location. The finer the grid, the finer the solution. Each demand point (or incident place) is characterized by different parameters: geographical coordinates, occurrence time of the event, injury-severity code and the actual place where the patient is. This latter information is very useful in the choice of the helicopter type to be sent: a very busy road in an urban environment, where tram wires are present as well as light poles cannot be an appropriate zone for a large rotor helicopter to land. On the contrary, places with large spaces are suitable for a big rotor helicopter, able to fly faster and to carry more-than-one patient. For a patient lying in brutal terrain with a lot of obstacles, rocks, rough ground and trees around or stuck on a cliff needing a hoist recovery, a small rotor

diameter helicopter is preferable.
The models take all the following input parameters:

1. n = Total number of grid cells
2. D = Total number of days to be taken into account
3. m = Total number of helicopter types considered
4. X_k^g, Y_k^g = Longitude and latitude of event k of day g
5. t_k^g = Occurrence time of event k of day g
6. $\beta^g{}_{\mathrm{kh}}$ = Compatibility of event k of day g with helicopter h
7. K^g = Total number of events for day g
8. τ_k^g = Maximum timing threshold for event k of day g
9. P_k^g = Marker that recognizes if event k occurred at day g is a first-aid or a succeeding intervention
10. H_k^g = Distance from event demand point k occurred in day g from the nearest available and appropriate trauma center
11. v_h = Cruise flight speed of the helicopter h
12. B = Total budget available
13. c_{2h},c_{1h} = operational per flight hour and leasing for helicopter h
14. ϑ_1, ϑ_2 = Stop time on demand point in 1st aid case and in succeeding case
15. ϑ_3 = Taking-off/ landing time from cruise condition
16. ϑ_4, ϑ_5 = Stop time on hospital site in 1st aid case and in succeeding case
17. $\vartheta_{\mathrm{ON\ h}}$, $\vartheta_{\mathrm{OFF\ h}}$ = Two engines ignition and shut-off time for helicopter h
18. δ = Minimum time between two consecutive missions
19. $long_j$, lat_j = Longitude and latitude of the centre of cell j
20. T = Maximum delay for recovery a green code event
21. ζ_k^g = Injury-severity code for each event k in day g (1= red code, 0= green code)
22. W = Worst-case time to reach a demand point

23. Γ = Number of maximum bases to be opened

To the injury-gravity code ζ_k^g is associated a score Θ_k^g which is for red code events, medium score for impervious green events and a lower score for green events. The mathematical problem includes **four** kinds of **binary variables** and **two** types of **continuous non-negative** ones.

(i) $\mathrm{y}_j = \begin{cases} 1 & if\ a\ base\ is\ opened\ in\ cell\ j \\ 0 & otherwise \end{cases}$

(ii) $\mathrm{x}_{\mathrm{jh}} = \begin{cases} 1 & if\ the\ helicopter\ h\ is\ based\ in\ cell\ j \\ 0 & otherwise \end{cases}$

(iii) $\mathrm{z}_{\mathrm{kgjh}} = \begin{cases} 1 & if\ request\ k\ of\ day\ g\ is\ served\ by\ helicopter\ h\ based\ in\ cell\ j \\ 0 & otherwise \end{cases}$

(iv) ω_k^g = Take-off time for event k of day g

(v) $\psi_{\mathrm{gk1k2}} = \begin{cases} 1 & if\ event\ k1\ of\ day\ g\ is\ served\ before\ event\ k2\ of\ day\ g \\ 0 & otherwise \end{cases}$

Note: variable ω_k^g is defined on green code events only (in *rigid* model) or on both green and red code events (in *flexible* model). It is defined in the interval $t_k^g \le \omega_k^g \le t_k^g + T$.
Variable z_{jhgk} is defined within a domain, called $DOMAIN_Z$, which guarantees that event k of day g can be served by helicopter h in cell j within the τ_k^g time threshold and compatibility of event with helicopter h is granted.
In formulas:

$$\begin{gathered} DOMAIN_Z = \{(j,h,g,k) : j = 1..n,\ h = 1..m,\ g = 1..D,\ k = 1..K^g \\ and\ \beta^g{}_{\mathrm{kh}} = 1\ and\ \frac{\Delta^g{}_{\mathrm{kh}}}{v_h} + \vartheta_{\mathrm{ON\,h}} <= \tau_k^g\} \end{gathered} \tag{3.1}$$

wherein $\Delta^g{}_{\mathrm{kh}}$ is the distance between the current HEMS base and the incident location. It is calculated basing on formula:

$$\Delta(A,B) = R \cdot arccos(sin(latA) \cdot sin(latB) + cos(latA) \cdot cos(latB) \cdot cos(longA - longB)) \tag{3.2}$$

which allows determining the shortest distance between two points on earth - supposed to be a sphere of radius R = 6372.795Km - identified by their own coordinates. Near to poles or between very far points, error using this formula is up to 0.3%. In this model distance depends on cell j

and event k location of day g hence, $\Delta^{g}{}_{\mathrm{kh}}$.

Objective function of the model is - hierarchically - to maximize the number of events weighted on scores and minimize the intervention times for each event (and hence costs associated), starting every mission as soon as possible.

$$
\begin{aligned}
maximize \sum_{j=1}^{n}\sum_{g=1}^{D}\sum_{k=1}^{K^g}\sum_{h=1}^{m} \Theta_k^g z_{\mathrm{jhgk}} \\
-\frac{\sum_{j=1}^{n}\sum_{g=1}^{D}\sum_{k=1}^{K^g}\sum_{h=1}^{m}\Theta_k^g(\frac{\Delta^{g}{}_{\mathrm{kh}}}{v_h}+\Xi^{g}{}_{\mathrm{kh}})z_{\mathrm{jhgk}}}{\sum_{h=1}^{m}\sum_{g=1}^{D}\sum_{k=1}^{K^g}(3W+\Xi^{g}{}_{\mathrm{kh}})} \\
-\sum_{(g,k):\zeta_k^g=0}\frac{\omega_k^g-t_k^g}{T\cdot\sum_{g=1}^{D}K^g}
\end{aligned}
\tag{3.3}
$$

wherein $\Xi^{g}{}_{\mathrm{kh}}$ is defined by the formula:

$$
\Xi^{g}{}_{\mathrm{kh}} = \frac{H_k^g}{v_h} + 4\vartheta_3 + \vartheta_1 P_k^g + \vartheta_2(1-P_k^g) + 2\vartheta_{\mathrm{ON\ h}} + \vartheta_{\mathrm{OFF\ h}} \tag{3.4}
$$

and represents the time of a mission which is not variable.

Finally **constraints** to the model are:

a) There's no helicopter when there is no base
$x_{\mathrm{jh}} \le y_j, \forall j = 1..n, \forall h = 1..m$

b) Could not be an intervention if there is no helicopter in a cell
$z_{\mathrm{kgjh}} \le x_{\mathrm{jh}}, \forall g, \forall k, \forall j = 1..n, \forall h = 1..m$

c) Total budget, hence summation of annual leasing cost, base opening, flight-hourly cost
$c_{\mathrm{2h}}[\sum_{j=1}^{n}\sum_{h=1}^{m}\sum_{g=1}^{D}\sum_{k=1}^{K^g}((2\frac{\Delta^{g}{}_{\mathrm{kh}}}{v_h}+2\frac{H_g^k}{v_h}+6\theta_3+3*\vartheta_{\mathrm{ON\ h}}+3*\vartheta_{\mathrm{OFF\ h}})z_{\mathrm{jhgk}})]$
$+\sum_{j=1}^{n}\tilde{c}_j y_j+\sum_{j=1}^{n}\sum_{h=1}^{m}c_{\mathrm{1h}}x_{\mathrm{jh}} \le B$

d) Time threshold with take-off delay (constraint active for *flexible* model only)
$z_{\mathrm{jhgk}}\frac{\Delta^{g}{}_{\mathrm{kh}}}{v_h}+(\omega_k^g-t_k^g) \le \tau_k^g \ \forall j = 1..n \forall h = 1..m, \forall g = 1..D, \forall k = 1..K[g]$

e) Time threshold with take-off delay of green code: if event k is a green code event, $\zeta_k = 0$ (constraint active for *rigid* model only)
$z_{\mathrm{jhgk}}\frac{\Delta^{g}{}_{\mathrm{kh}}}{v_h}+(\omega_k^g-t_k^g) \le \tau_k^g \ \forall j = 1..n \forall h = 1..m, \forall g = 1..D, \forall k = 1..K[g]$

f) Non-simultaneity of the same helicopter (for the *rigid* model only)
$z_{\mathrm{k1gjh}} + z_{\mathrm{k2gjh}} \le 1$, ∀j=1..n, ∀h=1..m, ∀g=1..D, ∀k1,k2 = 1..K_g, $k1 \neq k2$ s.t. ($|t_g{}^{\mathrm{k1}} - t_g{}^{\mathrm{k2}}| \le \delta$ and $code_g{}^{\mathrm{k1}} = 1$ and $code_g{}^{\mathrm{k2}} = 1$)

g) No multiple concurrent helicopters in the same cell
$x_j{}^{\mathrm{h1}} + x_j{}^{\mathrm{h2}} \leq 1 \forall j = 1..n, \forall h1, h2 = 1..m$

h) No multiple helicopter intervention for the same incident
$\sum_{j=1}^{n} \sum_{h=1}^{m} z_{\mathrm{jhgk}} \leq 1 \forall g = 1..D \forall k = 1..K_g$

i) Temporal take-off separation (constraint active for the *rigid* model only): if either event k1 or event k2 are green code, $\zeta_{\mathrm{k1}} = 0$ or $\zeta_{\mathrm{k2}} = 0$ then $|\omega_g{}^{\mathrm{k1}} - \omega_g^{\mathrm{k2}}| \geq \delta$ which decomposes into

$$\omega_g{}^{\mathrm{k1}} - \omega_g{}^{\mathrm{k2}} \geq \delta - M1 \cdot (2 - z_{\mathrm{jhgk1}} - z_{\mathrm{jhgk2}} + \psi_{\mathrm{gk1k2}})$$
$$\omega_g^k 1 - \omega_g^k 2 \leq -\delta + M1 \cdot (3 - z_{\mathrm{jhgk1}} - z_{\mathrm{jhgk2}} - \psi_{\mathrm{gk1k2}})$$
$$\forall j = 1..n \forall h = 1..m, \forall g = 1..D, \forall k = 1..K[g]$$

j) Temporal take-off separation (constraint active for *flexible* model only): $|\omega_g^k 1 - \omega_g^k 2| \geq \delta$ which decomposes into

$$\omega_g{}^{\mathrm{k1}} - \omega_g{}^{\mathrm{k2}} \geq \delta - M1 \cdot (2 - z_{\mathrm{jhgk1}} - z_{\mathrm{jhgk2}} + \psi_{\mathrm{gk1k2}})$$
$$\omega_g^{\mathrm{k1}} - \omega_g^{\mathrm{k2}} \leq -\delta + M1 \cdot (3 - z_{\mathrm{jhgk1}} - z_{\mathrm{jhgk2}} - \psi_{\mathrm{gk1k2}})$$
$$\forall j = 1..n \forall h = 1..m, \forall g = 1..D, \forall k = 1..K[g]$$

k) Maximum number of bases to be opened
$\sum_{j=1}^{n} \sum_{h=1}^{m} x_{\mathrm{jh}} \leq \Gamma$

wherein $distance$ is defined as in 3.2.

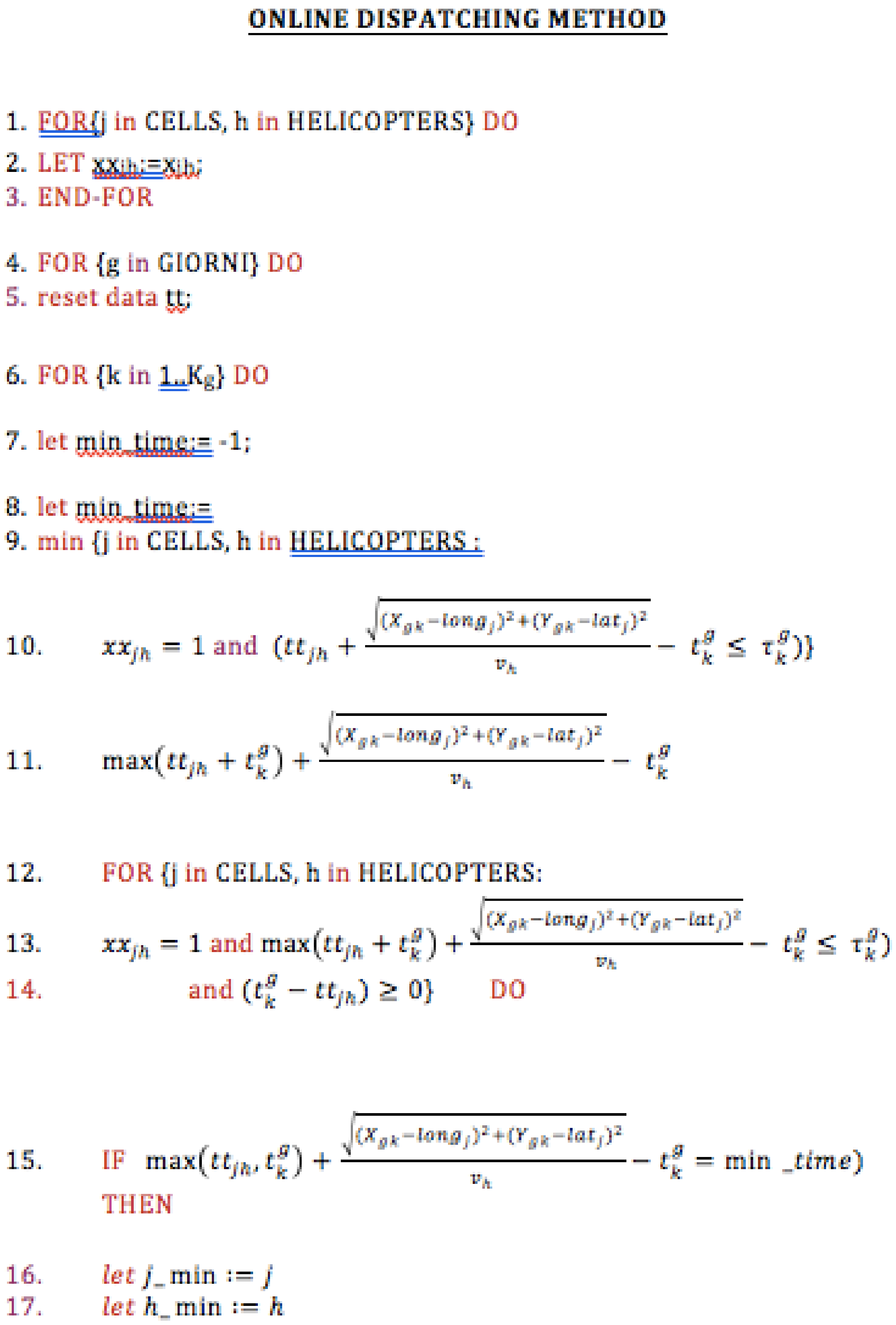
How constraints are modelled can change the current results of the model. While some of them are inserted as compatibility constraints - for instance, constraints a) models the fact that no helicopter can be present in a cell if there is no open base, b) represent the fact that could be not an intervention of helicopter h if the latter does not exist - others change significantly results. Constraint c) defines a maximum budget which cannot be exceeded; total costs are defined as the summation of the leasing cost for each helicopter. Constraints d) an e) guarantee that the incident place is reached within the maximum threshold even if the mission start is not immediate (respectively, for *flexible* and *rigid* model). Constraints h) guarantees two helicopters do not intervene on the same incident. Constraints g) have been modelled in order to avoid to lump helicopters on the same base. Constraints f) guarantee that if the helicopter is involved in a mission, it cannot be into another one. Constraints i) and j) allows the model to keep a minimum temporal gap between two consecutive mission starts for the same helicopter (constraints i) refer to the *rigid* BLHD problem, whilst constraints j) refer to the *flexible* BLHD problem).

The proposed model has a sort of *predictive* awareness: everyday, the model knows *a priori* how many incidents there will be, where, their occurrence time and their code; hence, it can decide to delay some calls (generally green code events) to serve critical patients whose incidents would happen shortly: in such a way, it can organize the turnover day by day, in an optimal manner. This kind of dispatching method has been developed because the first aim of the thesis is to locate HEMS bases in an optimal manner. Knowing *a priori* all incidents allows, therefore, better results. However, to remove such a *predictive* awareness and to validate results, a post-analysis manipulation exists: once the problem found an optimal solution, a new dispatching method acts. This new method allows to dispatch missions to helicopter in a way more similar to reality; in particular, it assigns events to helicopters as they chronologically arise. In this way, the results from the optimality are tested and no overestimation of total served mission is present. This dispatching method is called *online*. In the next section (Section 3.4) the pseudo-code of the *online* dispatching method is presented.

3.4 *Online* Dispatching Algorithm

In this section, the pseudo-code for the *online* dispatching method is shown. In Figure 3.2 and 3.3, one can see how missions are dispatched as they arise; hence no prediction is present and a decrease in the number of served mission must be expected.

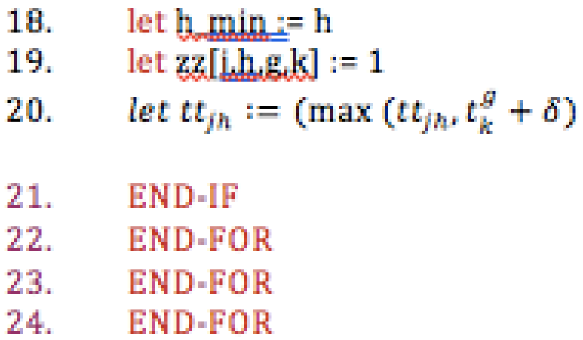
Rows 1. to 7. define parameters; parameters xx, yy and zz are the corresponding of the variables of the model, while parameter tt represents the hour until the helicopter h of the base in cell j is involved in a mission. Parameter min_time is the minimum time to serve a mission (j_min and h_min are the corresponding helicopter and base); the value of -1 means that that event cannot be served. Cycle *for* from row 9. to 11. is useful to initialize the parameter xx with the optimal solution coming from optimization. In cycles *for* of rows 13. to 23. it is assumed that events are provided in chronological order; parameter min_time is defined and parameter tt is reset for each day (the reason of which there is not an unique *for* cycle for both days and events). The second part, from row 25. to row 39. is aimed at selecting the (base,helicopter) couple which realizes the minimum. The term 'minimum' is referred to the minimum time for the helicopter h in cell j to reach the event k of day g.



ONLINE DISPATCHING METHOD

```
FOR{j in CELLS, h in HELICOPTERS} DO
    LET xxjh:=xjh;
END-FOR

FOR {g in GIORNI} DO
    reset data tt;

    FOR {k in 1..Kg} DO

        let min_time:= -1;

        let min_time:=
        min {j in CELLS, h in HELICOPTERS :

            $xx_{jh} = 1$ and $\left(tt_{jh} + \frac{\sqrt{(X_{gk}-long_j)^2+(Y_{gk}-lat_j)^2}}{v_h} - t_k^g \le \tau_k^g\right)\}$

            $\max\left(tt_{jh} + t_k^g\right) + \frac{\sqrt{(X_{gk}-long_j)^2+(Y_{gk}-lat_j)^2}}{v_h} - t_k^g$

        FOR {j in CELLS, h in HELICOPTERS:
            $xx_{jh} = 1$ and $\max\left(tt_{jh} + t_k^g\right) + \frac{\sqrt{(X_{gk}-long_j)^2+(Y_{gk}-lat_j)^2}}{v_h} - t_k^g \le \tau_k^g)$
                and $(t_k^g - tt_{jh}) \ge 0\}$    DO

            IF $\max\left(tt_{jh}, t_k^g\right) + \frac{\sqrt{(X_{gk}-long_j)^2+(Y_{gk}-lat_j)^2}}{v_h} - t_k^g = \min\_time)$
            THEN

                let $j$_min := $j$
                let $h$_min := $h$
```

Figure 3.2: Pseudo-code for *online* dispatching method



```
let h_min := h
let zz[j,h,g,k] := 1
let $tt_{jh}$ := (max ($tt_{jh}, t_k^g + \delta$)

END-IF
END-FOR
END-FOR
END-FOR
```

Figure 3.3: Pseudo-code for *online* dispatching method

CHAPTER 4

CASE STUDY DATA ANALYSIS

> [...] e il ponte, che ivi congiunge le due rive, par che renda ancor più sensibile all'occhio questa trasformazione, e segni il punto in cui il lago cessa, e l'Adda rincomincia, per ripigliar poi nome di lago dove le rive, allontanandosi di nuovo, lascian l'acqua distendersi e rallentarsi in nuovi golfi e in nuovi seni.
>
> A. Manzoni, *I Promessi Sposi* 1840

4.1 Case Study Description

Lombardy is an Italian region, placed in the northern part and shares borders with Switzerland to the north, with Piemonte region to the west, with Veneto region to the east and with Emilia-Romagna region to the south. Located at the base of Alps mountains and in the heart of Po valley, Lombardy gets off a strategic privileged position since placed on the principal routes connecting Mediterranean area with central Europe. Its shape makes it similar to a trapezoid, therefore it does not have issues characterizing long-streched regions or countries, such as huge inhabited zones. Lombardy area is approximately 23,860Km^2 equally divided into plain (47%) and mountains (41%); the remaining part is hilly (12%)[57]. Morphologically, Lombardy region is divided into five bands: alpine, pre-alpine, high-plane, low-plane, Po valley and Apenine. Among the highest mountains, there are Bernina peak (4029 m), Disgrazia peak (3678 m), Ortles

Area %

AAT	Non-mountainous area	Partly mountainous area	Fully mountainous area
BG	30%	2%	68%
BS	41%	1%	58%
CO	29%	3%	68%
CR	100%		
LC	22%	6%	72%
LO	100%		
MB	100%		
MI	100%		
MN	100%		
PV	84%		16%
SO			100%
VA	63%	5%	32%

Figure 4.1: Physical view of Lombardy region. The table shows physical percentage of each AAT.

peak (3905 m) and Adamello (3555 m). All physical items are visible in Figure 4.1. The region is wet by tenths of rivers and between them Po river, the longest in Italy which can count on several tributaries such as Ticino river, Adda river, Oglio river, and Mincio river. Not only rivers wet the region: hundreds of lakes, located especially in the pre-alpine area, are present; Maggiore lake, Lugano lake, Como lake, Iseo lake, Idro lake, and Garda lake (the largest in Italy). Lombardy population reaches 10,019,166 inhabitants (Istat January 2018). Active population (> 15 y.o.) stands at 8,856,074 inhabitants, with 1,139,463 foreign people[57]. Figure 4.2 shows age distribution among population in Lombardy. Largest cities in Lombardy are the twelve provincial capitals: Bergamo, Brescia, Como, Cremona, Lecco, Lodi, Mantua, Monza, Pavia, Sondrio, Varese, and Milan - the regional capital city. Every city has its own province. Figure 4.3 shows the division between provinces (black continuous line) and between municipalities with their own population density.

During the last years, interventions number is increased from 800,118 interventions in 2014 to 893,273 in 2017. Total emergency medical sheets opened are about to be 1,092,466, 87% of which are primary. Between primary missions, 14% are red-code, 56% yellow-code and 30% green-code (data from 2017, [81]). Presently there are 5 helicopters bases located in Sondrio, Como, Bergamo, Brescia e Milan-Bresso (see Figure 4.4). Como and Brescia are 24/7 operational bases, while the remaining are 12/7. Milan-Bresso, Sondrio and Como bases are equipped of a Leonardo AW139 helicopter whilst Bergamo and Brescia bases have an Airbus H145 model.

Interventions per base are clearly visible from Figure 4.1. Data are updated to the end of November 2018. Interrupted missions, training activations, and non-completed missions have been discarded.

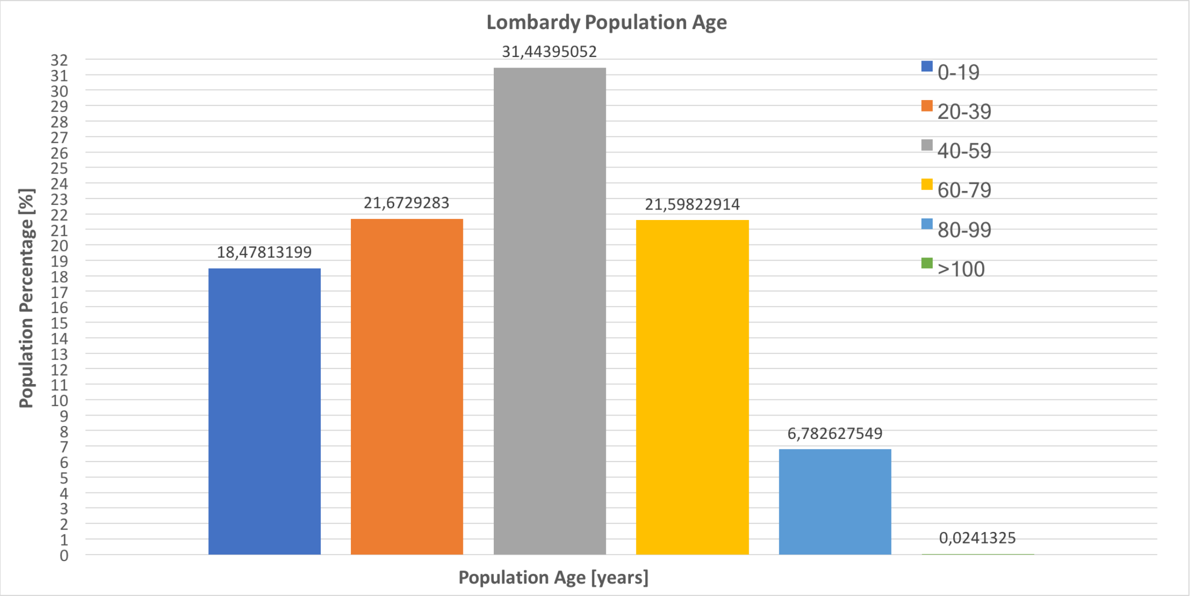


Figure 4.2: Age distribution among population in Lombardy

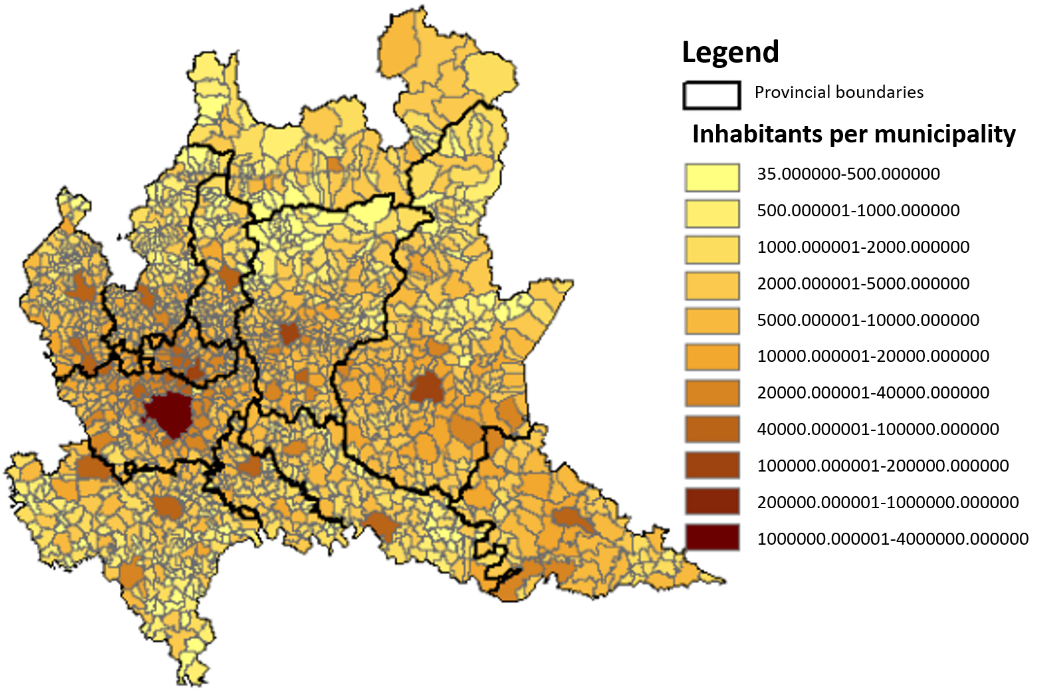


Figure 4.3: Population distribution among municipalities in Lombardy and provinces borders

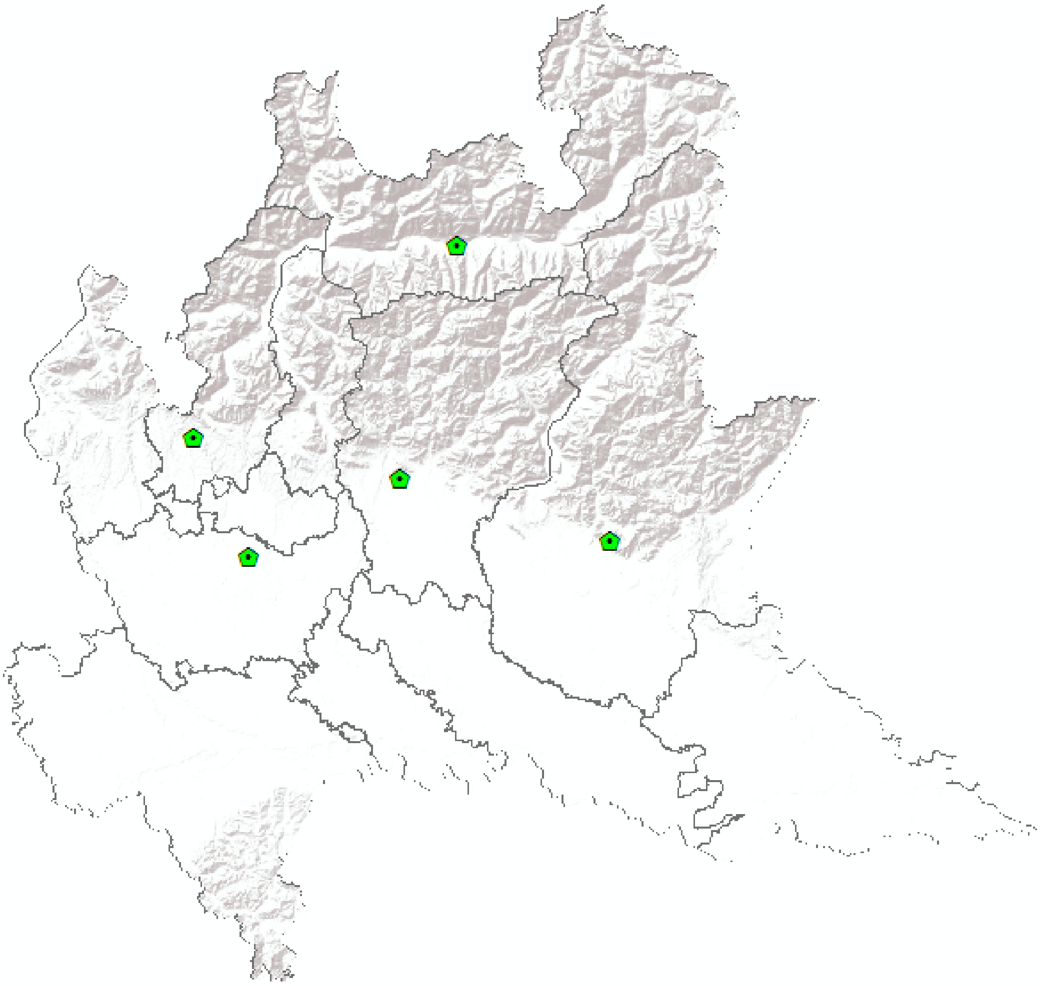
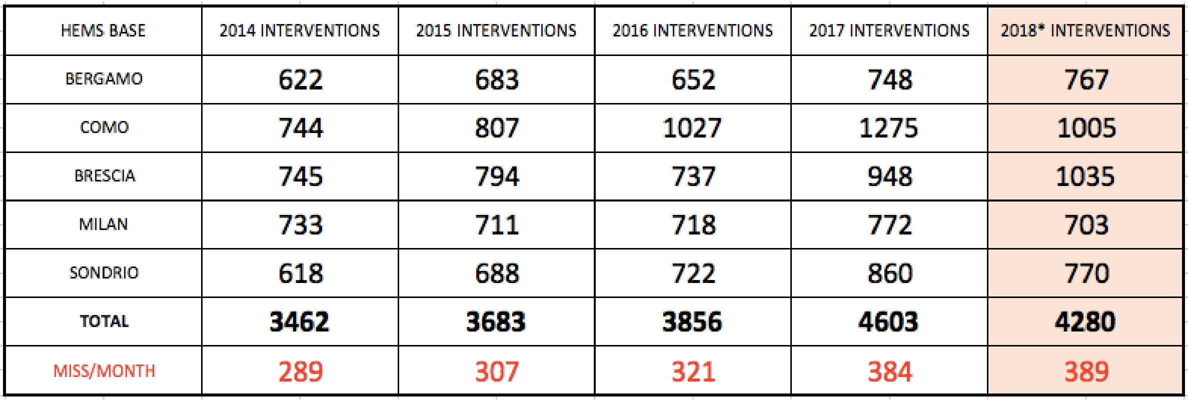
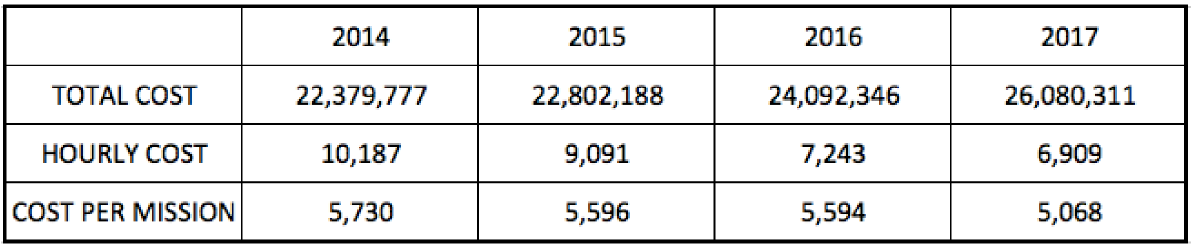


Figure 4.4: Current HEMS bases location in Lombardy



HEMS BASE	2014 INTERVENTIONS	2015 INTERVENTIONS	2016 INTERVENTIONS	2017 INTERVENTIONS	2018* INTERVENTIONS
BERGAMO	622	683	652	748	767
COMO	744	807	1027	1275	1005
BRESCIA	745	794	737	948	1035
MILAN	733	711	718	772	703
SONDRIO	618	688	722	860	770
TOTAL	**3462**	**3683**	**3856**	**4603**	**4280**
MISS/MONTH	289	307	321	384	389

Table 4.1: Interventions number per year from 2014 to late 2018



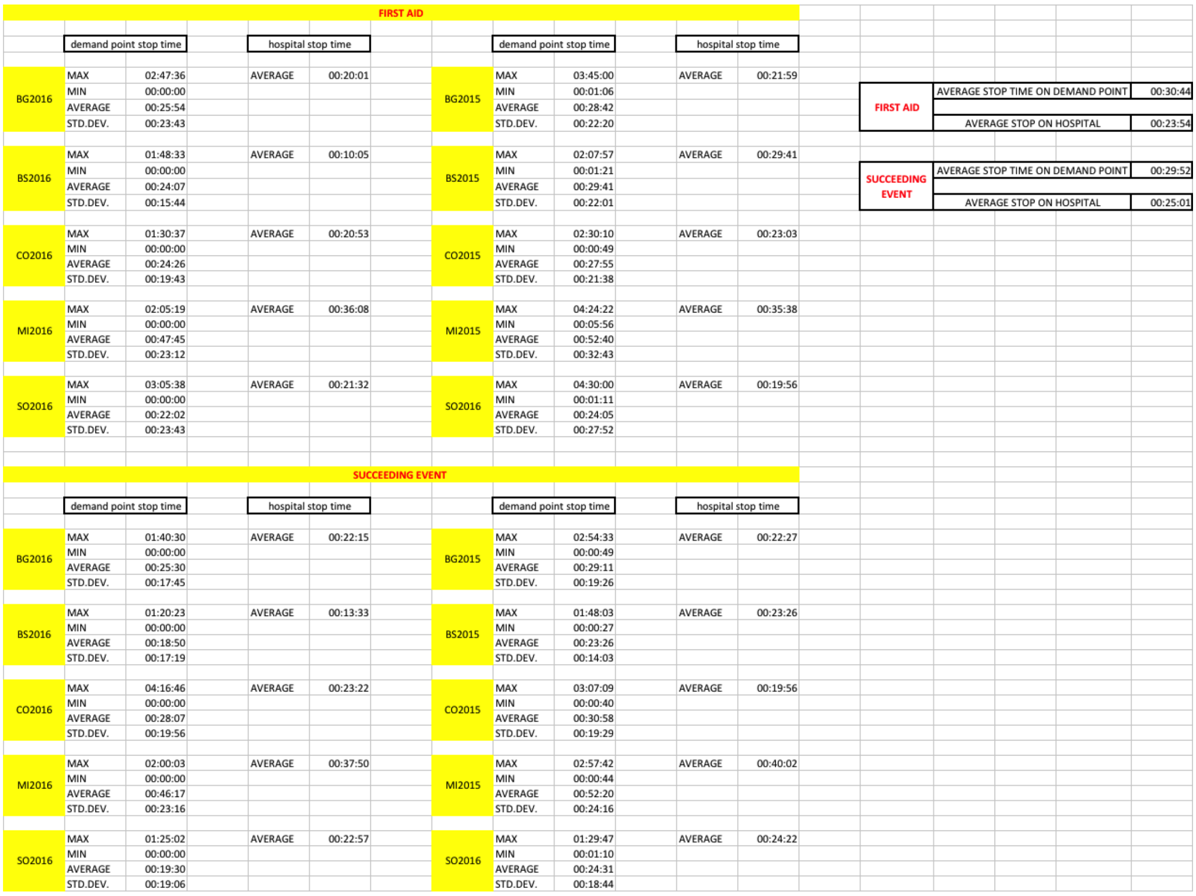
	2014	2015	2016	2017
TOTAL COST	22,379,777	22,802,188	24,092,346	26,080,311
HOURLY COST	10,187	9,091	7,243	6,909
COST PER MISSION	5,730	5,596	5,594	5,068

Table 4.2: HEMS cost in Lombardy during years from 2014 to 2017

A cost/activity analysis, performed during the years, highlighted how, although the total costs increased, the cost per mission decreased. This is evident if one looks at Table 4.2.

4.2 Pre-Processing Data Analysis

Preprocessing data analysis starts from rough data provided by AREU; these contain almost all kind of information for each event throughout the year 2015. It contains data such as event time and place, severity code, SOREU ID which dispatched the rescue request and the base ID which responded to that particular event. This rough data has been cleaned up, wheeled rescues have been divided by helicopter ones and finally split into the five different current HEMS bases plus an adding database containing extra-regional helicopter rescue (neighbouring regions or Switzerland). Data, again, have been more refined by dividing them by month and then by day, by hour and by minute. In such a way, a first analysis on base involvement could be carried off (see Figure 4.5. Moreover, the ephemeris are used to divide which rescue operation has to be considered daytime and which overnight. Further analysis has been conducted on stopping times of the helicopter on the demand point and on hospital, in case of first aid rescue or succeeding event. Succeeding event is a term used by AREU to indicate the helicopter is not the first medical aid intervening to incident. Results are shown in Figure 4.3, which shows two different years comparison; in this case data from 2016 were available and they were used to give more strength to the statistical analysis. The amount of time in the two cases is pretty the same; this is justified by the fact that a doctor coming with helicopter - unless a doctor is already on the site - for his own ethics, repeat almost all operations needed to understand the gravity of the patient injuries since people *in loco* generally have no medical academical education.



FIRST AID

		demand point stop time	hospital stop time				demand point stop time	hospital stop time	
BG2016	MAX	02:47:36	AVERAGE	00:20:01	BG2015	MAX	03:45:00	AVERAGE	00:21:59
	MIN	00:00:00				MIN	00:01:06		
	AVERAGE	00:25:54				AVERAGE	00:28:42		
	STD.DEV.	00:23:43				STD.DEV.	00:22:20		
BS2016	MAX	01:48:33	AVERAGE	00:10:05	BS2015	MAX	02:07:57	AVERAGE	00:29:41
	MIN	00:00:00				MIN	00:01:21		
	AVERAGE	00:24:07				AVERAGE	00:29:41		
	STD.DEV.	00:15:44				STD.DEV.	00:22:01		
CO2016	MAX	01:30:37	AVERAGE	00:20:53	CO2015	MAX	02:30:10	AVERAGE	00:23:03
	MIN	00:00:00				MIN	00:00:49		
	AVERAGE	00:24:26				AVERAGE	00:27:55		
	STD.DEV.	00:19:43				STD.DEV.	00:21:38		
MI2016	MAX	02:05:19	AVERAGE	00:36:08	MI2015	MAX	04:24:22	AVERAGE	00:35:38
	MIN	00:00:00				MIN	00:05:56		
	AVERAGE	00:47:45				AVERAGE	00:52:40		
	STD.DEV.	00:23:12				STD.DEV.	00:32:43		
SO2016	MAX	03:05:38	AVERAGE	00:21:32	SO2016	MAX	04:30:00	AVERAGE	00:19:56
	MIN	00:00:00				MIN	00:01:11		
	AVERAGE	00:22:02				AVERAGE	00:24:05		
	STD.DEV.	00:23:43				STD.DEV.	00:27:52		

SUCCEEDING EVENT

		demand point stop time	hospital stop time				demand point stop time	hospital stop time	
BG2016	MAX	01:40:30	AVERAGE	00:22:15	BG2015	MAX	02:54:33	AVERAGE	00:22:27
	MIN	00:00:00				MIN	00:00:49		
	AVERAGE	00:25:30				AVERAGE	00:29:11		
	STD.DEV.	00:17:45				STD.DEV.	00:19:26		
BS2016	MAX	01:20:23	AVERAGE	00:13:33	BS2015	MAX	01:48:03	AVERAGE	00:23:26
	MIN	00:00:00				MIN	00:00:27		
	AVERAGE	00:18:50				AVERAGE	00:23:26		
	STD.DEV.	00:17:19				STD.DEV.	00:14:03		
CO2016	MAX	04:16:46	AVERAGE	00:23:22	CO2015	MAX	03:07:09	AVERAGE	00:19:56
	MIN	00:00:00				MIN	00:00:40		
	AVERAGE	00:28:07				AVERAGE	00:30:58		
	STD.DEV.	00:19:56				STD.DEV.	00:19:29		
MI2016	MAX	02:00:03	AVERAGE	00:37:50	MI2015	MAX	02:57:42	AVERAGE	00:40:02
	MIN	00:00:00				MIN	00:00:44		
	AVERAGE	00:46:17				AVERAGE	00:52:20		
	STD.DEV.	00:23:16				STD.DEV.	00:24:16		
SO2016	MAX	01:25:02	AVERAGE	00:22:57	SO2016	MAX	01:29:47	AVERAGE	00:24:22
	MIN	00:00:00				MIN	00:01:10		
	AVERAGE	00:19:30				AVERAGE	00:24:31		
	STD.DEV.	00:19:06				STD.DEV.	00:18:44		

FIRST AID	AVERAGE STOP TIME ON DEMAND POINT	00:30:44
	AVERAGE STOP ON HOSPITAL	00:23:54
SUCCEEDING EVENT	AVERAGE STOP TIME ON DEMAND POINT	00:29:52
	AVERAGE STOP ON HOSPITAL	00:25:01

Table 4.3: Statistical analysis on on-scene and hospital stop time for different bases in two consecutive years

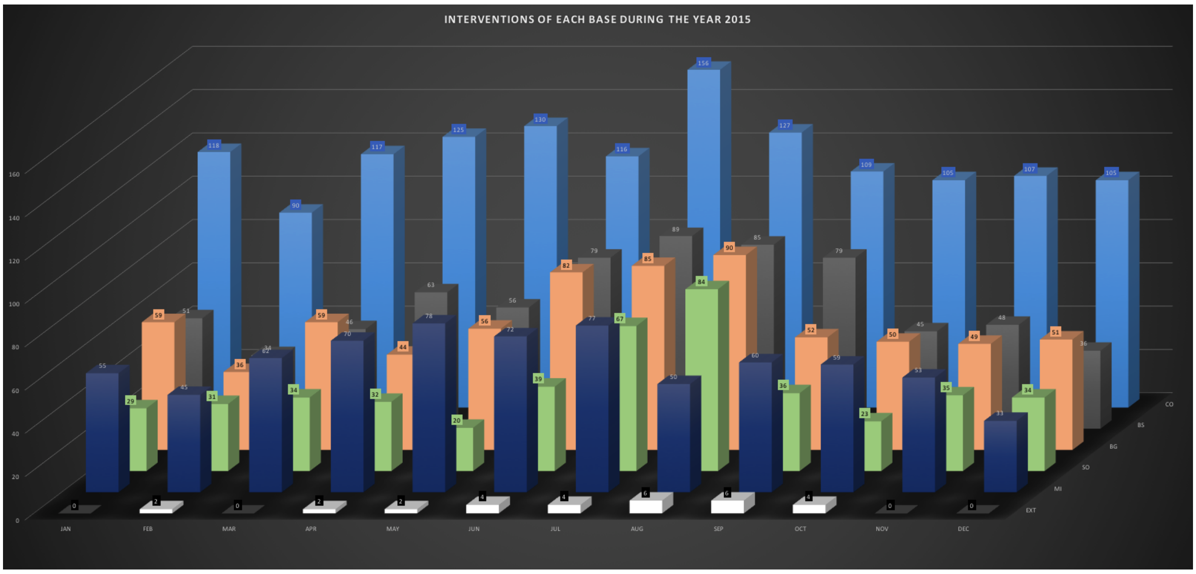


Figure 4.5: Statistical analysis on base involvement throughout the year 2015 for the current five HEMS bases and the extra-regional helicopters

It can be noticed the discrepancy in stop time between Milan-Bresso helicopter and the other ones. The average stop time on demand point of the AW139 of Milan-Bresso is more than double compared to other bases' helicopters. This fact can be justified if regional hospital capacity is analyzed; metropolitan hospitals and emergency rooms are the most overcrowded of the entire region. Therefore medical staff ensures that the nearest appropriate hospital is enough free to accept the patient; otherwise they wait on demand point until a hospital advice that it's ready to the emergency. Other hospitals and emergency rooms of the region do not suffer from such a problem and, in fact, the average time of the helicopter on demand point is about 20 minutes (the time needed to stabilize patient and to make primary checks) [**?**].

4.2.1 2015 Data

From month-by-month analysis discussed above, some interesting results are yet evident. From Figures 4.6 - 4.10 it results evident how some month - generally September to December - are characterized by a decrease in the number of incidents.

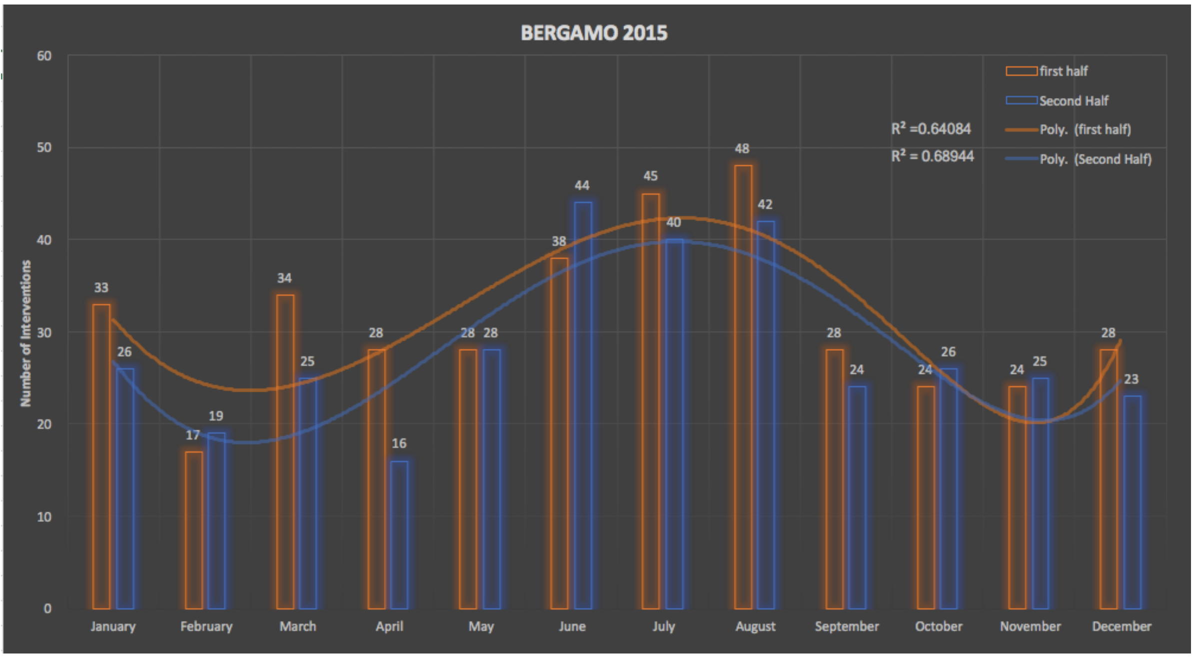


Figure 4.6: Trend of the number of interventions for Bergamo base in 2015 throughout the months

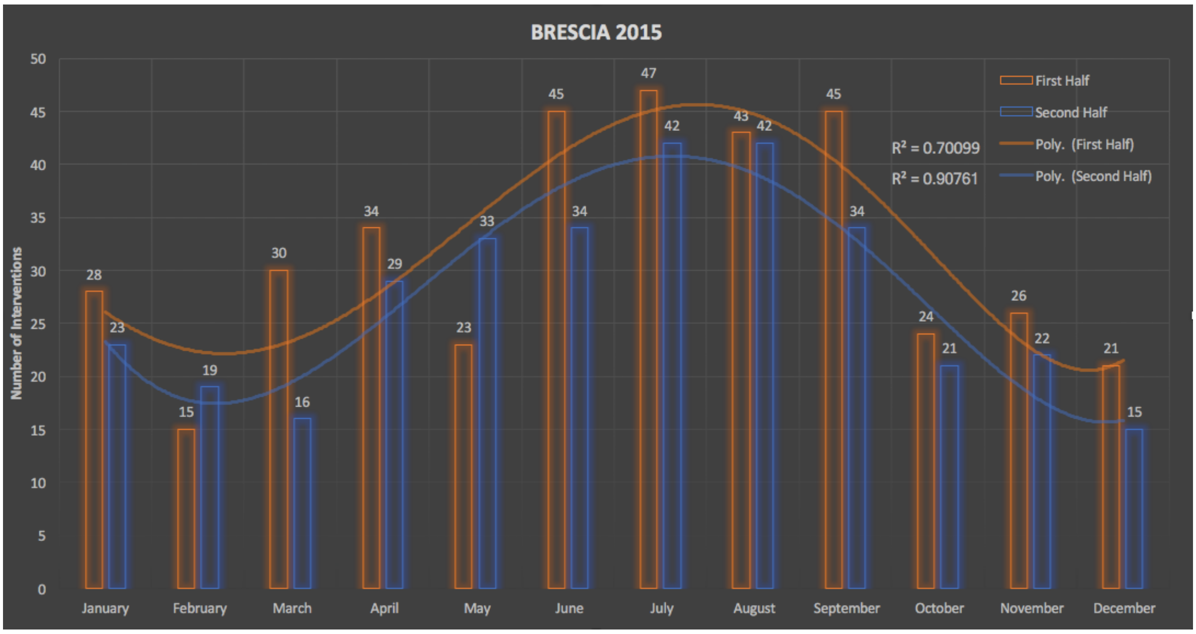


Figure 4.7: Trend of the number of interventions for Brescia base in 2015 throughout the months

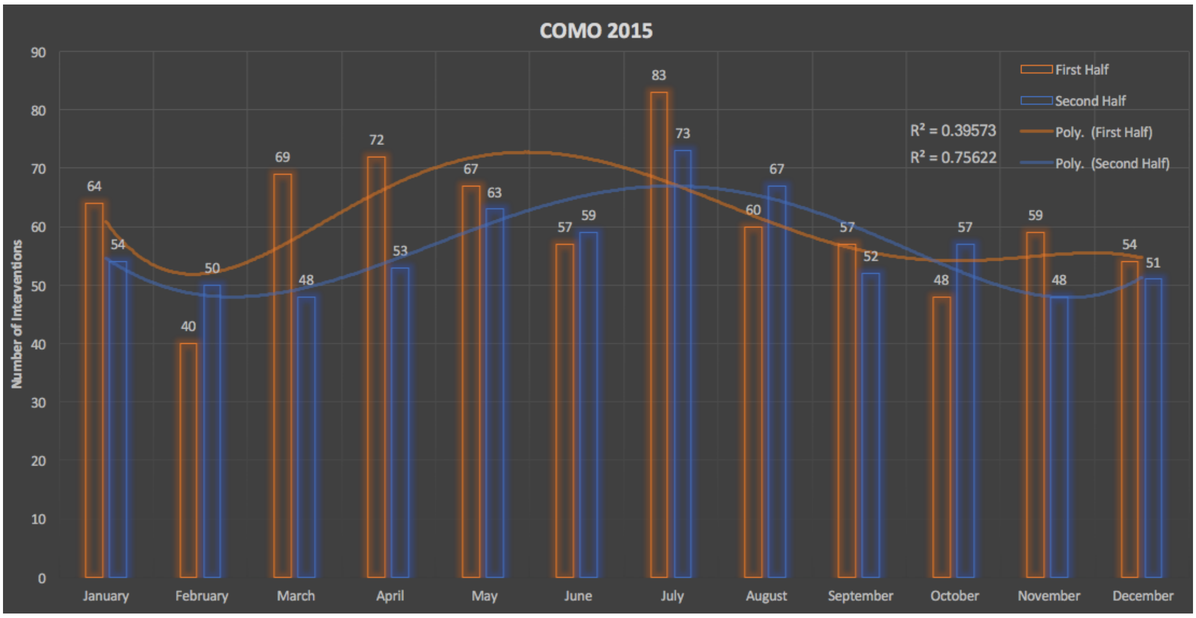


Figure 4.8: Trend of the number of interventions for Como base in 2015 throughout the months

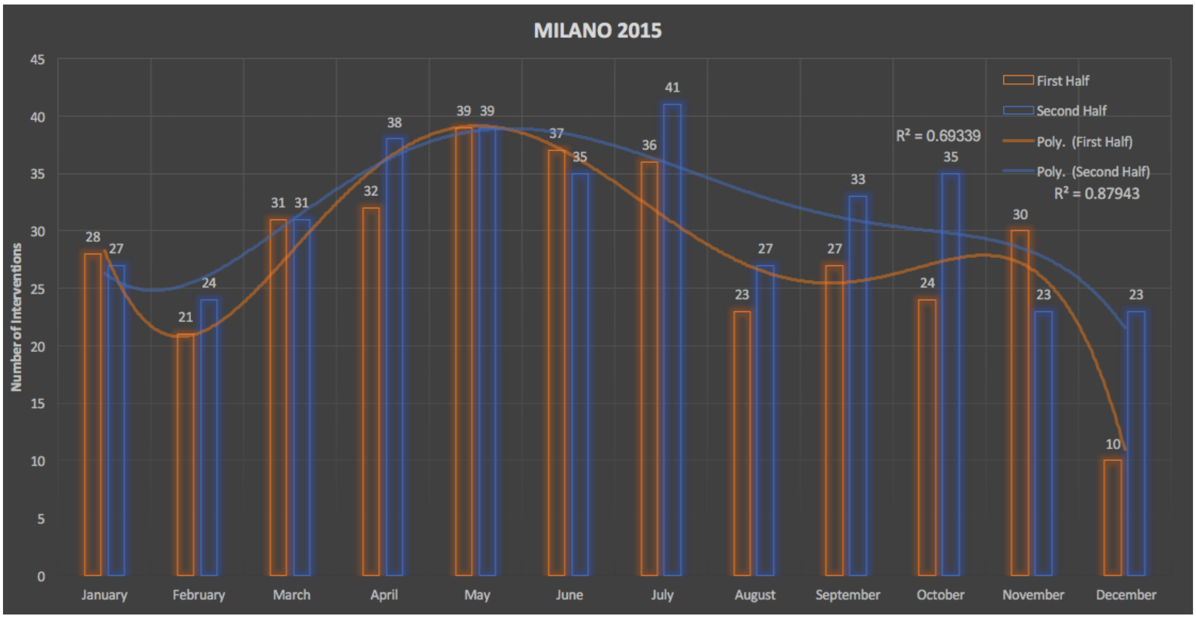


Figure 4.9: Trend of the number of interventions for Milan base in 2015 throughout the months

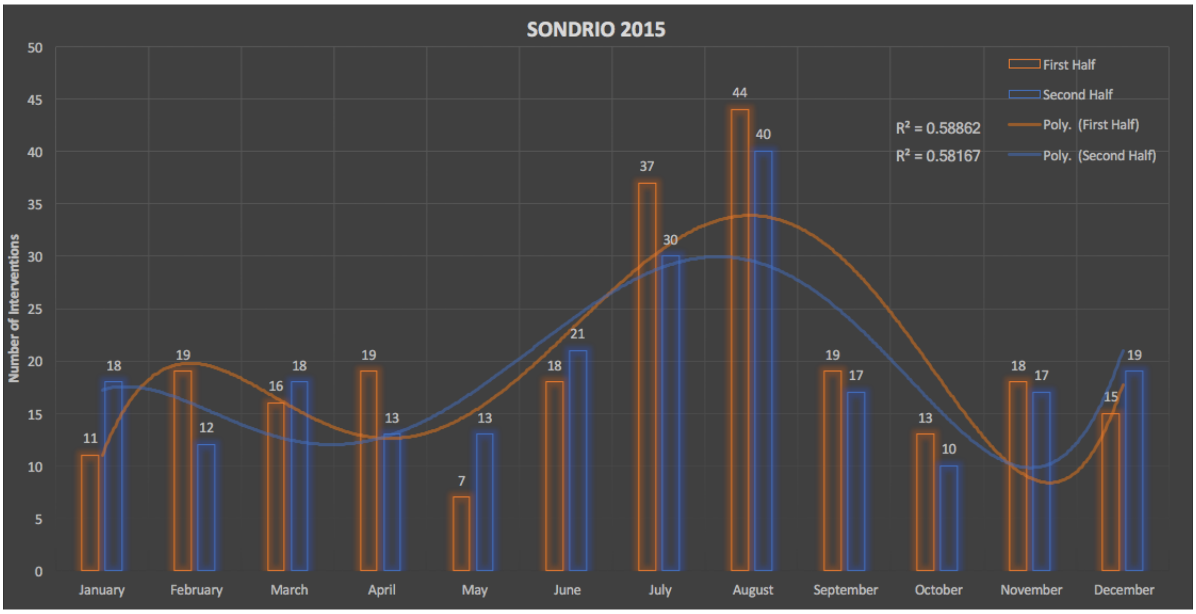


Figure 4.10: Trend of the number of interventions for Sondrio base in 2015 throughout the months

Therefore the natural question arising from these results is if it is possible to reduce the number of bases during the low-involvement months. This will be a part of the simulated scenarios in the next chapter. The months in which this scenario will be verified would be October, November, and December; these are the freer months is almost all bases, except for Como base which is highly-involved all year long, due to geographical position and the possibility to night operations.

During 2015, night ops were available in Como base, only (missions: 480). A small part, however, was conducted by the Milan-Bresso base (missions: 53).

CHAPTER 5

NUMERICAL EXPERIMENTS AND RESULTS

> It is a capital mistake to theorize before one has data. Insensibly one begins to twist facts to suit theories, instead of theories to suit facts.
>
> Sherlock Holmes

The models to solve the BLHD problem (described in Chapter 3) have been implemented in AMPL language [24] and solved with CPLEX solver, version 12.9 on a 8Gb RAM AMD A9-9420 Radeon R5 3.0GHz Windows 10.

The experiments campaign have been organized considering three different scenarios: the so-called *Green Field* scenario, in which no initial base is supposed to exist, the *Conditioned* scenario, in which chosen bases are forced to exist and the *Fictitious* scenario, in which the model limits are tested. From a preliminary study, the Green Field scenario would locate the bases in different positions with respect to the current ones since there has never been a systematic cost-benefit analysis based on mathematical optimization in Lombardy. Therefore current base positions are the results of past decisions and experiences. Green field solution is, however, rarely practically viable, as this would imply tearing down all existing bases and start building anew. For this reason, Conditioned scenario, which considers fixing some existing bases, have been performed. Inside the Green Field scenario, three kinds of experiments have been performed: the first, aimed at searching differences the solutions of the *rigid* model and *flexible* one; from the second on, only *rigid* model has been tested, since computationally affordable on long periods (>1 week). The second kind of experiment concerns the seasonal analyses. Moreover, during the Fall season, a sensitivity analysis on number of needed helicopters has been also performed. The third kind of experiment is performed on a very long time horizon: 6 months.

The chapter, therefore, is organized as follows:

- Green Field Scenario
  - Weekly Analysis (using both *Rigid* and *flexible* models)
    - EXP A: First Week of 2015;
    - EXP B: Second Week of 2015;
    - EXP C: Third Week of 2015;
    - EXP D: Last 10 Days of 2015;
  - Seasonal Analysis (using *rigid* model)
    - EXP GF1: Winter 2015;
    - EXP GF2: Spring 2015;
    - EXP GF3: Summer 2015;
    - EXP GF4: Fall 2015;
    - EXP GF5: Fall 2015 with 4 Helicopters;
  - Semestral Analysis (using *rigid* model)
    - EXP GF6: Cold Months 2015;
    - EXP GF7: Warm Months 2015;
- Conditioned Scenario (using *rigid* model)
  - Fixing Milan-Bresso and Como bases
    - EXP C1: Fixed Milan-Bresso and Como bases during Fall 2015 with 5 helicopters;
    - EXP C2: Fixed Milan-Bresso and Como bases during Fall 2015 with 4 helicopters;
- Fictitious Scenario (using *rigid* model)
  - A fictitious Month;
    - EXP F1: How model reacts with an extremely overcrowded month?
- Final Considerations on the Experimental Campaign
  - *Rigid* vs *Flexible* Model
  - *Predictive* vs *Online* Method
  - Towards a Stable Solution

The input parameters for the models, described in Chapter 3, are set as follow. Lombardy region area has been divided by mean of a grid into cells whose size is 10Km for a total of n= 244 cells. Every cell, therefore, covers a 100Km^2 area. Scores have been chosen to be Θ= 100 for a red code event, Θ= 40 for an impervious green code event and Θ= 1 for a green code event. On-incident and on-hospital stop times are fixed and derive from statistical considerations, as discussed in Chapter 4. The time threshold for a red-code mission to be served is fixed to τ= 30 minutes, for a green code is τ= 180 minutes. Parameter H is fixed and not variables with the events, meaning that the hypothesis of uniform distribution of hospitals is set (H= 15). Parameter P is defined as a binary flag that shows if the helicopter is the first medical aid to arrive on the scene. Parameter W is fixed to be 25 minutes (as suggested by Dr.Angelo Giupponi, Bergamo AAT Director). Cruise flight speeds are set as v_{AW139}=140kn, v_{H145}=120kn (as suggested by Cpt. Stazzonelli, AREU) as long as ignition time set to 5 minutes for AW139 and 2.5 minutes for H145 and shut-off times set to 3 minutes. Costs, provided by Dr. Giupponi [**? ?**], are discussed in result comments. Parameters ϑ_1, ϑ_2, ϑ_4, ϑ_5 come from statistical considerations (Chapter 4, Section 4.2). Parameter ϑ_3 represent the amount of time requested for landing/taking-off maneuvers with respect to a typical cruise flight and its value come from pilots' experience. Parameter δ has been estimated as 70 minutes from statistical considerations. Value of big M value for constraints i) and j) is set to the total hours in a day plus one, i.e. 25.

Graphical results are obtained using ESRI ArcGis Desktop 10.6 for Windows and mapped using the reference ellipsoid WGS1984 (World Geodetic System 1984) that, from 2000, is the mandatory standard for air navigation (decided by ICAO) and the same geographical coordinate system used in GPS coordinates. CPU time limit is set to two hours for all experiments except for the semestral ones, in which CPU time limit is set to four hours.

5.1 Green Field Scenario

5.1.1 Weekly Analysis

These very first experiments have the aim of compare the results coming from the *rigid* model to the problem with outputs of the *flexible* model. This experiment has been run since the flexible approach to the problem is computationally unviable for one month or more; for this reason, a weekly comparison has been carried out.

5.1.1.1 Experiment A: First Week of 2015

The first week of the year 2015 (Jan. 1st to Jan. 7th) counts 81 events, 70 of which red codes, and the remaining part green codes. In both cases the unserved events are null. Figure 5.1 shows incidents locations and opened bases with the two different models. In the same figure, it is also possible to see the current position of HEMS bases for an immediate comparison.

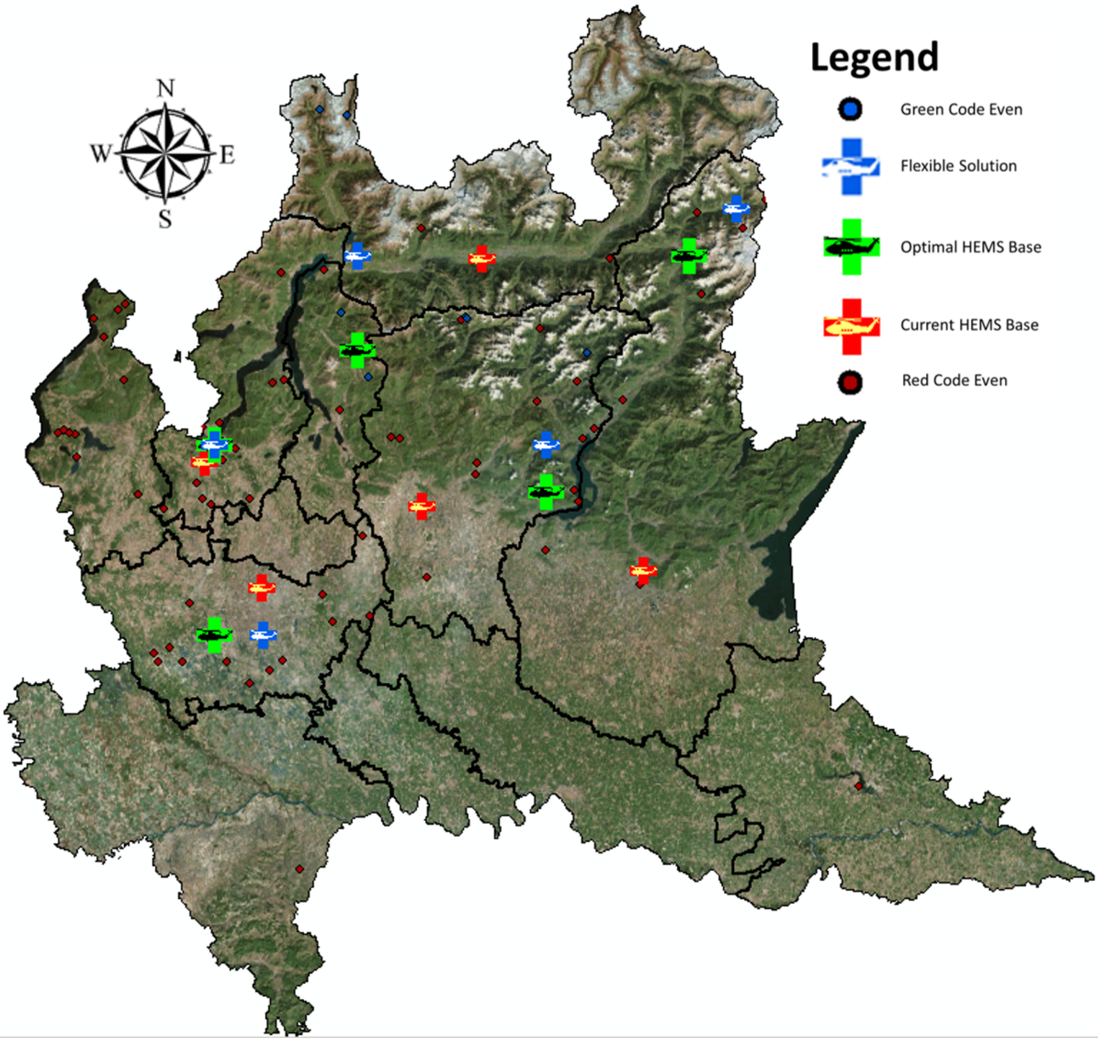
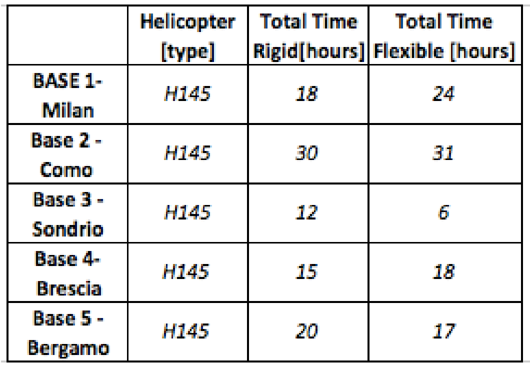


Figure 5.1: Map showing incidents location, the current HEMS bases location and the proposed ones for the first week of 2015

In the first instance, the base position is slightly different in the *rigid* model and in the *flexible* one. Como location is the best choice, as Figure 5.1 shows and symbols are superimposed. Brescia and Bergamo bases are shifted to the north-west; Bergamo base in flexible solution is shifted at the same latitude of Sondrio base. The latter, on the other hand, has been shifted to the east, keeping the same latitude. In both cases, five H145 has been chosen and the total time used is shown in Figure 5.1.

Costs difference is very poor, having €159’208 (*flexible*) and €160’001 (*rigid*) of operational costs and the fixed cost of leasing helicopter for a week, of €40’833.



	Helicopter [type]	Total Time Rigid[hours]	Total Time Flexible [hours]
BASE 1- Milan	*H145*	*18*	*24*
Base 2 - Como	*H145*	*30*	*31*
Base 3 - Sondrio	*H145*	*12*	*6*
Base 4- Brescia	*H145*	*15*	*18*
Base 5 - Bergamo	*H145*	*20*	*17*

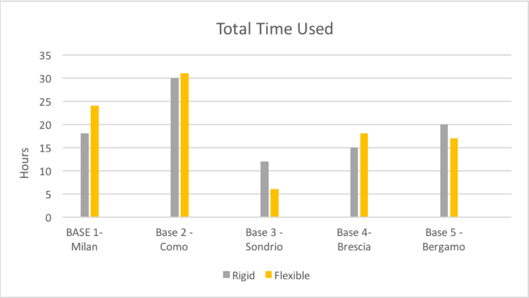


Table 5.1: Table and graphics showing total time used by each helicopter in each cell and gamma value for the first week of January 2015

5.1.1.2 Experiment B: Second week of 2015

The second week of the year 2015 (Jan. 8th to Jan. 14th) has a total of 71 events, divided in 63 red codes and 8 green codes. In Figure 5.2, incidents location and HEMS (both current and proposed) are visible.

The number of unserved events is zero for both cases. As Figure 5.2 shows, solutions from the two models are different: Como base is located exactly where it currently is as well as Bresso base whose solutions are located close to the current base location. A common solution has been found 33Km south of Brescia base, while Bergamo and Caiolo bases are no longer present: the respective bases have been placed in the segment connecting current Brescia and Caiolo bases, in the northern territories of Iseo lake. In particular, from the figure, it seems that Caiolo base has moved towards south (for both models) and Bergamo base moved towards east, few kilometers north to current Brescia base (for both models). In both cases, five H145 has been chosen and the total time used in the two models is shown in Figure 5.2.

Costs are quite the same, having €141’457 (*flexible*) and €139’693 (*rigid*) of operational costs and the fixed cost of leasing helicopter for a week, of €204’165.

5.1.1.3 Experiment C: Third week of 2015

The third week of the year 2015 (Jan. 15th to Jan. 21st) counts 51 red codes, 3 green codes for a total of 54 events, which are visible in Figure 5.3; in the same figure, it is also possible to see the proposed position of the bases using both models and the nowadays location of HEMS bases for an immediate comparison.

The number of unserved events is zero. Bergamo base is the one which diverges more from the current position and for which the solution coming from *rigid* and *flexible* models are different, as shown in Figure 5.3: the bases are opened 34Km (*rigid*) and 43Km (*flexible*) to the north-east of current base. But also Caiolo base proposed solutions are quite far from the current Caiolo base

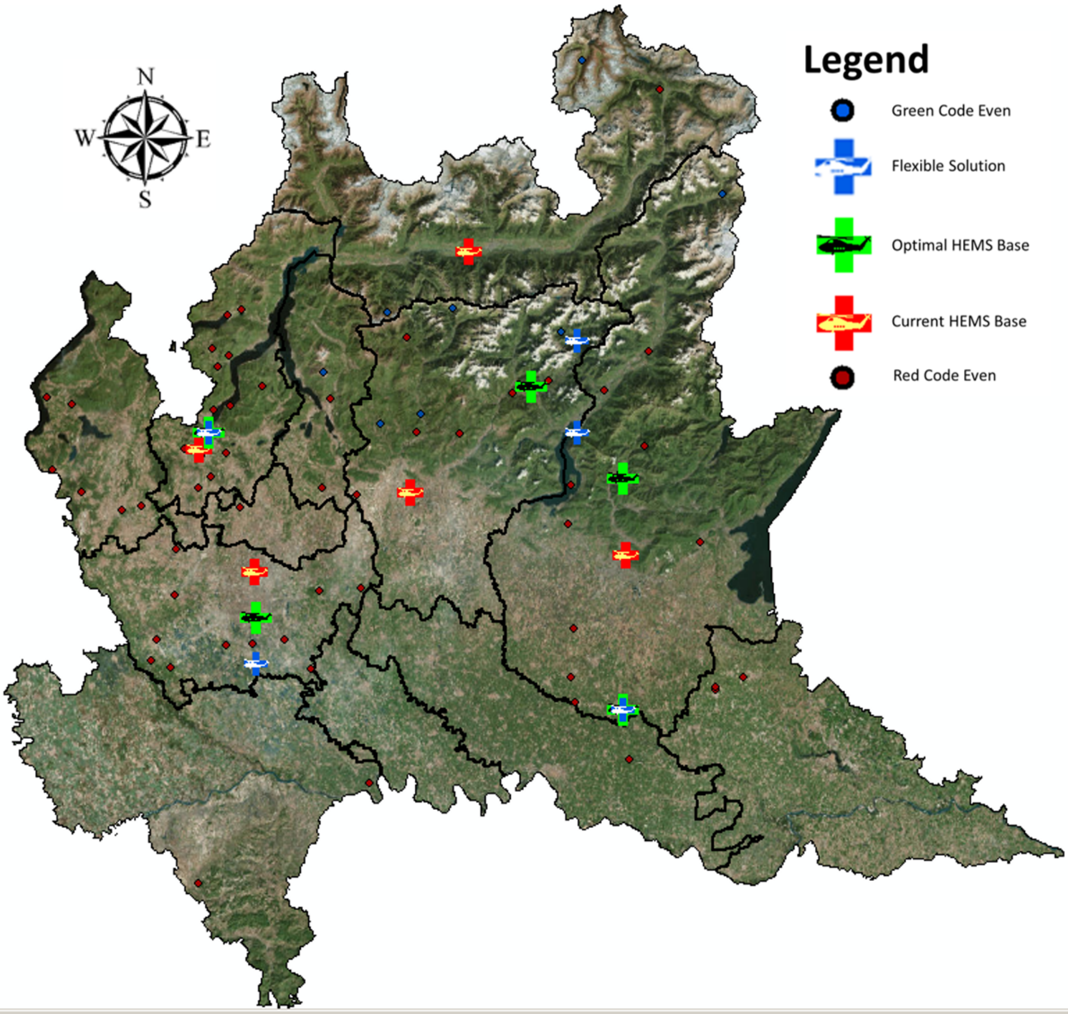


Figure 5.2: Map showing incidents location, the current HEMS bases location and the proposed ones for the second week of 2015

(about 47Km NE) but solutions of two models match. The other four bases are located close to the nowadays distribution and they all are the solution of both models. In both cases five H145 has been chosen and the total time used in the two models is shown in Figure 5.3.
Analyzing costs, a total of €306'557 has been spent for the *rigid* model (€102'392 for flight operations and €204'165 for leasing) and a total of €306'442 for the *flexible* algorithm (€102'278 for flight operations and €204'165 for leasing).

5.1.1.4 Experiment D: Last 10 days of 2015

The last ten days of the year 2015 (Jan. 22nd to Jan. 31st) counts 103 events (87 red codes and 16 green codes). Figure 5.4 shows incidents' locations and opened bases with the two different models. In the same figure, it is also possible to see the current position of HEMS bases for an

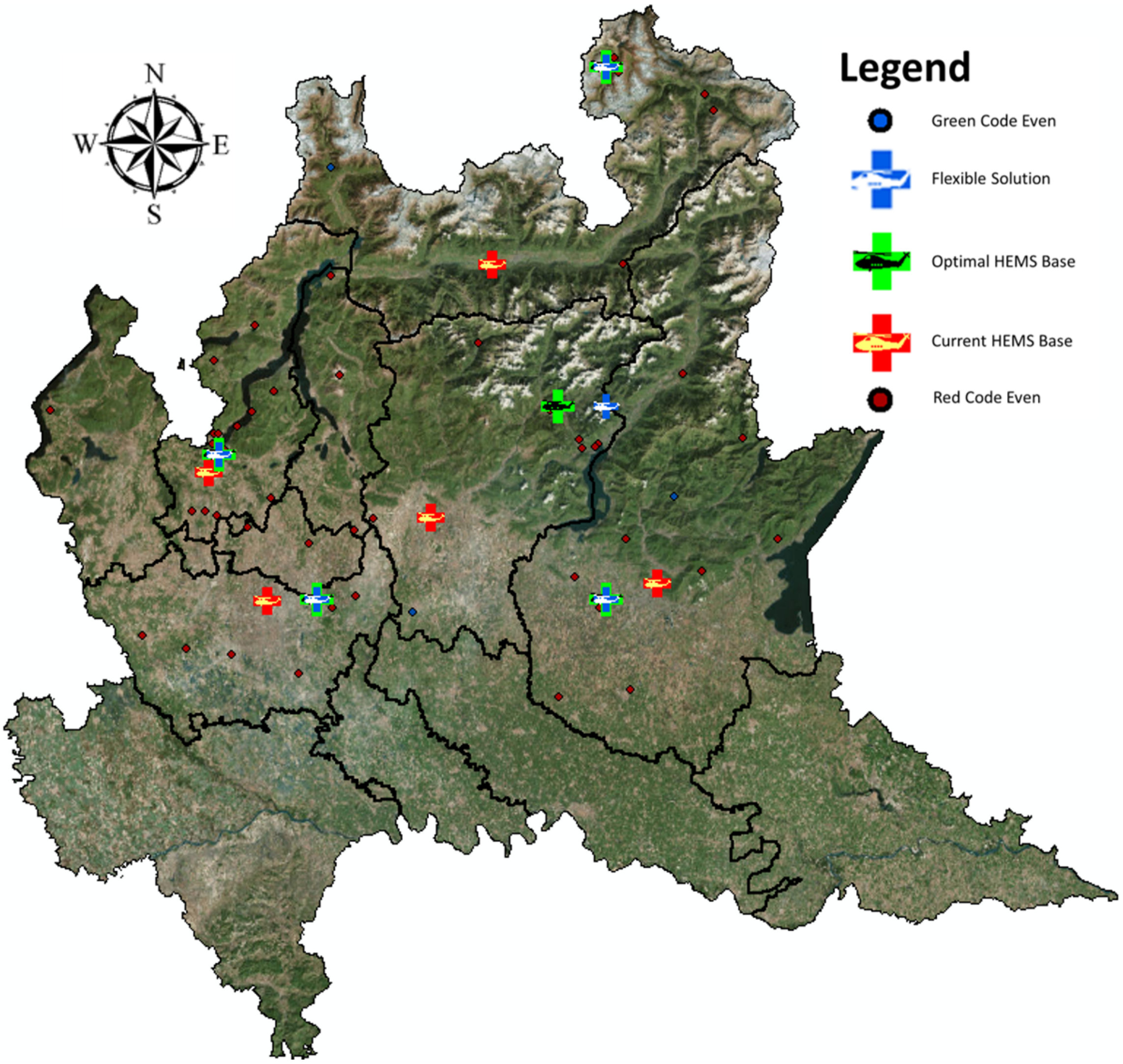
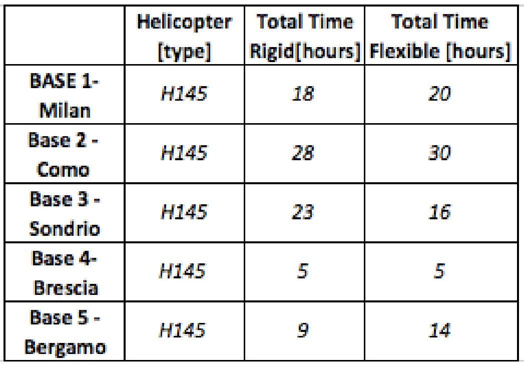


Figure 5.3: Map showing incidents location, the current HEMS bases location and the proposed ones for the third week of 2015



	Helicopter [type]	Total Time Rigid[hours]	Total Time Flexible [hours]
BASE 1- Milan	*H145*	*18*	*20*
Base 2 - Como	*H145*	*28*	*30*
Base 3 - Sondrio	*H145*	*23*	*16*
Base 4- Brescia	*H145*	*5*	*5*
Base 5 - Bergamo	*H145*	*9*	*14*

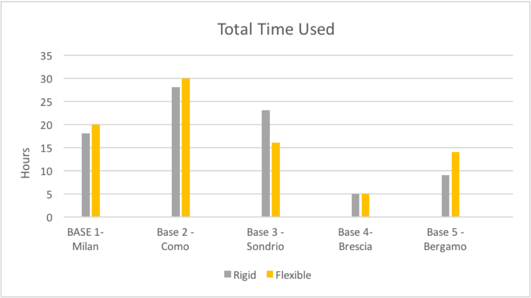
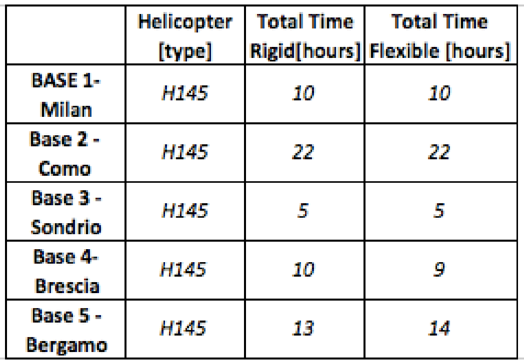


Table 5.2: Table and graphics showing total time used by each helicopter in each cell and gamma value for the second week of January 2015



	Helicopter [type]	Total Time Rigid[hours]	Total Time Flexible [hours]
BASE 1- Milan	*H145*	*10*	*10*
Base 2 - Como	*H145*	*22*	*22*
Base 3 - Sondrio	*H145*	*5*	*5*
Base 4- Brescia	*H145*	*10*	*9*
Base 5 - Bergamo	*H145*	*13*	*14*

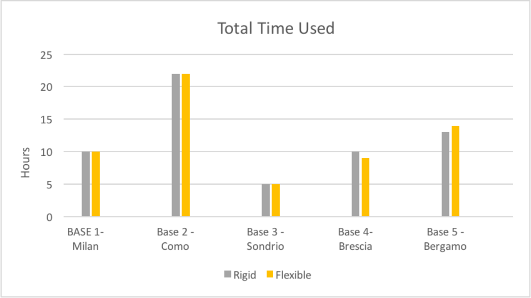


Table 5.3: Table and graphics showing total time used by each helicopter in each cell and gamma value for the third week of January 2015

immediate comparison.

The number of unserved events is null. Base position is exactly the same in *rigid* model and in *flexible* one, except for Como base which differs of just 10Km. However, the proposed locations for new bases are completely different from the current distribution: except for Como whose new base is located close to the current one (10Km distant), Bresso base is now in Lodi province, Bergamo base has been moved on the shores of the Como lake (near Resegone mountain), Brescia base has shifted towards north, 10Km north of Lovere and Caiolo base is now 35 Km east of its current position. In both cases, five H145 has been chosen and the total time used is shown in Table 5.4.

Costs difference is about 1%, counting €203'571 (*flexible*) and €201'927 (*rigid*) of operational costs and the fixed cost of leasing helicopter for a week, both of €291'667.

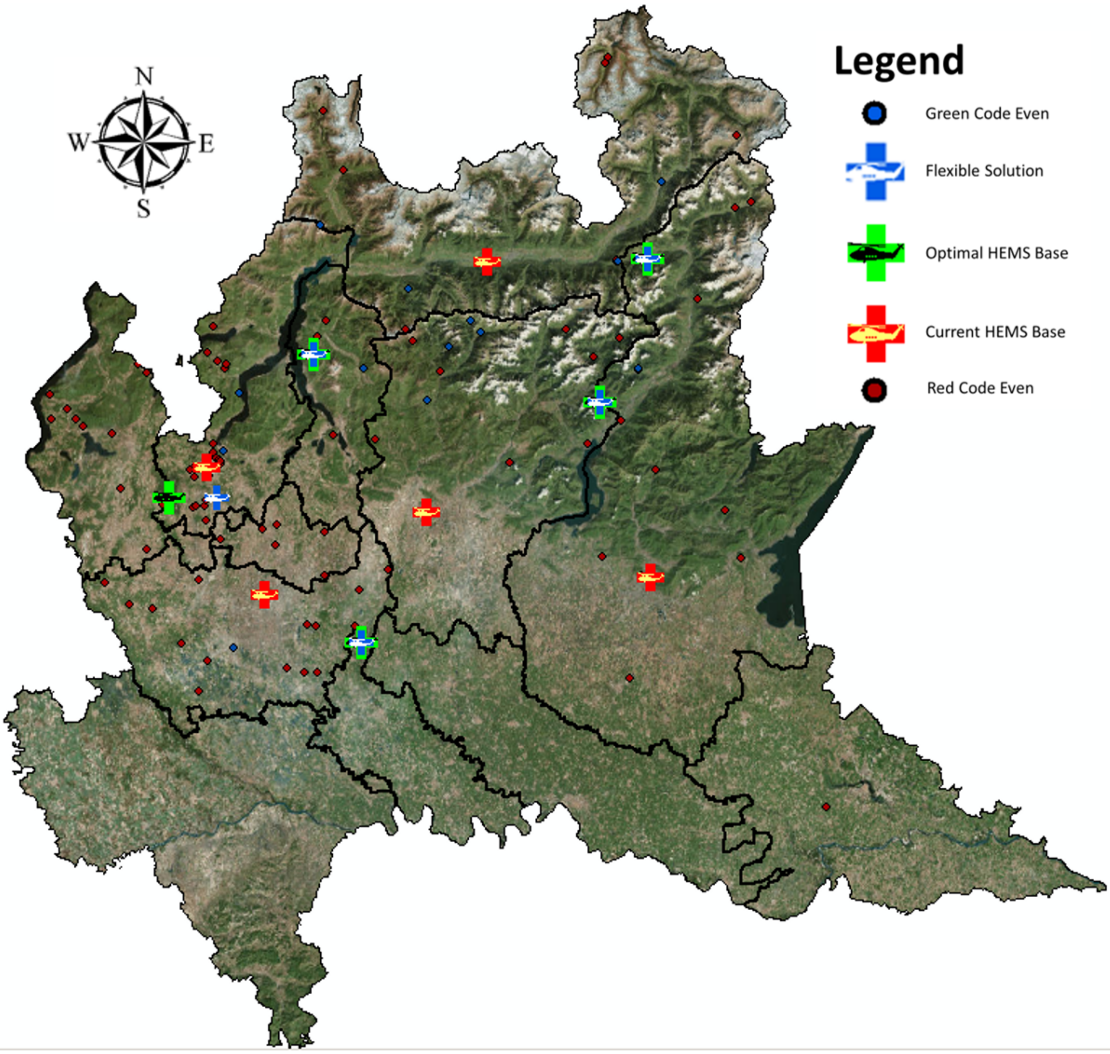
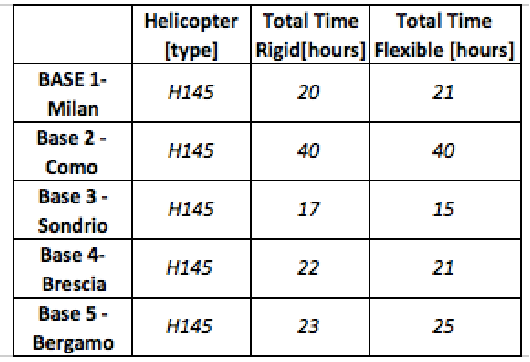


Figure 5.4: Map showing incidents location, the current HEMS bases location and the proposed ones for the last ten days of 2015



	Helicopter [type]	Total Time Rigid[hours]	Total Time Flexible [hours]
BASE 1- Milan	*H145*	*20*	*21*
Base 2 - Como	*H145*	*40*	*40*
Base 3 - Sondrio	*H145*	*17*	*15*
Base 4- Brescia	*H145*	*22*	*21*
Base 5 - Bergamo	*H145*	*23*	*25*

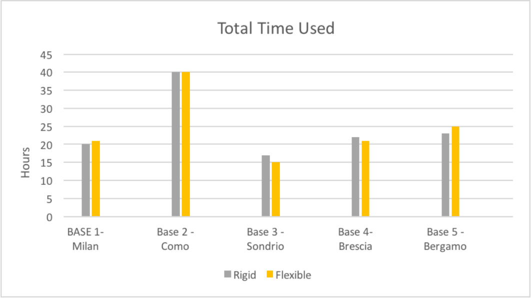


Table 5.4: Table and graphics showing total time used by each helicopter in each cell and gamma value for the last ten days of January 2015

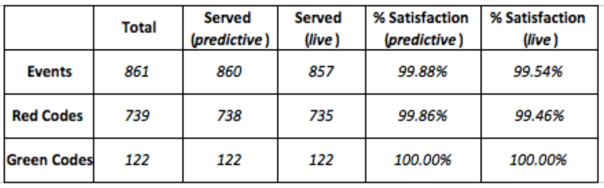
5.1.2 Seasonal Location-Allocation Problem

This first set of experiments is aimed at locating bases and allocate events in Lombardy, in green field scenario basing on seasonal variations of the events, using five helicopters (as current configuration); an additional experiment is set up to investigate if a lower number of helicopters are sufficient during the low involment season (Fall). The experiments are organized as follows: in the first instance, a brief analysis of events, their distribution and the total number of missions is shown. Then an analysis of base optimal location with respect to the current distribution. Analyses on total time used for each helicopter in the considered time-period and the average delay of the helicopter interventions is made. Finally, a comparison between the total number of served missions with *predictive* and *online* methods is conducted. To close every experiment, a table showing a comparison between the total number of served mission with the optimal and the current bases location using *online* dispatching method, when applicable. All data - except the table comparing the total number of served mission - have to be considered as in *predictive* method.

5.1.2.1 Experiment GF1: Winter 2015

This experiment is intended to discover the optimal base location, counting on five helicopters in as many bases, for the winter season. Winter (January, February, March) 2015 incidents distribution is visible in Figure 5.5. The season counts 861 incidents, 739 of which are red-code and 122 green code.

Just one event (red-code) is not served due to the presence of six (more than the total number of helicopters) simultaneous incidents in the time-windows of a single mission (delta value, 70 minutes). This happens on February 10th at 2.14pm in Ponte di Legno. Events distribution is visible in Figure 5.5 as well as the opened base; in the same figure, it is possible to see also the nowadays distribution of bases for an immediate comparison. The proposed position for the



	Total	Served (*predictive*)	Served (*live*)	% Satisfaction (*predictive*)	% Satisfaction (*live*)
Events	*861*	*860*	*857*	*99.88%*	*99.54%*
Red Codes	*739*	*738*	*735*	*99.86%*	*99.46%*
Green Codes	*122*	*122*	*122*	*100.00%*	*100.00%*

Table 5.5: Details about total, served and unserved events and satisfaction percentage for Winter 2015

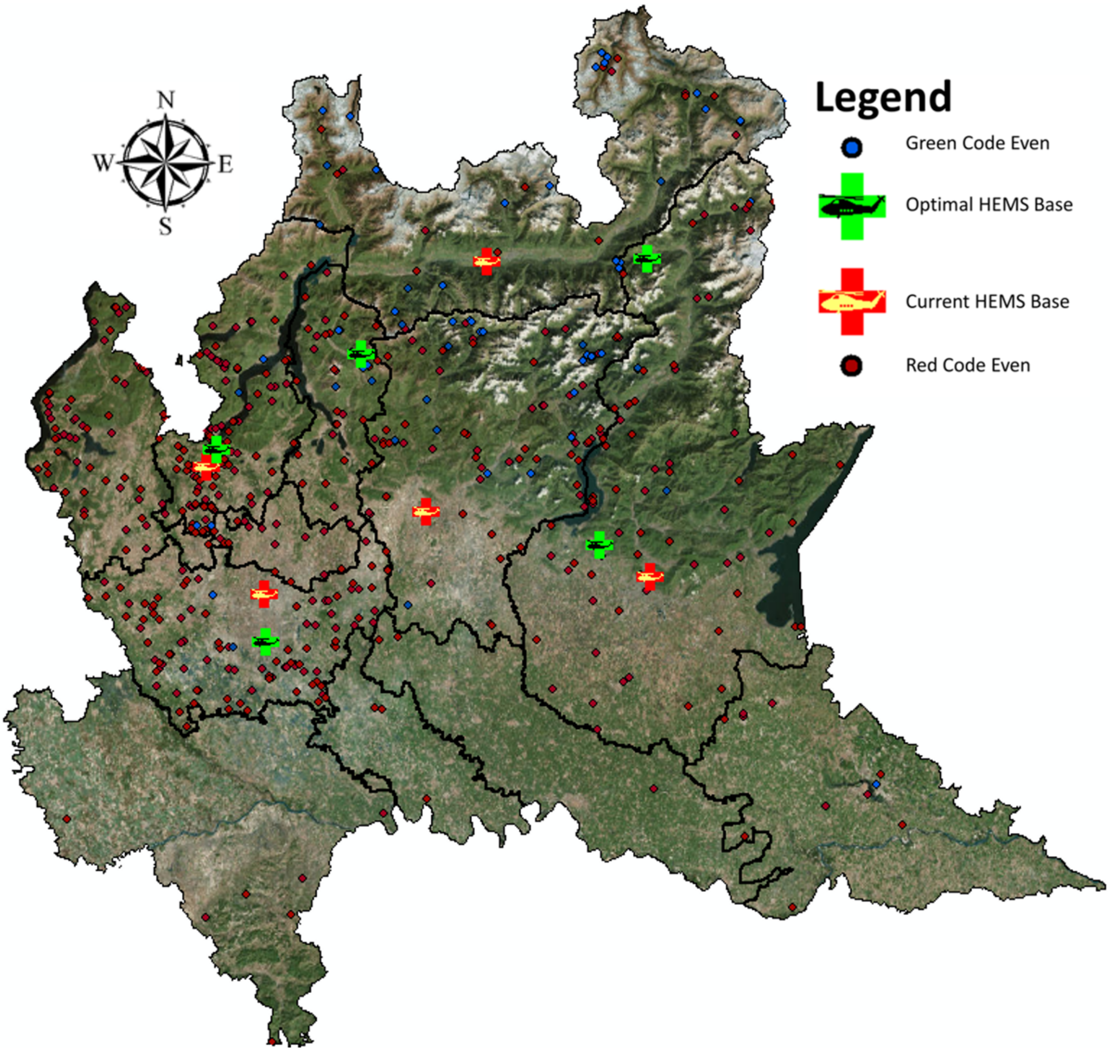
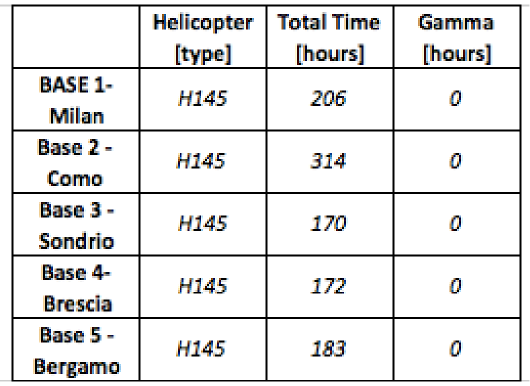


Figure 5.5: Map showing incidents location, the current HEMS bases location and the proposed ones for Winter 2015



	Helicopter [type]	Total Time [hours]	Gamma [hours]
BASE 1- Milan	*H145*	*206*	*0*
Base 2 - Como	*H145*	*314*	*0*
Base 3 - Sondrio	*H145*	*170*	*0*
Base 4- Brescia	*H145*	*172*	*0*
Base 5 - Bergamo	*H145*	*183*	*0*

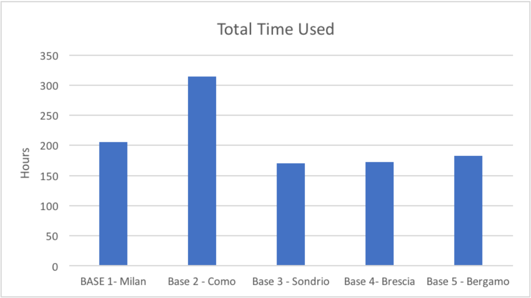


Table 5.6: Table and graphics showing total time used by each helicopter in each cell and gamma value for Winter 2015

new bases is quite different with respect to the existent ones, except for Villa Guardia (Como) base. Bresso (Milan) base is located 10 km south with respect to the current one, in proximity of the city centre; Brescia base is located 12Km north-east while Bergamo base is situated 35Km north-north-east from the current one. Finally, Caiolo (Sondrio) base is positioned 33Km to the east. The chosen helicopters are five Airbus H145 (as visible from Table 5.6), since its leasing cost is less than the one of AW139; although its cruise velocity is lower, due to the incidents distribution, an higher cruise velocity is, in this case, almost useless. The cost for opening five bases, for leasing five H145 helicopters and for making them fly is €4’321’660; in particular, €1’696’660 are designed to operations (flight time) and €2’625’000 (€175’000/month x 3months) are intended for leasing. For what concerns green codes, as seen in 3, they can be delayed for a maximum of 180 minutes to allow helicopters to first rescue red-code patients. In this analysis, an average delay of 58 minutes exists (on the events actually delayed) and Figure 5.6 shows better the trend along the season, with the orange line representing the average; if all green-code events are considered, the average delay time lowers to 8 minutes (green line). Table 5.6 shows the total time used for each helicopter, defined as the total time during which at least one engine is running; it consists of flight time from base to demand point, from demand point to hospital and way back plus additional time for landing and taking-off and, finally, in three start-up time and three shut-off. The same figure also shows another parameter: γ. This is considered as the extra-threshold time, i.e. the time the helicopter flew beyond its limit (represented by parameter σ). As each helicopter has a value of sigma of 2000 hours per year, it means that in three months this limit is 500 hours.

Table 5.5 shows the total number of served missions, both with the *predictive* and the *online* method. Out of a total of 861 missions, the *predictive* method allows to serve 860 missions and reject one red code; using the *online* method, four are the rejected missions (red codes), for a total of 857 missions with a regular outcome. This results must not be misunderstood: the

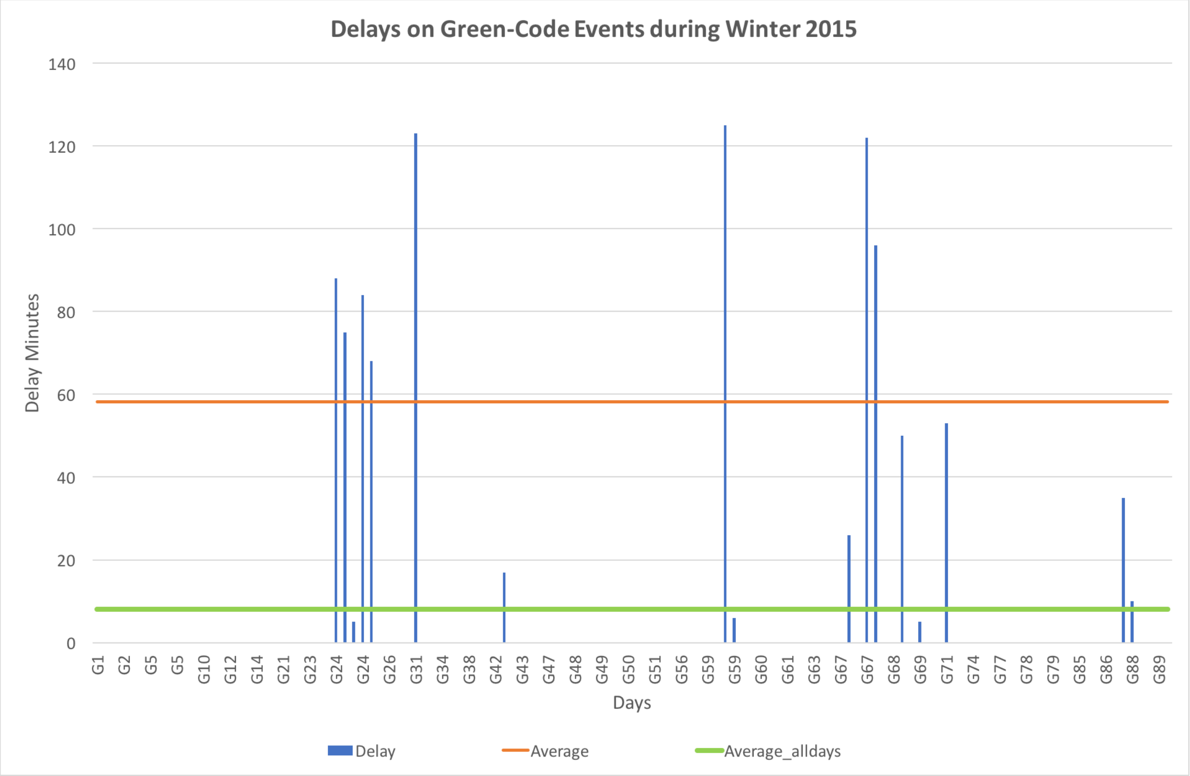
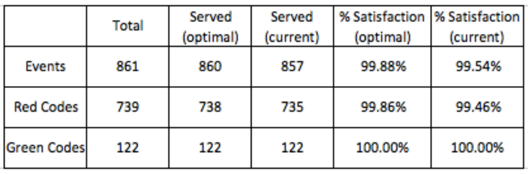


Figure 5.6: Table showing delay minutes vs day for green-code events for Winter 2015

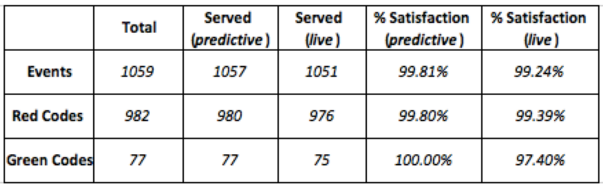


	Total	Served (optimal)	Served (current)	% Satisfaction (optimal)	% Satisfaction (current)
Events	861	860	857	99.88%	99.54%
Red Codes	739	738	735	99.86%	99.46%
Green Codes	122	122	122	100.00%	100.00%

Table 5.7: Table showing the total number of events served with the two (current and optimal) base disposition during Winter 2015

effective number of missions performed in this period is 753, due to weather conditions (16.67% of total non-served missions), mechanical failures (15.43%), or other causes (67.90%) which cannot be diversified (arrival on-site of a more competitive vehicle or mission aborted by claimant). Therefore, with such a base distribution, the HEMS service is capable to serve at least 104 more missions using the *online* method without decreasing of performances or rejected missions.

Table 5.7 shows the total number of missions that could be served with the two (the optimal and the current) base disposition on territory; analysis has been performed with the *online* dispatching method. The number of mission served with the current base locations is slightly lower, due to the low-involvment of the season.



	Total	Served (*predictive*)	Served (*live*)	% Satisfaction (*predictive*)	% Satisfaction (*live*)
Events	*1059*	*1057*	*1051*	*99.81%*	*99.24%*
Red Codes	*982*	*980*	*976*	*99.80%*	*99.39%*
Green Codes	*77*	*77*	*75*	*100.00%*	*97.40%*

Table 5.8: Details about total, served and unserved events and satisfaction percentage for Spring 2015

5.1.2.2 Experiment GF2: Spring 2015

In this experiment, an optimal solution for events happened during Spring (April-May-June) 2015 is obtained. In this period, a total of 1059 events happened (see Figure 5.7), of which 982 red-code and 77 green-code.

Two are the events that could not be served (red code) due to overcrowding in a small time span. In particular, the interested days are on May 12^{th} and June 30^{th}. Events location is visible in Figure 5.7; in the same figure, it is possible to see also the optimal location for bases and the current configurations. This optimal layout diverges from the current by the fact that Bresso base is moved towards Bergamo province, locating its base in the Monza-Brianza territory, near Busnago. Bergamo base, on the other hand, is moved in the northern territories, near the Como Lake 35Km North-North-West of the current base. Also Caiolo base is moved 37Km South-East, near Boario Terme location. Villa Guardia and Brescia Base, instead, are close to their current position. The helicopters used in this layout are five Airbus H145, as Figure 5.9 shows. Again, the reason of this choice is the same: H145 is characterized by lower associated costs but - from point of view of performances - it is slower than AW139; nonetheless this, it is more suitable for primary HEMS operations since events are close to each other. In secondary HEMS missions such as inter-regional organs or fluid transportations (not considered in this work), the AW139 becomes more competitive. Regarding cost analysis, the flight operations associated with the events costs €2'116'790 and the leasing cost of five H145 is €2'625'000, for a total expense of €4'741'790. Seven green codes events have been delayed, with a delay average on delayed days of 56 minutes; if considering all days with at least one green-code event, the delay average lowers to 5 minutes. These two averages, as well as the delay distribution along season, are visible in Figure 5.8. The discrepancy in the two values is due to the number of days characterized by a delay in the green-code: just four. Each helicopter is used for a total amount of time which is visible in Figure 5.9; the latter shows also the γ amount.

In Table 5.8 it is possible to notice the total number of served missions, both with *predictive* and the *online* method. The *Predictive* method allows serving 1057 missions out of a total of 1059 missions, and reject two red codes; using the *online* method, eight are the rejected missions (six red codes and two green codes), for a total of 1051 missions with a regular outcome. Again, these

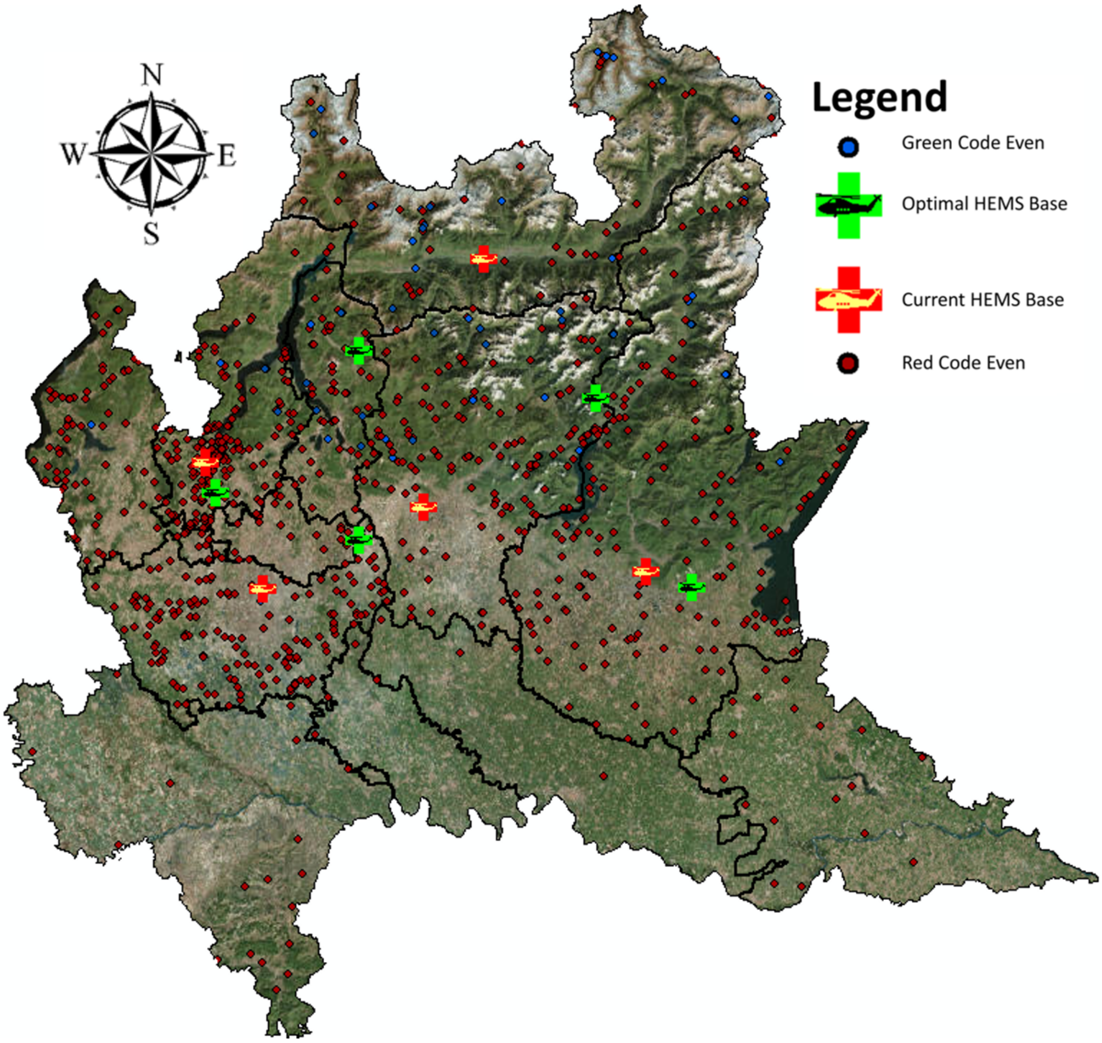


Figure 5.7: Map showing incidents location, the current HEMS bases location and the proposed ones for Spring 2015

results must not be misunderstood: the effective number of missions performed in this period is 911, due to weather conditions (11.49% of total non-served missions), mechanical failures (1.35%), or other causes (87.16%) which cannot be diversified (arrival on-site of a more competitive vehicle or mission aborted by claimant). Therefore, with such a base distribution, the HEMS service is capable to serve at least 140 more missions using the *online* method without decreasing of performances.

Table 5.10 shows the total number of missions that could be served with the two (the optimal and the current) base disposition on territory; analysis has been performed with the *online* dispatching method. In this case, the number of non-served missions by the current HEMS bases location is higher, and the satisfaction percentage lowers beyond the 99% threshold. The total

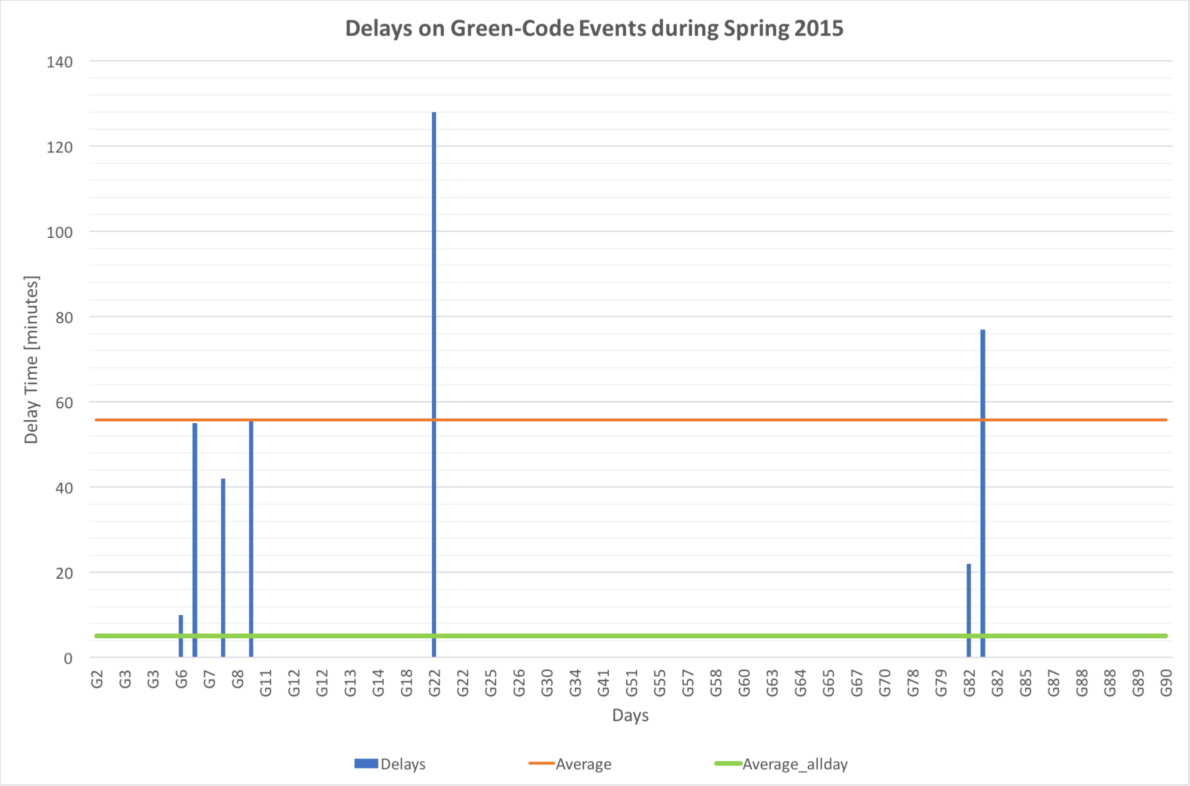


Figure 5.8: Table showing delay minutes vs day for green-code events for Spring 2015

	Helicopter [type]	Total Time [hours]	Gamma [hours]
BASE 1- Milan	*H145*	*243*	*0*
Base 2 - Como	*H145*	*419*	*0*
Base 3 - Sondrio	*H145*	*249*	*0*
Base 4- Brescia	*H145*	*183*	*0*
Base 5 - Bergamo	*H145*	*212*	*0*

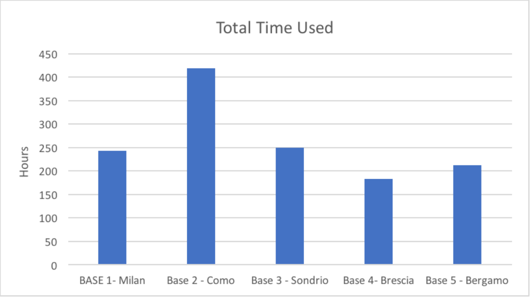
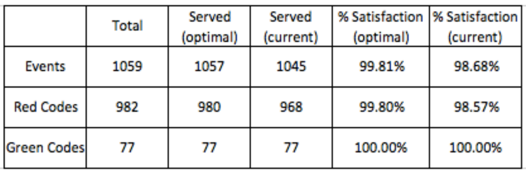
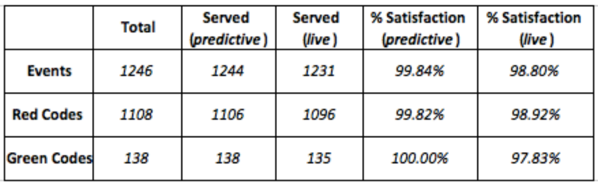


Table 5.9: Table and graphics showing total time used by each helicopter in each cell and gamma value for Spring 2015



	Total	Served (optimal)	Served (current)	% Satisfaction (optimal)	% Satisfaction (current)
Events	1059	1057	1045	99.81%	98.68%
Red Codes	982	980	968	99.80%	98.57%
Green Codes	77	77	77	100.00%	100.00%

Table 5.10: Table showing the total number of events served with the two (current and optimal) base disposition during Spring 2015



	Total	**Served (*predictive*)**	**Served (*live*)**	**% Satisfaction (*predictive*)**	**% Satisfaction (*live*)**
Events	*1246*	*1244*	*1231*	*99.84%*	*98.80%*
Red Codes	*1108*	*1106*	*1096*	*99.82%*	*98.92%*
Green Codes	*138*	*138*	*135*	*100.00%*	*97.83%*

Table 5.11: Details about total, served and unserved events and satisfaction percentage for Summer 2015

number of missions that could be served with the optimal location of bases is 12.

5.1.2.3 Experiment GF3: Summer 2015

In this experiment, the events happened in Summer 2015 are reproduced. The period between July and September is the one that counts the major HEMS requests over the year. The event cloud is visible in Figure 5.9, which is composed of a total number of 1246 requests, 1108 of which are red-code and the remaining 138 are green-code.

Nonetheless summer is a highly crowded period, the number of non-served missions is not elevated: 2 missions in red-code could not be performed, in particular during days August 28th and August 30th. Figure 5.9 shows the incidents distribution over territory and the proposed HEMS base to be open; in the figure, it is also possible to have a view of the current HEMS base, in order to give an immediate comparison between current solution and the optimal one. The proposal sets four bases near current positions, i.e. Bresso, Villa Guardia, Brescia, Caiolo. What is worth noticing is that Bergamo base does not exist in this scenario, while a new base is open near Veneto border, in Valle Dorizzo, 11Km south-west of Bagolino and 23Km east of Lovere. Five Airbus H145 are allocated to each base and their using time is displayed in Figure 5.12. The γ parameter, in this case, continues to remain null, meaning that even in this period the maximum contract threshold is not overcome. The total cost for this scenario is €5’161’100 divided as follow: €2’536’100 for flights and €2’625’000 for leasing. The operational costs are - of course - higher with respect to other seasons since the number of total events is much numerous. Green codes accumulated an average delay time of 72 minutes, as visible in Figure 5.10, which lowers to an

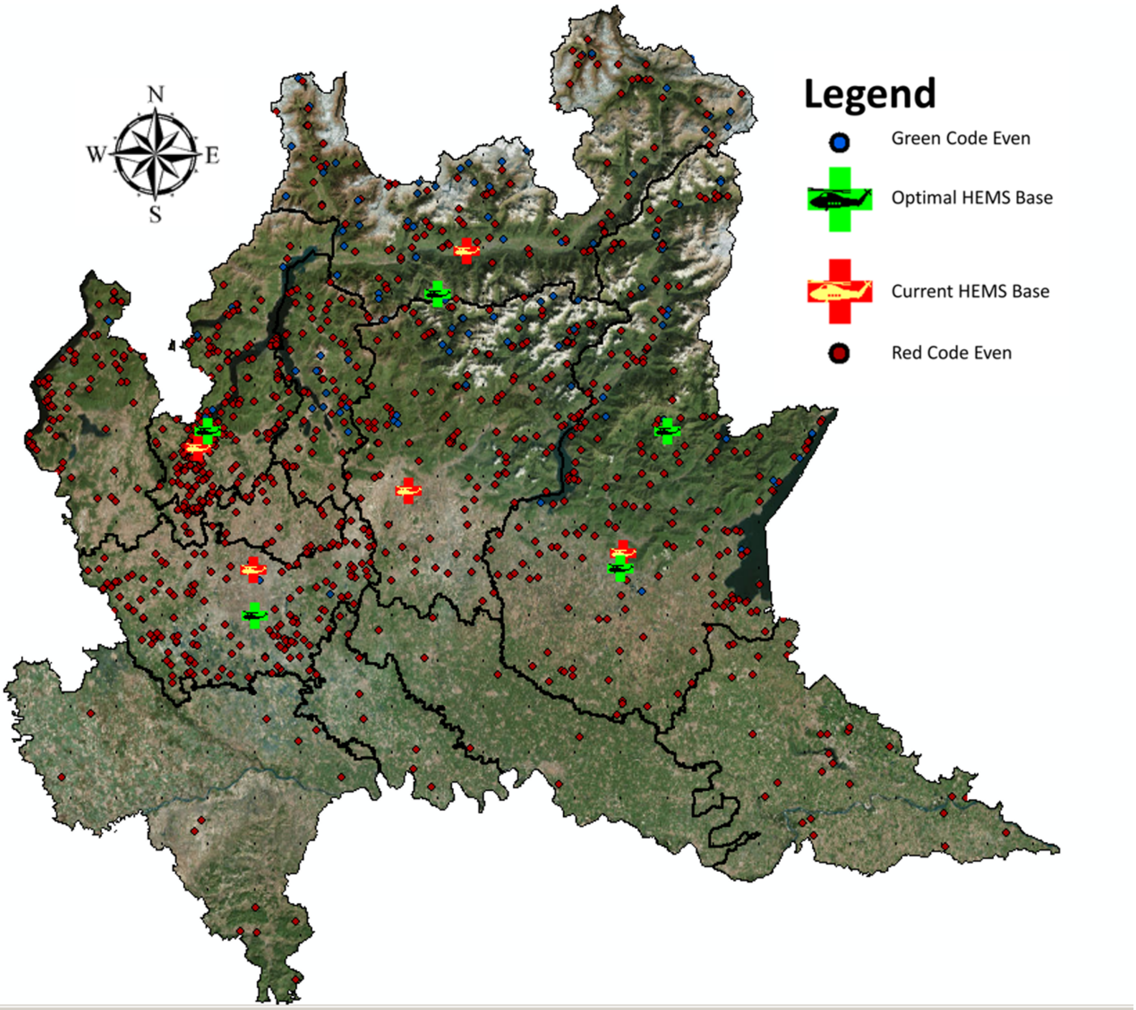


Figure 5.9: Map showing incidents location, the current HEMS bases location and the proposed ones for Summer 2015.

average of 22 minutes if considering all the day with a green-code event.

Table 5.11 shows the total number of served missions, both with the *predictive* and *online* method. Out of a total of 1246 missions, the *predictive* method allows serving 1244 missions and reject two red codes; using the *online* method, 15 are the rejected missions (12 red and 3 green codes), for a total of 1231 missions with a regular outcome. However, one must keep in mind that the effective number of missions performed in this period is 1094, due to weather conditions (6.58% of total non-served missions), mechanical failures (2.62%), or other causes (90.80%). Therefore, with such a base distribution, the HEMS service is capable to serve at least 137 more missions using the *online* method without decreasing of performances or rejecting more missions.

Table 5.13 shows the total number of missions that could be served with the two (the optimal and the current) base disposition on territory; analysis has been performed with the *online*

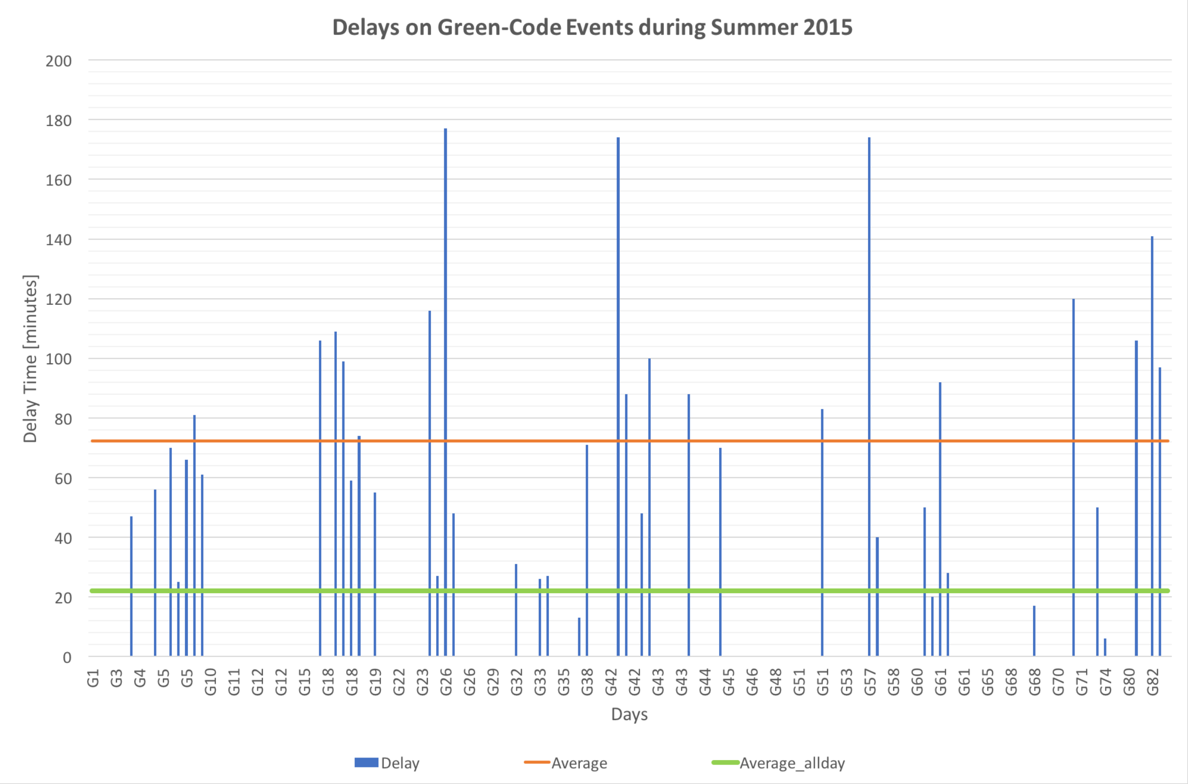
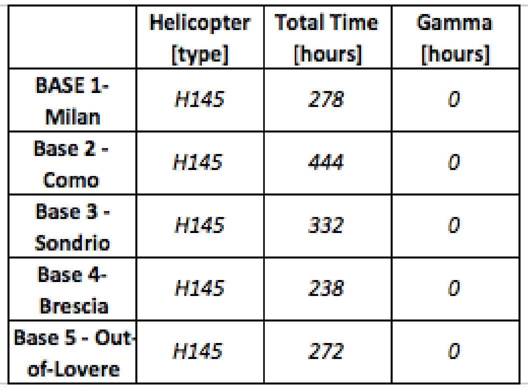


Figure 5.10: Table showing delay minutes vs day for green-code events for Summer 2015



	Helicopter [type]	Total Time [hours]	Gamma [hours]
BASE 1- Milan	*H145*	*278*	*0*
Base 2 - Como	*H145*	*444*	*0*
Base 3 - Sondrio	*H145*	*332*	*0*
Base 4- Brescia	*H145*	*238*	*0*
Base 5 - Out-of-Lovere	*H145*	*272*	*0*

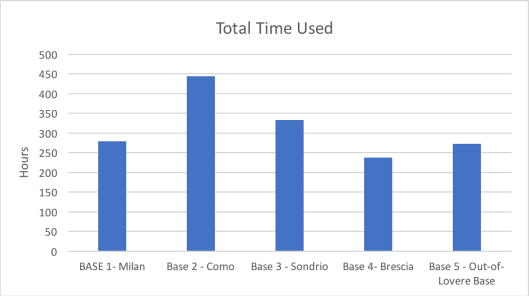
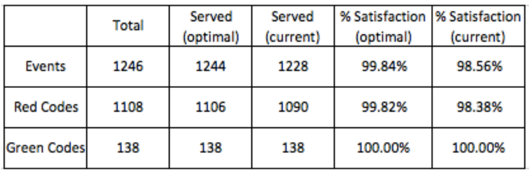
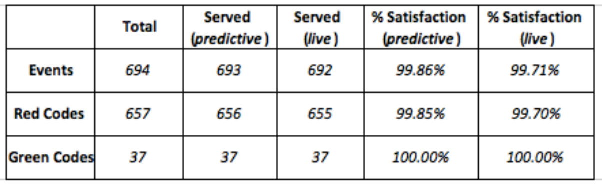


Table 5.12: Table and graphics showing total time used by each helicopter in each cell and gamma value for Summer 2015



	Total	Served (optimal)	Served (current)	% Satisfaction (optimal)	% Satisfaction (current)
Events	1246	1244	1228	99.84%	98.56%
Red Codes	1108	1106	1090	99.82%	98.38%
Green Codes	138	138	138	100.00%	100.00%

Table 5.13: Table showing the total number of events served with the two (current and optimal) base disposition during Summer 2015



	Total	**Served *(predictive)***	**Served *(live)***	**% Satisfaction *(predictive)***	**% Satisfaction *(live)***
Events	*694*	*693*	*692*	*99.86%*	*99.71%*
Red Codes	*657*	*656*	*655*	*99.85%*	*99.70%*
Green Codes	*37*	*37*	*37*	*100.00%*	*100.00%*

Table 5.14: Details about total, served and unserved events and satisfaction percentage for Fall 2015 with 5 helicopters

dispatching method. In summer, the maximum difference in total missions served is highlighted by the high involvment of the season. Sixteen missions (all red codes) less are served by the actual configuaration, lowering the satisfaction percentage below the 99%.

5.1.2.4 Experiment GF4: Fall 2015

This scenario reproduce the events happened in Fall 2015, considering months from October to December. This experiment will be compared with the following one, which uses one helicopter less. Total events (visible in Figure 5.11) are 694, composed by 657 red-code and 37 green-code events.

There is just one non-served mission and it is red-code: in that day (October 11th) multiple events occurred in the space of 70 minutes. In Figure 5.11 it is possible to see not only the events and their distribution, but also the proposed position for opening bases and the nowadays one which allows an immediate comparison. In this optimal proposed scenario, the bases position is quite different from the real distribution: the only one which has been located near the current position is Villa Guardia base. Milan Bresso base has been shifted to the south-west, beyond the city towards Abbiategrasso; Bergamo base has been moved 30Km to the north, Caiolo base shifted 38Km to the sout-east and Brescia base is moved in Bergamo province, near Cremona city. Again, five Airbus H145 have been chosen; this is represented - as long as their respective use-time and gamma - in Figure 5.15. The total cost, in this case, is €3’981’610, €1’356’610 for flights to be performed and €2’625’000 for leasing. Operational costs are lower with respect to the previous seasons since the total number of events is much lower (almost half). Green codes (visible in

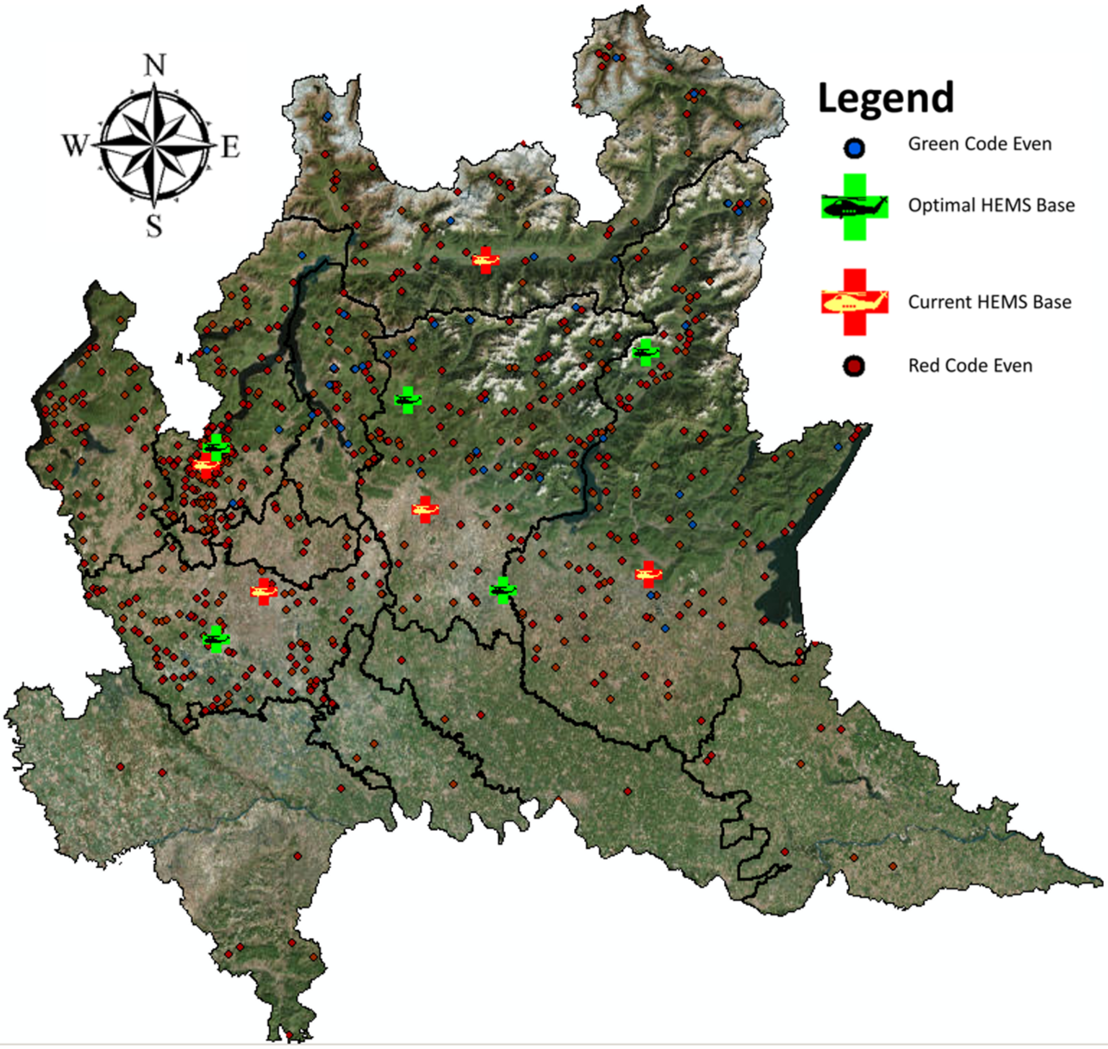


Figure 5.11: Map showing incidents location, the current HEMS bases location and the proposed ones for Fall 2015 with 5 helicopters.

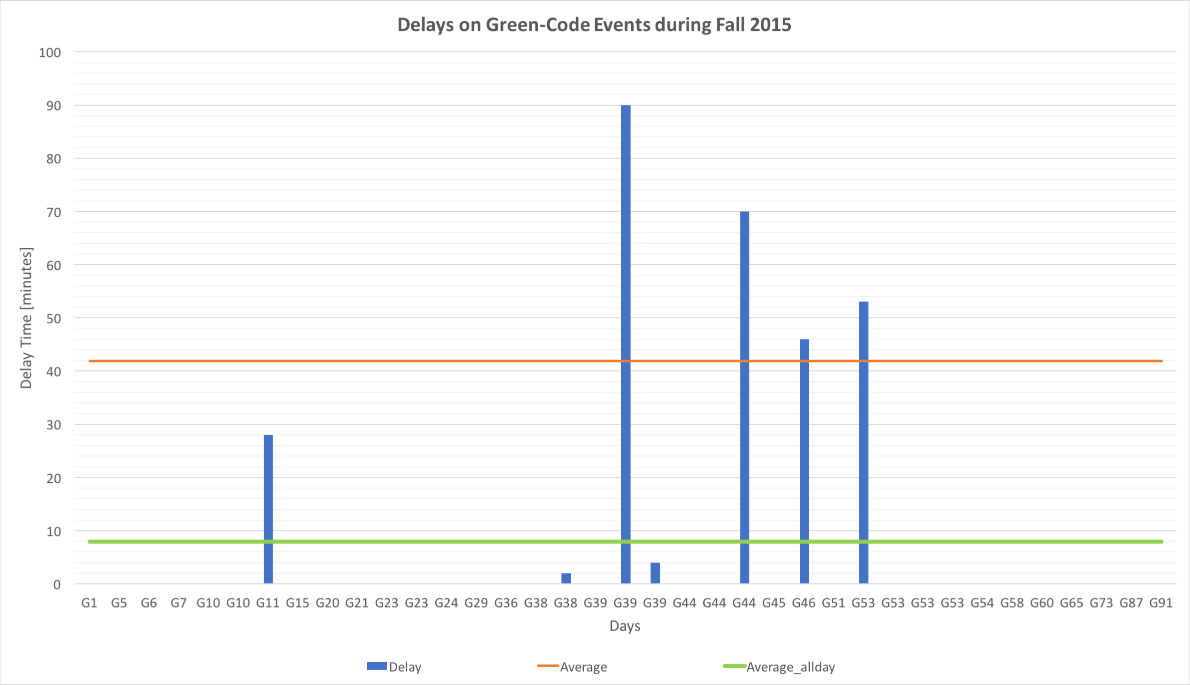
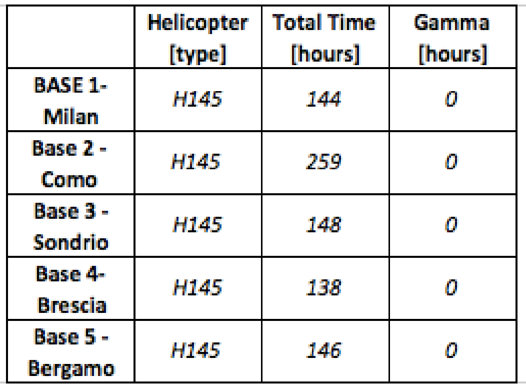


Figure 5.12: Table showing delay minutes vs day for green-code events for Fall 2015 with 5 helicopters



	Helicopter [type]	Total Time [hours]	Gamma [hours]
BASE 1- Milan	*H145*	*144*	*0*
Base 2 - Como	*H145*	*259*	*0*
Base 3 - Sondrio	*H145*	*148*	*0*
Base 4- Brescia	*H145*	*138*	*0*
Base 5 - Bergamo	*H145*	*146*	*0*

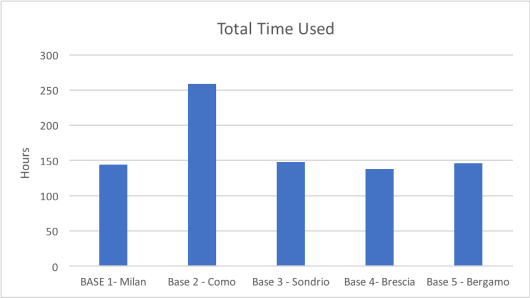
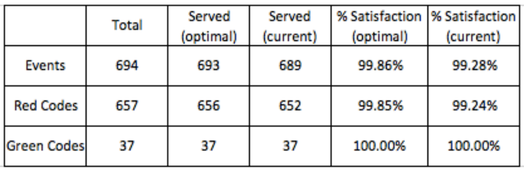


Table 5.15: Table and graphics showing total time used by each helicopter in each cell and gamma value for Fall 2015 with 5 helicopters

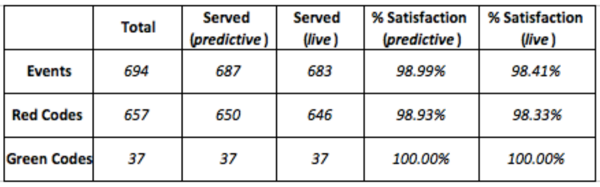
Figure 5.12) are characterized by a delay of 42 minutes (orange line), but it reduces to 8 (green line) considering all green events.

In Table 5.14 it is possible to notice the total number of served missions, both with the *predictive* and the *online* method. The *Predictive* method allows serving 693 missions out of a total of 694 missions, and reject just one red code; using the *online* method, two are the rejected missions (red codes), for a total of 655 missions with a regular outcome. The effective number of missions



	Total	Served (optimal)	Served (current)	% Satisfaction (optimal)	% Satisfaction (current)
Events	694	693	689	99.86%	99.28%
Red Codes	657	656	652	99.85%	99.24%
Green Codes	37	37	37	100.00%	100.00%

Table 5.16: Table showing the total number of events served with the two (current and optimal) base disposition during Fall 2015 using 5 helicopters



	Total	**Served (*predictive*)**	**Served (*live*)**	**% Satisfaction (*predictive*)**	**% Satisfaction (*live*)**
Events	*694*	*687*	*683*	*98.99%*	*98.41%*
Red Codes	*657*	*650*	*646*	*98.93%*	*98.33%*
Green Codes	*37*	*37*	*37*	*100.00%*	*100.00%*

Table 5.17: Details about total, served and unserved events and satisfaction percentage for Fall 2015 with 4 helicopters

performed in this period is 586; the lower number finds its cause in weather conditions (19.44% of total non-served missions), mechanical failures (0.93%), or other causes (79.63%). Therefore, with such a base distribution, the HEMS service is capable to serve at least 69 more missions using the *online* method before rejecting one more mission.

Table 5.16 shows the total number of missions that could be served with the two (the optimal and the current) base disposition on territory; analysis has been performed with the *online* dispatching method. During Fall season the number of requests is at its minimum, and this reflects also on number of missions served with the two different configurations of bases location. Just four is the number of red code events that could not be served, due to the different positions of bases.

5.1.2.5 Experiment GF5: Fall 2015 with 4 Helicopters (Low Involvement Months)

This experiment has been designed to reduce the number of open bases during the low-involvement period of the year, saving taxpayer's money. The period considered for this analysis is from October to December. The distribution of incidents is visible in Figure 5.13; in this period a total of 694 events happened, of which 657 red-code and 37 green-code. Statistically, during Fall the total number of HEMS request is at its minimum; for this reason a scenario with a lower number of helicopters is investigated in this experiment.

A total of 7 red-code events are not served due to the presence of multiple (more than the total number of helicopters) incidents in the time-windows of a single mission (delta value, 70 minutes). These happen on days October 11th (3 events, 2 between 10.45am and 11.30am and the last

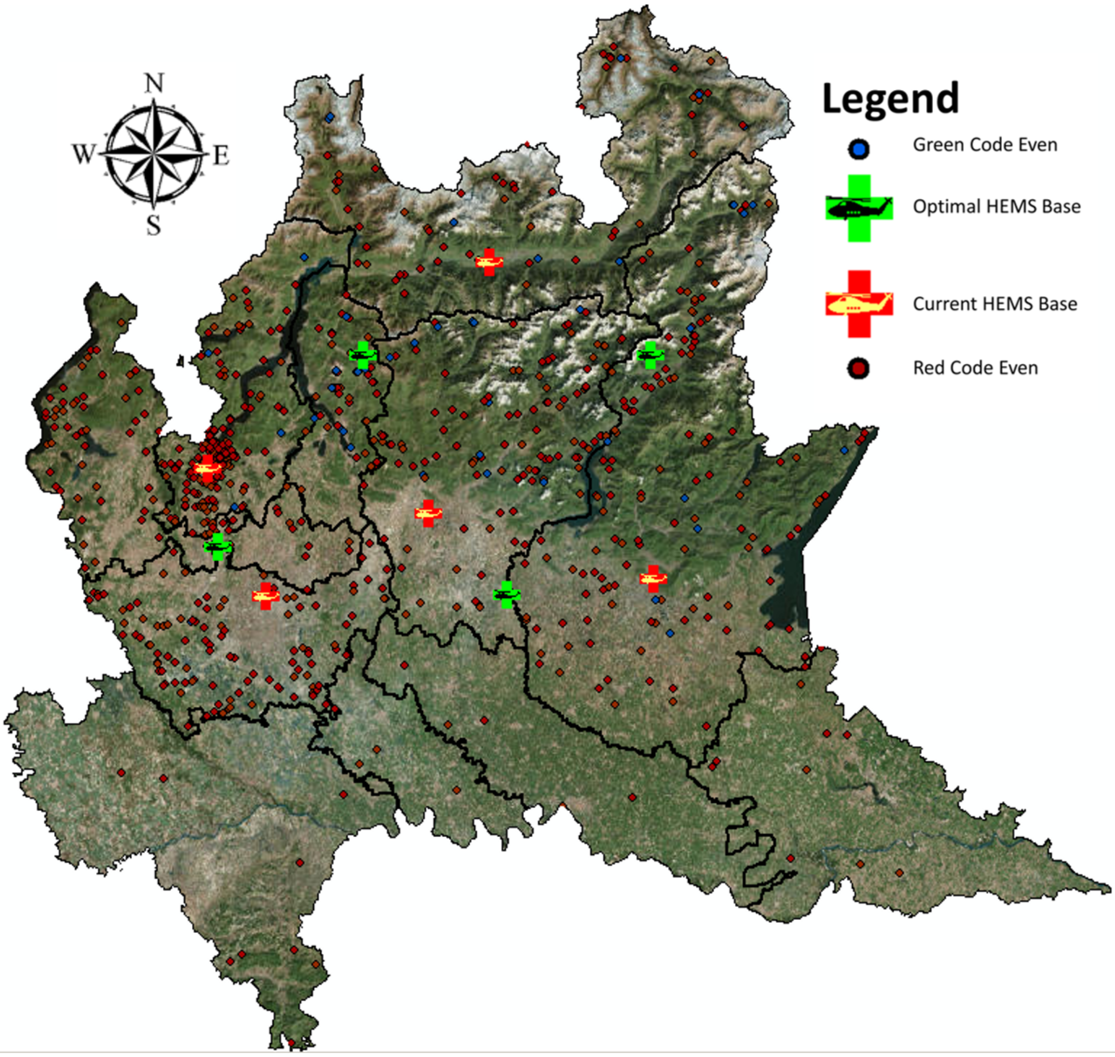


Figure 5.13: Map showing incidents location, the current HEMS bases location and the proposed ones for Fall 2015 with 4 helicopters

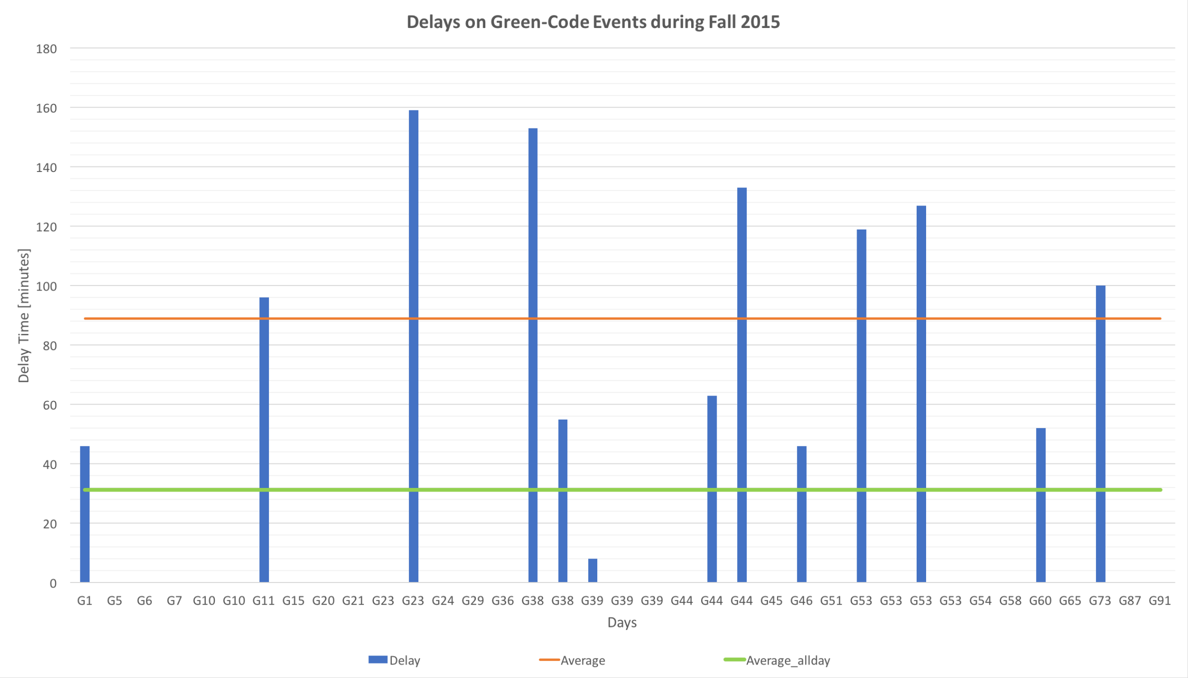
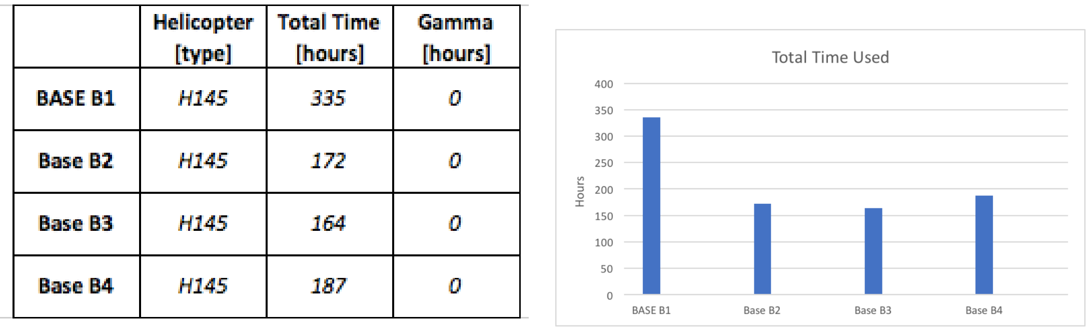


Figure 5.14: Table showing delay minutes vs day for green-code events for Fall 2015 with 4 helicopters

between 4pm and 5pm), November 2nd, 9th and 11th and December 30th. Figure 5.13 shows the events and the proposed base to be open; also nowadays distribution of bases is visible. In this case, positions of the base are pretty different with respect to the current one: the four bases are located in-between the five bases, one in the middle position between Milan and Como bases (named B1), one between Bergamo and Brescia ones (B2), one between Brescia and Sondrio (B3) bases and the last one in between Como and Sondrio (B4). This shows how seasonal variations of events highly influences the optimal location of bases. In this case, four Airbus H145 have been chosen - as visible from Figure 5.18. The total cost for such a layout is €3'491'380, €1'391'380 for flights and €2'100'000 for leasing. The costs in this layout are €490'230 less with respect to fall scenario with five helicopters: this shows that it is possible to reduce - in a seasonal manner - the number of used helicopters, avoiding a few events but saving almost half a million. Green codes are all performed with an average delay of 89 min (orange line), which becomes at 31 minutes (green line) if considering all green events. See Figure 5.14 for accurate trend along season. Figure 5.18 shows the total time used for each helicopter, defined as the total time during which at least one engine is running. The same figure also shows the parameter gamma, whose value is now 400 hours since four helicopters are considered.

Table 5.17 shows the total number of served missions, both with the *predictive* and the *online* method. Out of a total of 694 missions, the *predictive* method allows serving 687 missions and



	Helicopter [type]	Total Time [hours]	Gamma [hours]
BASE B1	*H145*	*335*	*0*
Base B2	*H145*	*172*	*0*
Base B3	*H145*	*164*	*0*
Base B4	*H145*	*187*	*0*

Table 5.18: Table and graphics showing total time used by each helicopter in each cell and gamma value for Fall 2015 with 4 helicopters

reject seven red codes; using the *online* method, eleven are the rejected missions (red codes), for a total of 683 missions with a regular outcome. The effective number of missions performed in this period is 586. Therefore, with such a base distribution and counting on just four helicopters, the HEMS service is capable to serve at least 97 more missions using the *online* method without decreasing of performances or presenting rejected missions. No comparisons with the current situation is possible, since the latter presents five bases, all year long.

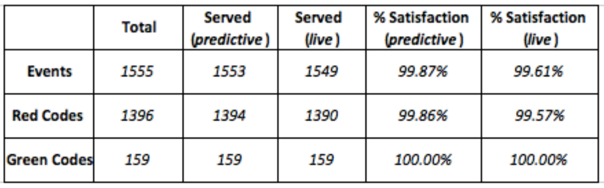
5.1.3 Semestral Location-Allocation Problem

This new set of experiments involves the reproduction of the events of the year 2015 into two parts: the cold months (October to March) and the warm months (April to September). In this way, the optimality solution is extended from a temporal point of view and two optimal solutions can be compared, only. Experiments are organized as previously.

5.1.3.1 Experiment GF6: 2015 Cold Months

This sixth experiment is performed to analyze the optimal solution for months from October to March. The cold period takes into account months of the same year: September to December 2015 and January to March 2015. This is - between two - the period with less turnout of events; five bases at most can be opened and these are displayed in Figure 5.15. Total number of requests is 1555, split in 1396 red codes and 159 green codes.

In this period with this configuration, two events are not served only and both red-code due to overcrowding of events in days October, 11th and February, 10th. These two events are the same not served which solver found in Winter (EXP1) and Fall (EXP4) analyses. Figure 5.15 shows all 1555 incidents and their distribution; moreover, it shows also the current location of the bases and the optimal one as found by solver. The optimal base distribution is slightly different from the current one: all bases are close to the current position. Bergamo and Milan bases are shifted to the west (both of 15Km). Brescia base is moved 20Km north-west of the current position,



	Total	Served (*predictive*)	Served (*live*)	% Satisfaction (*predictive*)	% Satisfaction (*live*)
Events	*1555*	*1553*	*1549*	*99.87%*	*99.61%*
Red Codes	*1396*	*1394*	*1390*	*99.86%*	*99.57%*
Green Codes	*159*	*159*	*159*	*100.00%*	*100.00%*

Table 5.19: Details about total, served and unserved events and satisfaction percentage during cold months of 2015

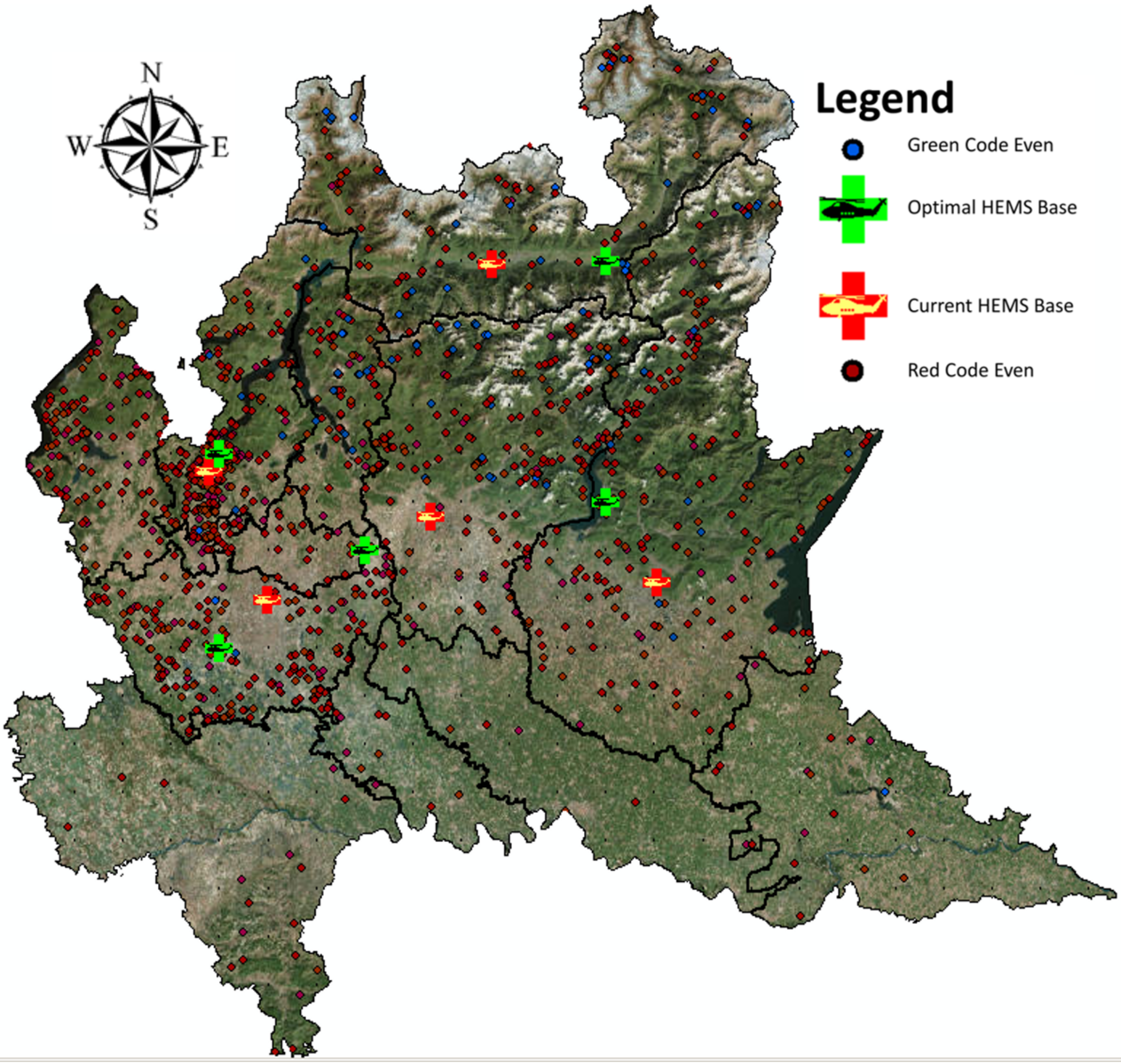


Figure 5.15: Map showing incidents location, the current HEMS bases location and the proposed ones during cold months of 2015

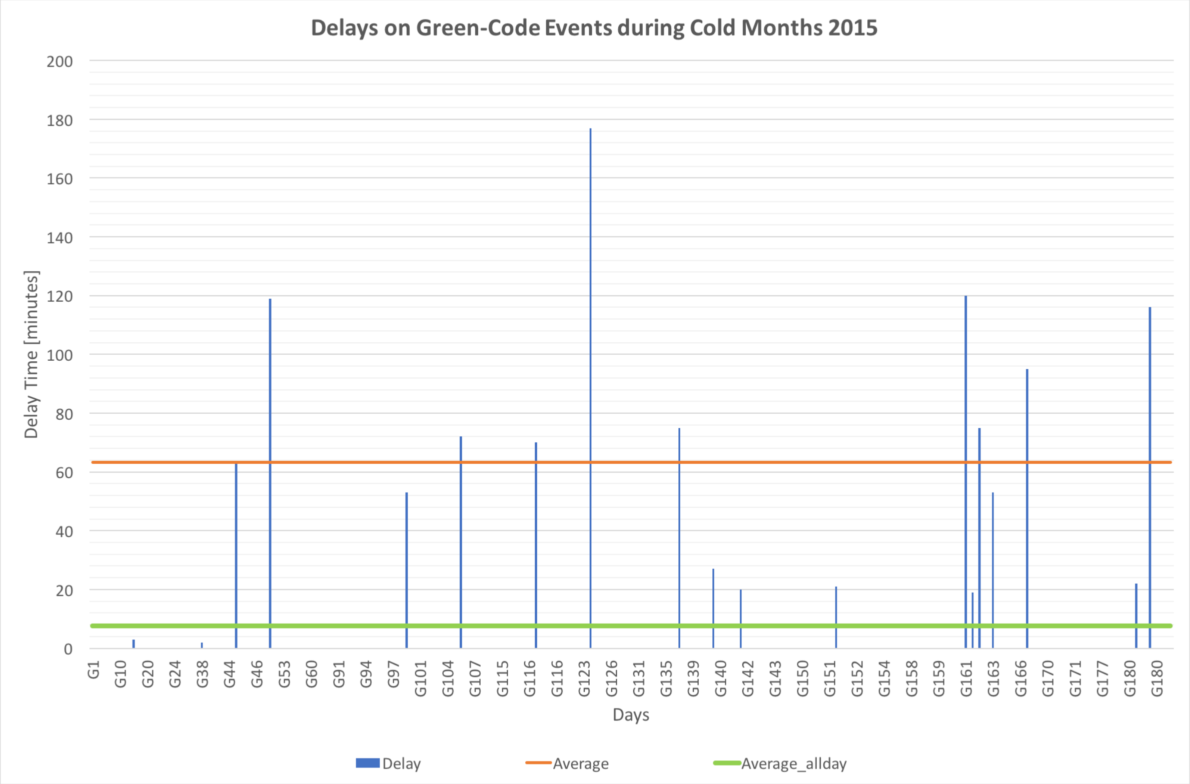
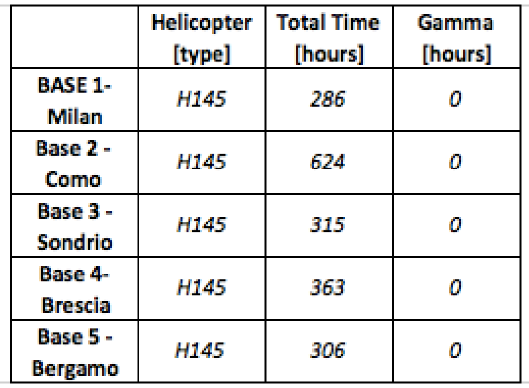


Figure 5.16: Table showing delay minutes vs day for green-code events during cold months of 2015

among the Iseo lake shore; Sondrio base is shifted 24Km to the east, at the same latitude. Como base is located almost superimposed to the current one. Five Airbus H145 are allocated to each base and their using time is displayed in Figure 5.20. The γ parameter, in this case, continues to remain null, meaning that even in this period the maximum contract threshold (1000 hours for six months) is not overcome. It can be noticed that Como base is highly involved with respect to the others. Costs in this scenario are so divided: €3’074’150 for operations and €5’250’000 for leasing (€175’000/month x 6 months x 5 helicopters) for a total of €8’324’150. Green codes accumulated delays for 20 hours, with an average of 63 minutes which lowers to 8 minutes if considering all days with green codes. The trend can be visible in Figure 5.16

Table 5.19 shows the total number of served missions, both with *predictive* and *online* method. Out of a total of 1555 missions, *predictive* method allows serving 1553 missions and reject two red codes; using *online* method, six are the rejected missions (red codes), for a total of 1549 missions with a regular outcome. The effective number of missions performed in this period is 1299. Therefore, with such a base distribution and counting on five helicopters, the HEMS service is capable to serve at least 250 more missions using *online* method without decreasing of performances or presenting rejected missions.



	Helicopter [type]	Total Time [hours]	Gamma [hours]
BASE 1- Milan	*H145*	*286*	*0*
Base 2 - Como	*H145*	*624*	*0*
Base 3 - Sondrio	*H145*	*315*	*0*
Base 4- Brescia	*H145*	*363*	*0*
Base 5 - Bergamo	*H145*	*306*	*0*

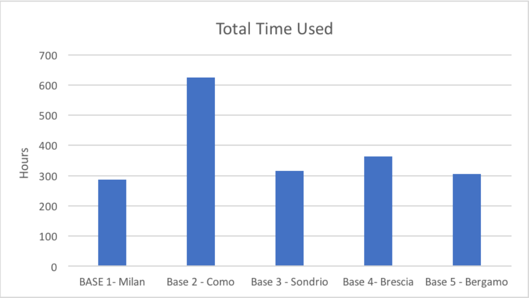
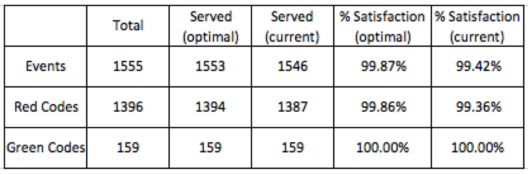


Table 5.20: Table and graphics showing total time used by each helicopter in each cell and gamma value during cold months of 2015



	Total	Served (optimal)	Served (current)	% Satisfaction (optimal)	% Satisfaction (current)
Events	1555	1553	1546	99.87%	99.42%
Red Codes	1396	1394	1387	99.86%	99.36%
Green Codes	159	159	159	100.00%	100.00%

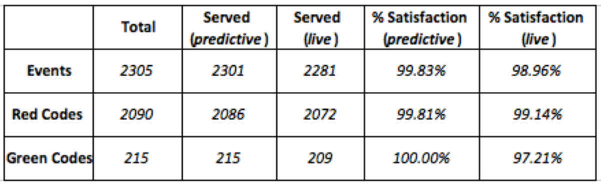
Table 5.21: Table showing the total number of events served with the two (current and optimal) base disposition during Cold months of 2015

Table 5.21 shows the total number of missions that could be served with the two (the optimal and the current) base disposition on territory; analysis has been performed with the *online* dispatching method. Although it is the less involved semster of the year, the number of total rescue request is higher, compared to a single season; however, the number of missions not served due to different location of bases is not high, just 7. The 99% threshold is, however, safe.

5.1.3.2 Experiment GF7: 2015 Warm Months

The experiment is aimed at performing an optimal analysis in warm months of year 2015 (April to September). This period is the one with most involvement of the bases due to the high HEMS request number. At most five bases can be opened for serving a total of 2305 events distributed as in Figure 5.17.

In this period and with this configuration, four events are not served due to overcrowding of events and they are all red-code events; these happened in days May 12th, June 30th, August 28th, August 30th. They correspond to the ones in the seasonal analysis. 2305 event points (2090 red codes and 215 green codes) are represented in Figure 5.17 with their own location. The solution, in this case, is curious: three out of five bases are aligned at the same latitude, while Sondrio base is shifted 17Km south-east of its current position and Villa Guardia base located exactly where it



	Total	Served (*predictive*)	Served (*live*)	% Satisfaction (*predictive*)	% Satisfaction (*live*)
Events	*2305*	*2301*	*2281*	*99.83%*	*98.96%*
Red Codes	*2090*	*2086*	*2072*	*99.81%*	*99.14%*
Green Codes	*215*	*215*	*209*	*100.00%*	*97.21%*

Table 5.22: Details about total, served and unserved events and satisfaction percentage during warm months of 2015

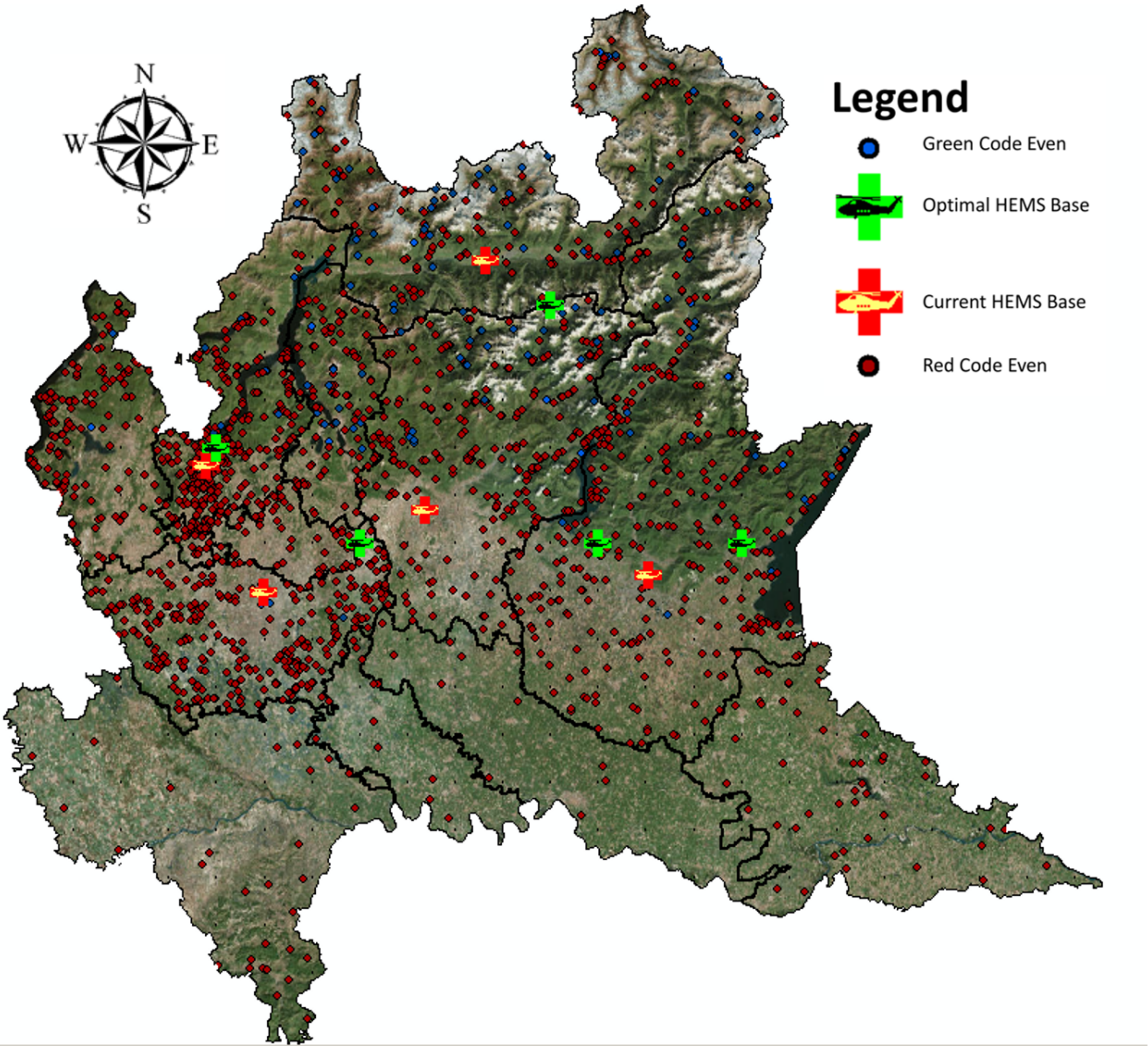


Figure 5.17: Map showing incidents location, the current HEMS bases location and the proposed ones during warm months of 2015

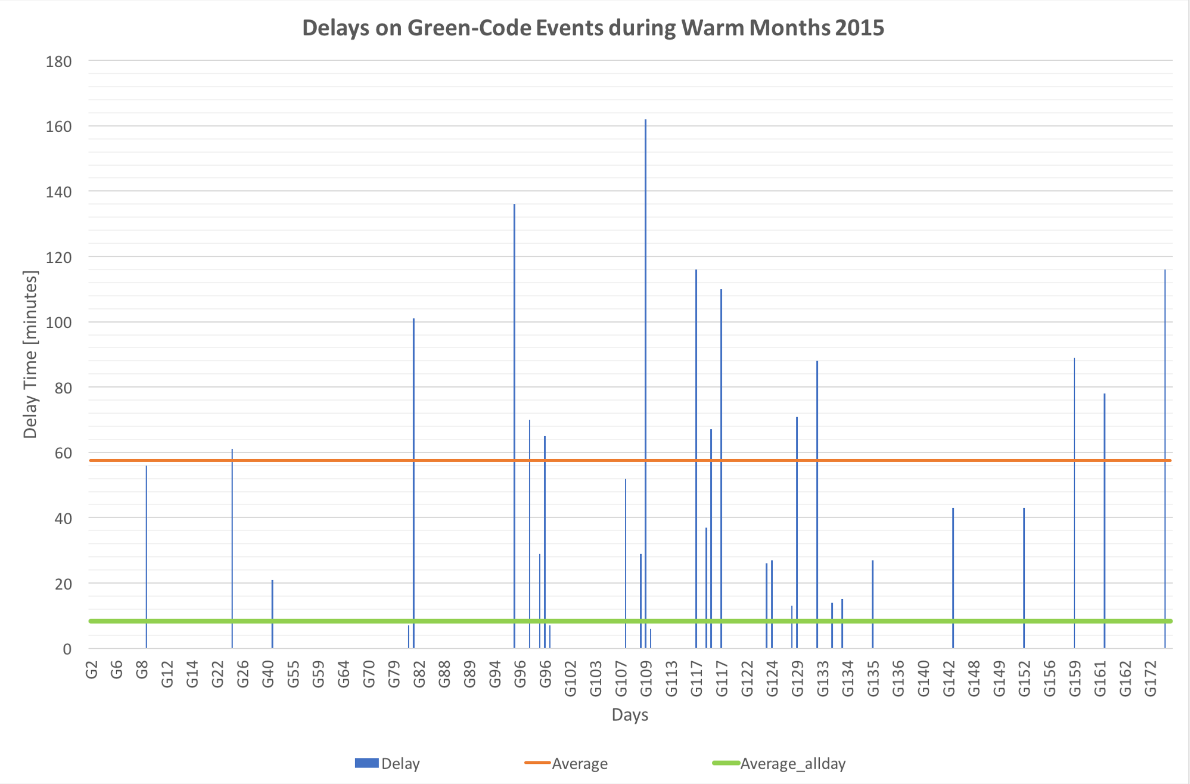
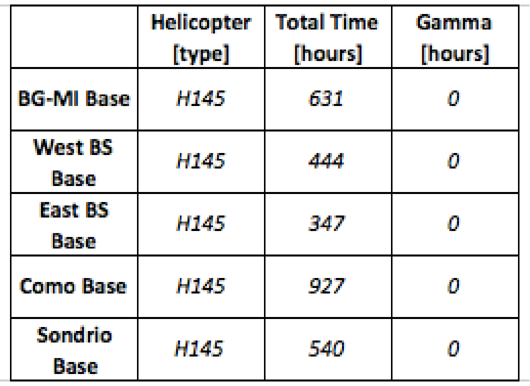


Figure 5.18: Table showing delay minutes vs day for green-code events during warm months of 2015

actually is. The three aligned bases are divided into two groups: one between Milan Bresso and Bergamo bases and one surrounding Brescia base. These three bases form a triangle in which base lays on the segment joining Milan, Bergamo and Brescia cities and the vertex is on the alpine region, close to Sondrio. Five Airbus H145 are used and their time is shown in Figure 5.23. γ parameter keeps being null, even in the high-involvement period, like this one. For the sake of simplicity. Total expense in this scenario rises up to €9’934’980 divided as follows: €4’684’980 for flight operations and €5’250’000 for leasing in six months. Green codes accumulated a total delay of 1 day and 5.7 hours. The average value is 58 minutes and the alldays-average is 8 minutes. Visit Figure 5.18 for more details.

Table 5.22 shows the total number of served missions, both with *predictive* and *online* method. Out of a total of 2305 missions, *predictive* method allows to serve 2301 missions and reject four red codes; using *online* method, 24 are the rejected missions (18 red codes and 6 green codes), for a total of 2281 missions with a regular outcome. The effective number of missions performed in this period is 2005 due to technical stops (2.00%), bad weather conditions (9.00%) or other non-specific reasons (89.00%). Therefore, with such a base distribution, the HEMS service is capable to serve at least 276 more missions using *online* method without decreasing of performances.



	Helicopter [type]	Total Time [hours]	Gamma [hours]
BG-MI Base	*H145*	*631*	*0*
West BS Base	*H145*	*444*	*0*
East BS Base	*H145*	*347*	*0*
Como Base	*H145*	*927*	*0*
Sondrio Base	*H145*	*540*	*0*

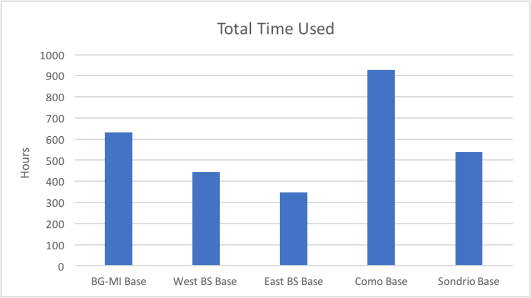
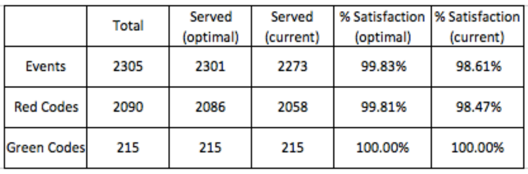


Table 5.23: Table and graphics showing total time used by each helicopter in each cell and gamma value during warm months of 2015



	Total	Served (optimal)	Served (current)	% Satisfaction (optimal)	% Satisfaction (current)
Events	2305	2301	2273	99.83%	98.61%
Red Codes	2090	2086	2058	99.81%	98.47%
Green Codes	215	215	215	100.00%	100.00%

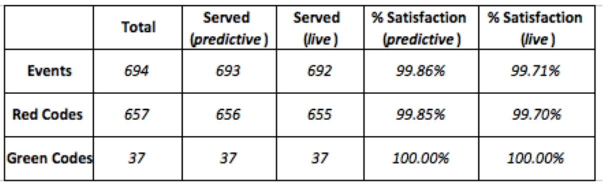
Table 5.24: Table showing the total number of events served with the two (current and optimal) base disposition during Warm months of 2015

Table 5.24 shows the total number of missions that could be served with the two (the optimal and the current) base disposition on territory; analysis has been performed with the *online* dispatching method. This semester is the more involved of the year, and the experiment counts the higher number of total rescue requests, 2305. If with the optimal solution of bases just four events could not be served, with the current one the number rises to 32, i.e. 28 served missions (all red codes) less than the previous case. Although the satisfaction level is above the 98%, the absolute value of the non-served missions is high.

5.2 Conditioned Scenario

5.2.1 Fixing Milan and Como bases

Conditioned analyses are aimed at giving a more affordable solution to optimize the HEMS services. Results from Green Field analyses show that almost every base should be shifted to reach the optimum. This is economically impossible in reality. For this reason, conditioned analyses have been carried on, to investigate the optimum in a case in which some bases are fixed. These bases are chosen to be the Como's and Bresso's. The choice is justified by the fact that Como base is a mandatory choice (as it could be seen from Green Field analyses); Milan is



	Total	Served (*predictive*)	Served (*live*)	% Satisfaction (*predictive*)	% Satisfaction (*live*)
Events	*694*	*693*	*692*	*99.86%*	*99.71%*
Red Codes	*657*	*656*	*655*	*99.85%*	*99.70%*
Green Codes	*37*	*37*	*37*	*100.00%*	*100.00%*

Table 5.25: Details about total, served and unserved events and satisfaction percentage for Fall 2015-conditioned analysis with 5 helicopters

the capital city of Lombardy region, therefore it cannot be lacking of HEMS.

5.2.1.1 Experiment C1: Fixed Milan-Bresso and Como bases during Fall 2015 with 5 helicopters

This experiment is intended to discover the optimal base location, counting on five helicopters in as many bases, for the fall season. Milan Bresso and Como base are forced to exist and each of them is equipped with a Leonardo AW139 helicopter. Fall 2015 incidents distribution is visible on Figure 5.19. The season counts 694 incidents, 657 of which are red-code and 37 green code.

Just one event (red-code) is not served due to the presence of six (more than the total number of helicopters) simultaneous incidents in the time-windows of a single mission (70 minutes). This happens on October 11th, as the case in experiment GF4. Events distribution is visible in Figure 5.19 as well as the opened base; in the same, figure it is possible to see also the nowadays distribution of bases for an immediate comparison. The proposed position for the new bases is different with respect to the existent ones, except for bases which have been fixed. Bergamo base is shifted to the west, near Trezzo sull'Adda municipality, while Caiolo and Brescia base moved one close to each other: Caiolo base shifted 25Km to SE direction while Brescia moved 27Km towards north. It is worth noticing that there is a huge concentration of bases in the western part of Lombardy: 3 bases in $360Km^2$. The chosen helicopters are two Leonardo AW139 (imposed in Bresso and Como as in reality) and three Airbus H145. Figure 5.26 shows details of used time for each machine. It can be seen, from the previous figure, that Como base is less used: this result can be defensible as considering that some events are considered in impervious places, hence the medium class AW139 helicopter cannot reach them. For this reason Milan and Como bases are under-utilised, as visible in Figure 5.26. On the contrary, Bergamo base sees now an explosion of total flight-hour accumulated and follow Brescia and Caiolo. The cost for leasing three H145 helicopters, two AW139 and for making them fly is €4'398'850; in particular, €1'473'850 are designed to operations (flight time) and €2'925'000 (H145: €175'000/month x 3months, AW139: €225'000/month x 3 months) are intended for leasing. This configuration costs about €417'000 more than the GF configuration of experiment GF4 with 5 H145 helicopters. In this analysis, an average delay of 56 minutes exists (on the events actually delayed) and Figure 5.20 shows better

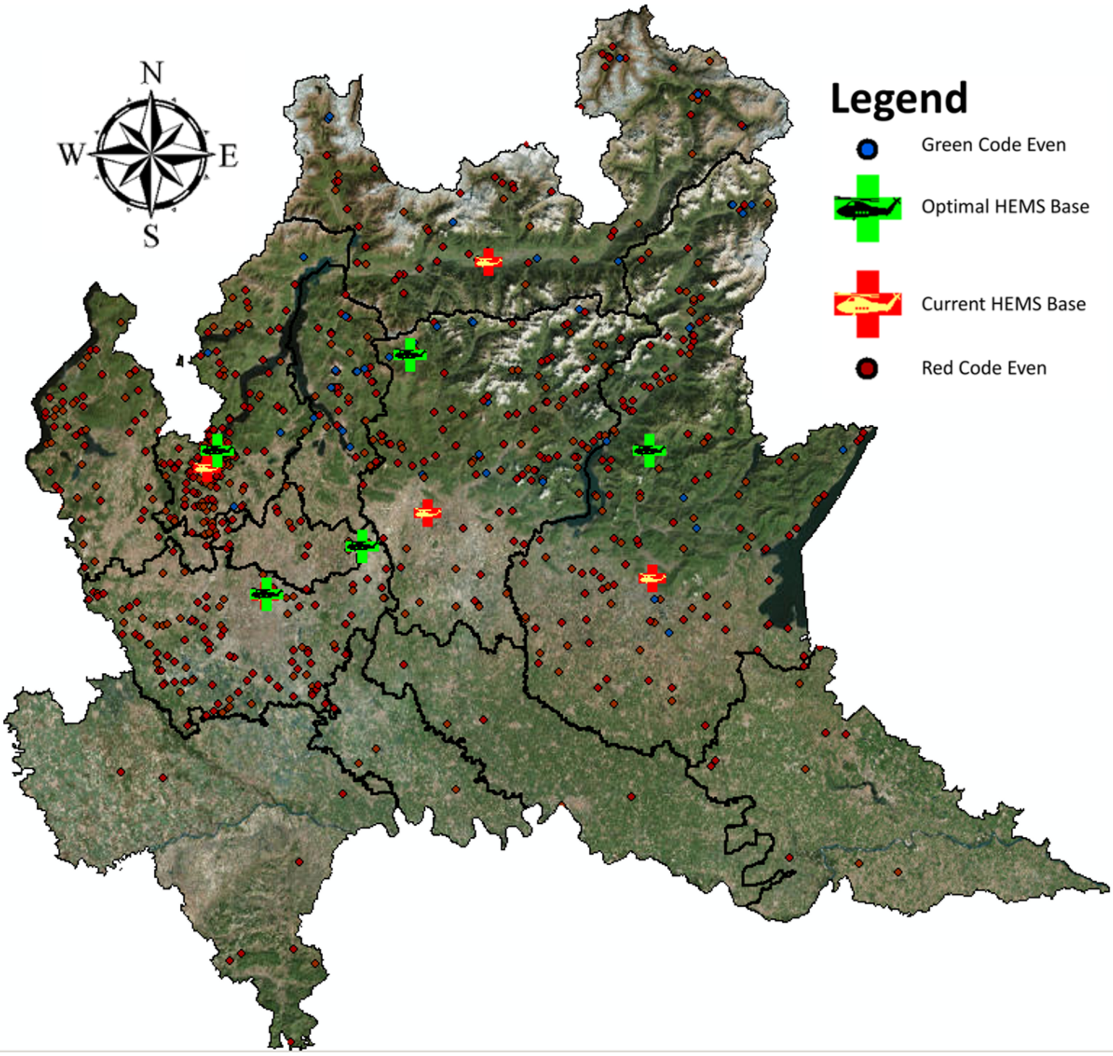


Figure 5.19: Map showing incidents location, the current HEMS bases location and the proposed ones for Fall 2015-conditioned analysis with 5 helicopters

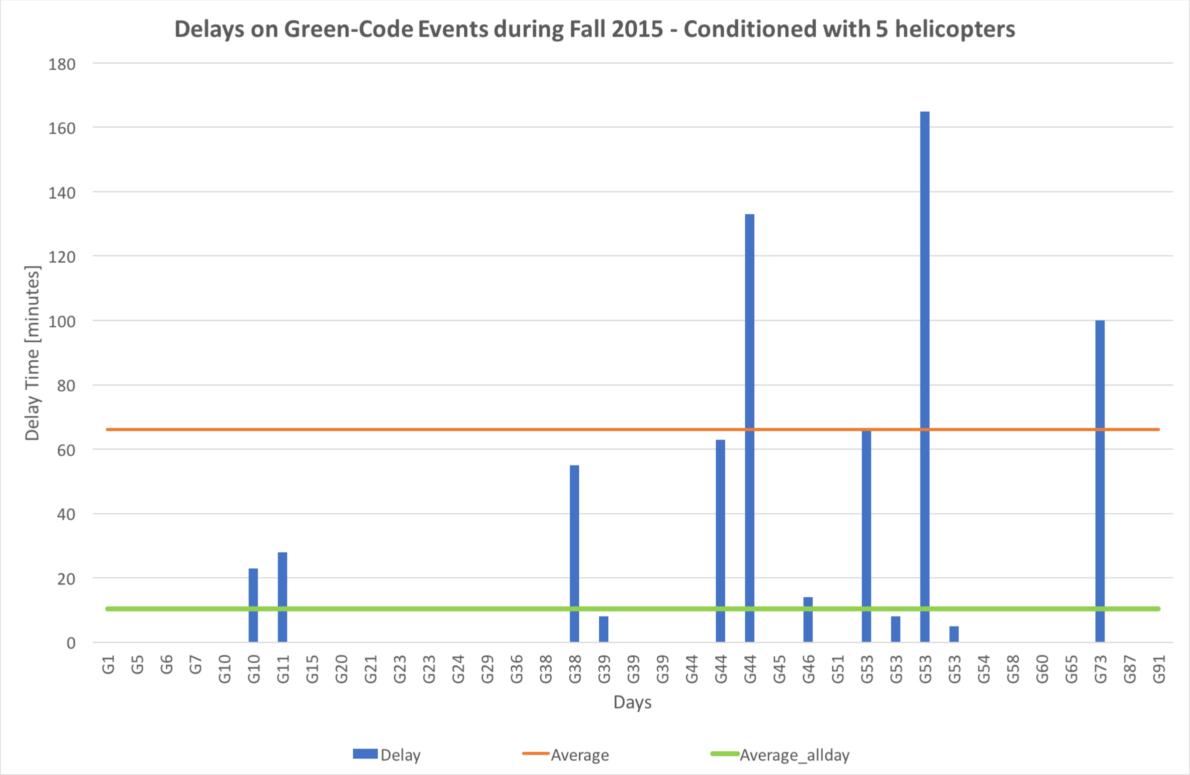
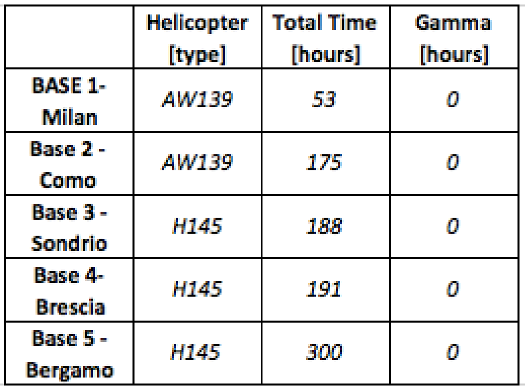


Figure 5.20: Table showing delay minutes vs day for green-code events for Fall 2015-conditioned analysis with 5 helicopters

the trend along the season, with orange line representing the average; if all green-code events are considered, the average delay time lowers to 18 minutes (green line). Here again, the proposed solution is characterized by a higher average delay (56 minutes vs 42 minutes) with respect to the green field analysis (5.12) and also a much higher all-day delay (18 minutes vs 8 minutes).

Table 5.25 shows the total number of served missions, both with *predictive* and *online* method. Out of a total of 694 missions, *predictive* method allows to serve 693 missions and reject one red code; using *online* method, two are the rejected missions (red codes), for a total of 692 missions with a regular outcome. Being the effective number of missions performed in this period 586, with such a base distribution, the HEMS service is capable to serve at least 106 more missions without having rejected missions.

Table 5.27 shows the total number of missions that could be served with the two (the optimal and the current) base disposition on territory; analysis has been performed with the *online* dispatching method. Again, the same results of the EXP 4: total number of non-served missions with the current configuration is four, if compared with the number of total missions non-served by the optimal bases location.



	Helicopter [type]	Total Time [hours]	Gamma [hours]
BASE 1- Milan	*AW139*	*53*	*0*
Base 2 - Como	*AW139*	*175*	*0*
Base 3 - Sondrio	*H145*	*188*	*0*
Base 4- Brescia	*H145*	*191*	*0*
Base 5 - Bergamo	*H145*	*300*	*0*

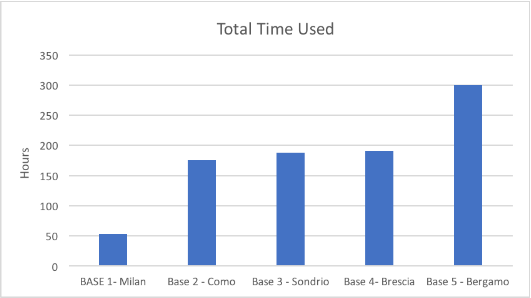
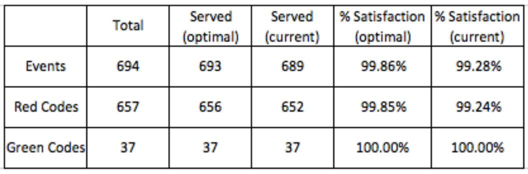
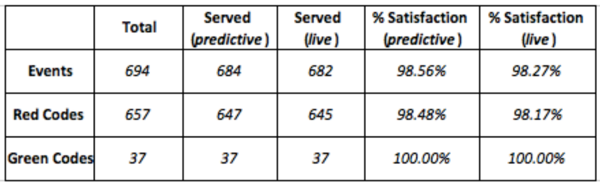


Table 5.26: Table and graphics showing total time used by each helicopter in each cell and gamma value for Fall 2015-conditioned analysis with 5 helicopters



	Total	Served (optimal)	Served (current)	% Satisfaction (optimal)	% Satisfaction (current)
Events	694	693	689	99.86%	99.28%
Red Codes	657	656	652	99.85%	99.24%
Green Codes	37	37	37	100.00%	100.00%

Table 5.27: Table showing the total number of events served with the two (current and optimal) base disposition during Warm months of 2015



	Total	**Served (*predictive*)**	**Served (*live*)**	**% Satisfaction (*predictive*)**	**% Satisfaction (*live*)**
Events	*694*	*684*	*682*	*98.56%*	*98.27%*
Red Codes	*657*	*647*	*645*	*98.48%*	*98.17%*
Green Codes	*37*	*37*	*37*	*100.00%*	*100.00%*

Table 5.28: Details about total, served and unserved events and satisfaction percentage for Fall 2015-conditioned analysis with 4 helicopters

5.2.1.2 Experiment C2: Fixed Milan-Bresso and Como bases during Fall 2015 with 4 helicopters

In this experiment, an optimal solution for events happened during the same Fall as before (October-November-December) 2015 is obtained, but considering just a total number of helicopters of four. The same total number of 694 events happened (657 red codes and 37 green codes) as represented in Figure 5.21.

Ten are the events that could not be served (all red codes) due to overcrowding in a small time span. In particular, the interested are on October 11th(3 events) and November 2nd. Events

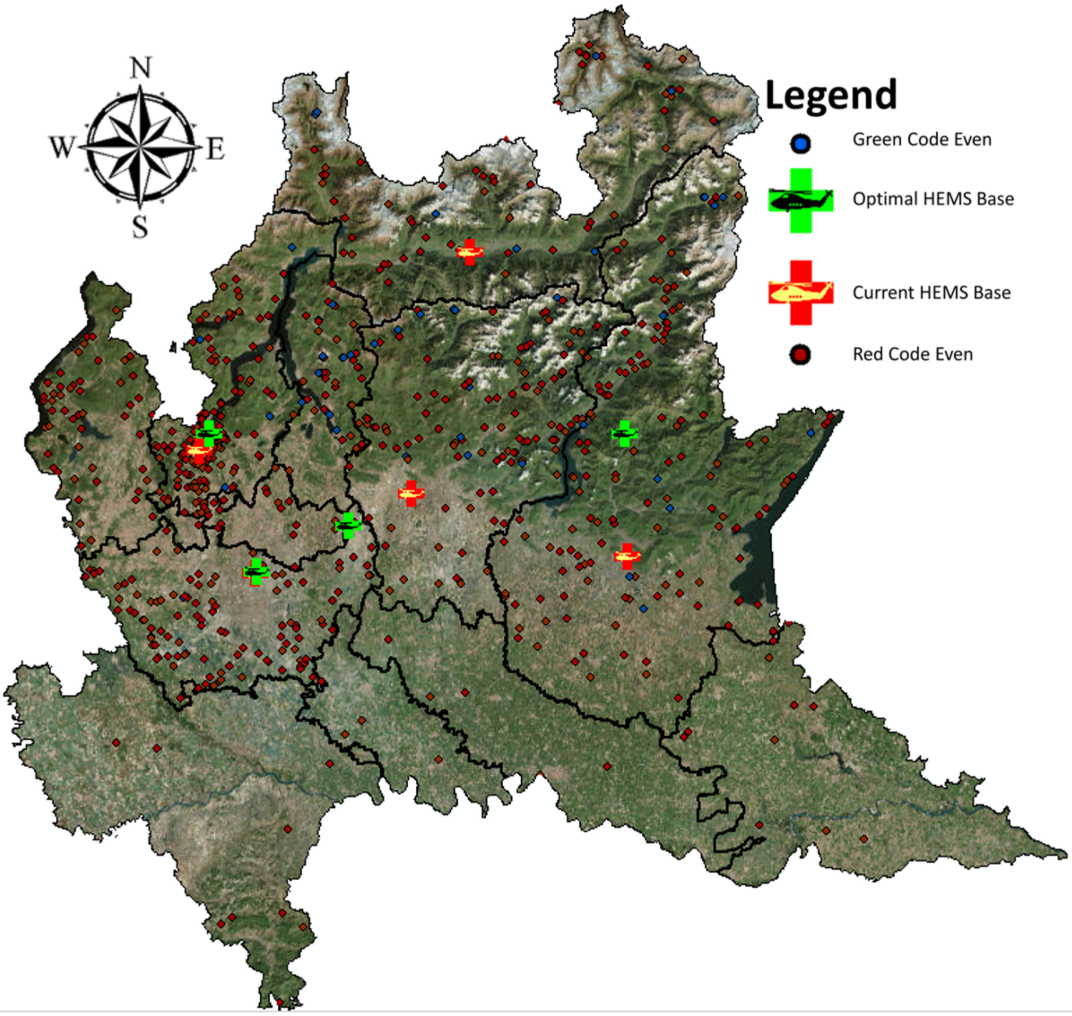


Figure 5.21: Map showing incidents location, the current HEMS bases location and the proposed ones for Fall 2015-conditioned analysis with 4 helicopters

location is visible in Figure 5.21; in the same figure, it is possible to see also the optimal location for bases and the current configurations. Apart from Bresso and Como bases which have been fixed, the results perfectly superimpose with the previous one (experiment C1) but Caiolo base which exists no more. Bergamo base shifted to Milan province border, 15Km to the west and Brescia moved 27Km to the north. The helicopters used in this layout are three Airbus H145 and two Leonardo AW139, as Figure 5.29 shows. In this scenario, Caiolo helicopter flies more than Como one, due to the capacity of the H145 helicopter to intervene in narrow valleys and impervious locations. Each helicopter is used for a total amount of time which is visible in Figure 5.29; the latter shows also the γ amount. Regarding cost analysis, the flight operations associated to the events costs €1’507’980 and the leasing cost of the four helicopters (2xAW139 +2xH145) is €2’400’000, for a total expense of €3’907’980, much higher than €3’491’380 spent for four H145

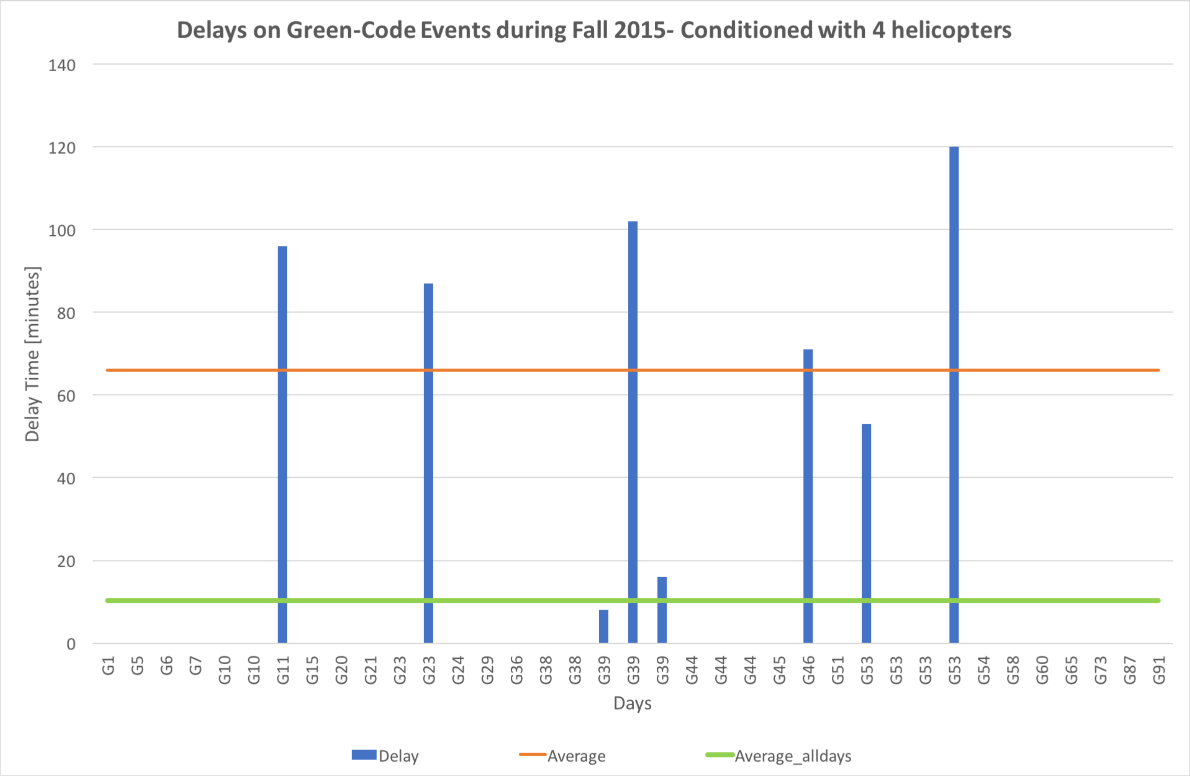
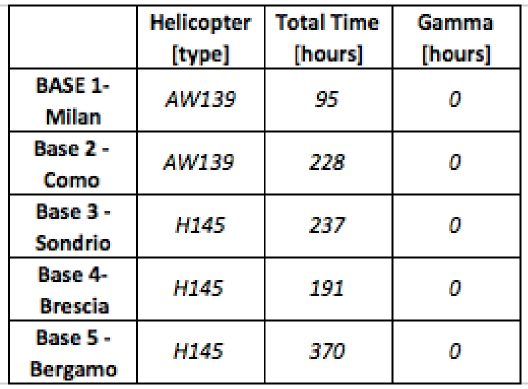


Figure 5.22: Table showing delay minutes vs day for green-code events for Fall 2015-conditioned analysis with 4 helicopters

helicopters in green field experiment (GF5). Seven green codes events have been delayed, with a delay average on delayed days of 69 minutes; if considering all days average, the value lowers to 15 minutes. These two averages, as well as the delay distribution along season, are visible in Figure 5.22. These averages are quite lower than the green field ones, found in experiment GF5 (avg: 89 minutes and avg_alldays:31 minutes): these results are defensible, thinking that three events less have been served.

In Table 5.28 it is possible to notice the total number of served missions, both with *predictive* and *online* method. *Predictive* method allows serving 684 missions out of a total of 694 missions, and reject ten red codes; using *online* method, twelve are the rejected missions (all red codes), for a total of 682 missions with a regular outcome. Again, these results must not be misunderstood: the effective number of missions performed in this period is 586. Therefore, with such a base distribution, the HEMS service is capable to serve at least 96 more missions without decreasing of performances. No comparisons with the current situation is possible, since the latter presents five bases, all year long.



	Helicopter [type]	Total Time [hours]	Gamma [hours]
BASE 1- Milan	*AW139*	*95*	*0*
Base 2 - Como	*AW139*	*228*	*0*
Base 3 - Sondrio	*H145*	*237*	*0*
Base 4- Brescia	*H145*	*191*	*0*
Base 5 - Bergamo	*H145*	*370*	*0*

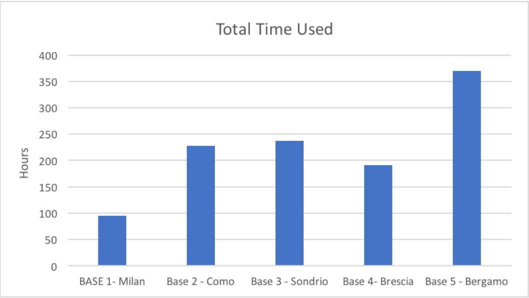


Table 5.29: Table and graphics showing total time used by each helicopter in each cell and gamma value for Fall 2015-conditioned analysis with 4 helicopters

5.3 Fictitious Scenario

In this last section of the work, a fictitious month has been developed to test the real capacity of the model. To generate the fictitious month, the first ten days of each month from April to September have been considered for a total of 60 days. Then they have been grouped two by two to half the total number of days: in such a way a single day contains requests of two (consecutive) days.

5.3.1 A Fictitious Month

This last experiment is intended to discover the limits of the model, loading it with a high workload. Since there are a huge number of requests, a high number of unserved requests are expected. Moreover, in this experiment, no locating optimality is performed: bases already exist in two configurations (the warm month optimal one and the current one), and the model has just to assign as more missions as possible. Both *predictive* and *online* method are used.

5.3.1.1 Experiment F1: How model reacts with an extremely overcrowded month?

This experiment is intended to discover the potentiality of the model, counting on five helicopters in as many bases (located in the same position of the Warm months, EXP 7), for the previously discussed fictitious month. The month counts 786 incidents, 715 of which are red-code and 71 green code, as visible in Figure 5.23. From Figure 5.30 it is possible to see the comparison between the number of total missions, total red-code missions and green-code missions with *predictive* method. Figure 5.31, on the other hand, presents the same comparison but with the use of the *online* allocation method.

Results confirm the model strength: with the optimal base location, results are slightly better then the ones obtained using the current positioning of the bases. In particular, the satisfaction

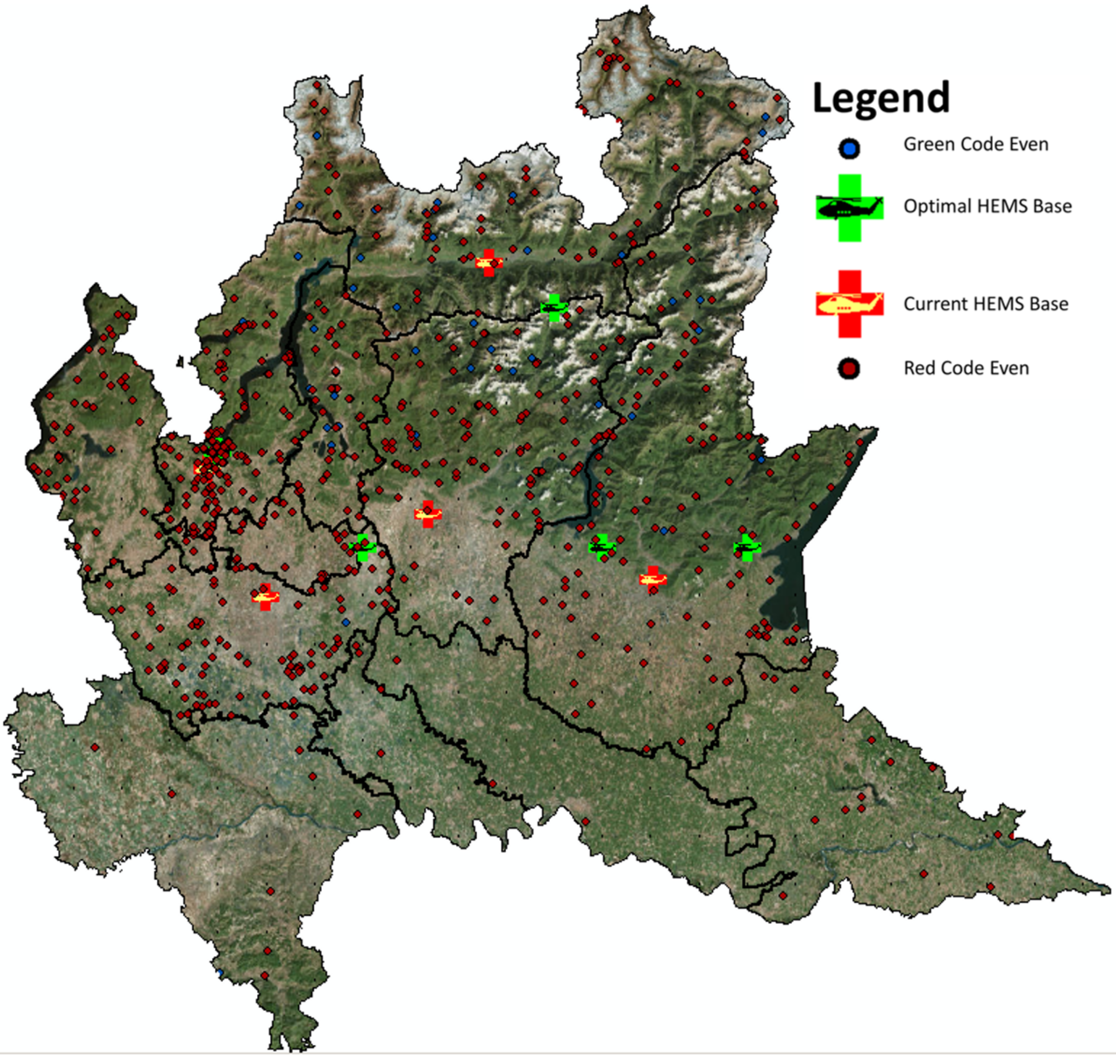
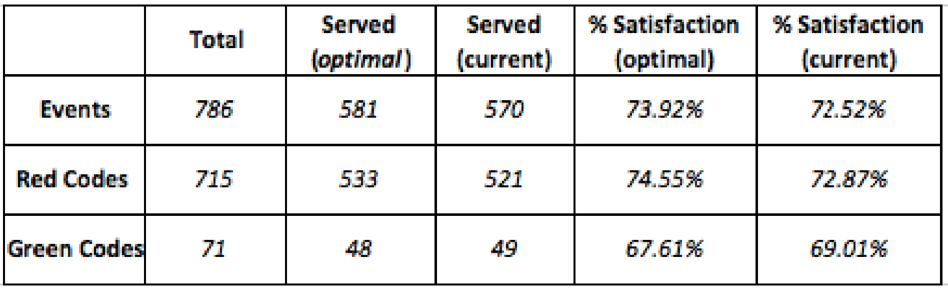


Figure 5.23: Map showing incidents location, the current HEMS bases location and the optimal ones for the warm months period

	Total	Served (*optimal*)	Served (current)	% Satisfaction (optimal)	% Satisfaction (current)
Events	*786*	*760*	*750*	*96.69%*	*95.42%*
Red Codes	*715*	*689*	*680*	*96.36%*	*95.10%*
Green Codes	*71*	*71*	*70*	*100.00%*	*98.59%*

Table 5.30: The table shows the comparison between the total number of served missions with the optimal solution found and the current position of the base, using *predictive* mission allocation method



	Total	Served (*optimal*)	Served (current)	% Satisfaction (optimal)	% Satisfaction (current)
Events	*786*	*581*	*570*	*73.92%*	*72.52%*
Red Codes	*715*	*533*	*521*	*74.55%*	*72.87%*
Green Codes	*71*	*48*	*49*	*67.61%*	*69.01%*

Table 5.31: The table shows the comparison between the total number of served missions with the optimal solution found and the current position of the base, using *online* mission allocation method

level from the optimal base is at least one percentage point more than the one coming from current positions of the bases, with one exception: the current positions of the bases allows to serve one extra green-code event, using *online* method. However, this is not in contrast with what said so far: a closer look allows to see that the configuration is able to serve one more green code but presents twelve served red codes less; and having the red code missions the highest score (100), the results obtained with the optimal solution is in any case better.

5.4 Final Considerations on the Experimental Campaign

In this final section, two discussions are presented, the first comparing *rigid* model and *flexible* one, their peculiarities, their differences and the optimal results from the two; the second comparing the two dispatching methods, the *predictive* one and the *online* one, their definitions, characteristics, diversities and similarities of solutions.

5.4.1 *Rigid* vs *Flexible* Model

Two are the mathematical models formulated, which try to describe the HEMS services. The first one is called *rigid*, since it needs a helicopter to be always available, in case of red-code event. While green-code events take-offs can be delayed for a maximum time of 3 hours, red code events cannot be delayed: as soon as the AAT receives the call for an emergency situation, the first helicopter available (if there are more, the one which takes the shortest time to reach destination) must take-off immediately. If no helicopters are present at the moment the call is received, the mission is considered rejected. This is the origin of the name of this model: no delays are permitted at all, while in reality a helicopter flying from hospital to base can be intercepted and another mission can be re-assigned, if technical or medical factor allows to (out-of-fuel, incoming of darkness or bad weather, biological fluids' presence in the cockpit). That's why a second model has been developed, to overcome this strong constraint: the take-offs of red-code events can be delayed too, but with the constraint that patient can be reached within 30 minutes from the call. This allows more elasticity to the model; elasticity overloads computational efforts, reason why this second model cannot be executed on long periods. It has been performed on four one-week periods, the four weeks of January 2015. Results in both cases present small differences between the *rigid* solution and the *flexible* one; sometimes solutions of the two models are superimposed (EXP C and D), often they are near (EXP A and B). This endorses the use of the *rigid* model instead of the use of the *flexible* one: since results are very similar, the usage of the *rigid* allows to obtain valid results with low computational efforts, hence for longer periods of time. Although solutions of the two models are similar, they are different from the current location of bases.

5.4.2 *Predictive* vs *Online* Method

Beside the two previously described models, two dispatching methods have been developed. Term "dispatching method" means the way missions are assigned to helicopters and in which order helicopter should take-off to serve them. In particular the so-called *predictive* method is characterized by knowing a priori all events that will happen in a particular day and that is the reason of its name; therefore, some strategic delay of some green-code missions are practicable in order to cover as much as possible the red-code events. Albeit this kind of dispatching is more effective for optimal base location, surely it is not usable in reality: none knows *a priori* what will happen during the day. For this reason, another allocation method has been developed: the so-called *online* method. With this tool, it is possible to analyze the order and the total number of missions actually served. The optimization model takes into account the *predictive* method, in order to ensure that the maximum number of events are covered. Hence, the *online* method is performed a posteriori, meaning that once the optimal base locations have been chosen, the allocation of missions is re-calculated. Since *online* method is less effective than *predictive* one, a statistical analysis has been performed aimed at seeing what are the results difference between two methods. Figure 5.24 shows the comparison between the percentage of served mission using both methods. As it can be seen from figure, the satisfaction percentage is - in both case - very high (above 99%); *predictive* method is an average satisfaction percentage of 99.61% while *online* is a bit lower, with 99.14%.

In particular, the simulation characterized by counting on just four helicopters have a lower number of served missions (EXP GF5 and EXP C2) with the *online* dispatching method. A decrease in satisfaction with the *online* method is also present during the high-involved period, i.e. for simulation Summer 2015 and Warm Months: in these cases, the number of served missions using the *online* method the percentage lowers to a minimum of 98.5%. However, it can be noticed that no huge difference in the total number of served mission exists: this endorses the use of the *predictive* method and it guarantees the safe use of it in the optimization model.

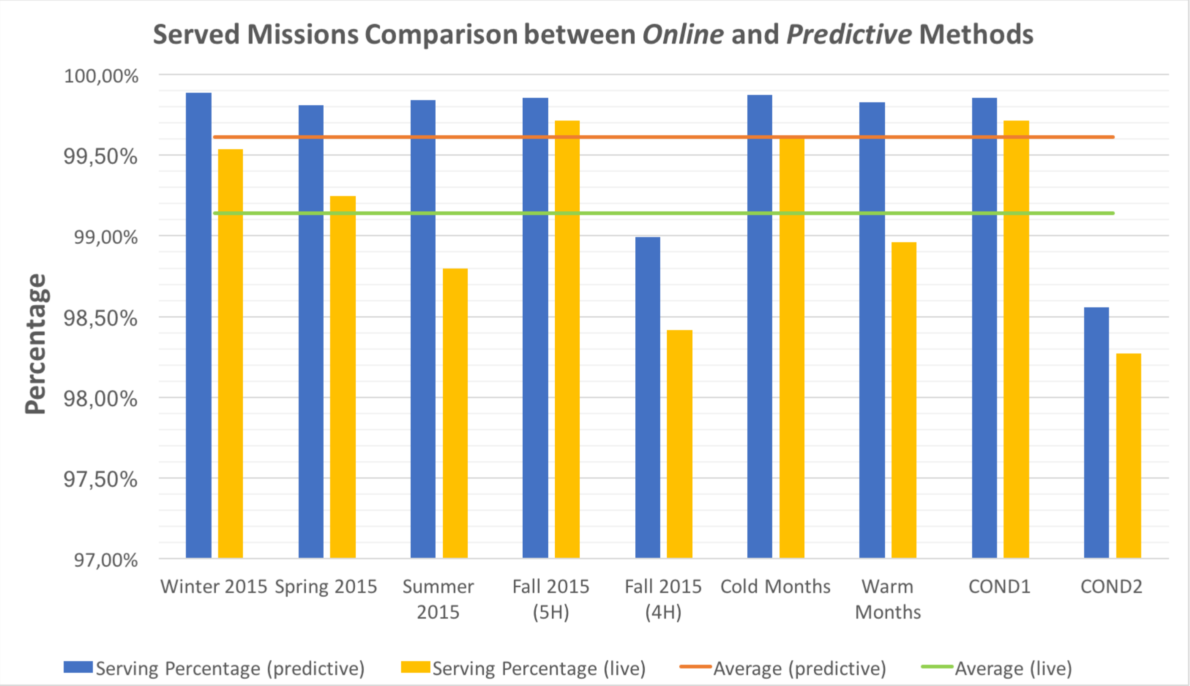


Figure 5.24: Graphical comparison between missions served with *predictive* and *online* methods

5.4.3 Towards a Stable Solution

One can observe that it is not possible - logistically and financially - to move all the HEMS bases seasonally or semestrally. Therefore a comparison between solutions obtained in the experiments is carried out. Comparing Figure 5.15 and Figure 5.17 an interesting result can be appreciated: almost all bases have been located in very near cells. Villaguardia base is located exactly in the same cell; also the base located in between Bergamo and Milan cities is exactly in the same point (on the border between the two provinces). Brescia base is moved towards Iseo lake and, although the two solutions do not overlap, they are very close; also Caiolo base solutions are very similar, with a discrepancy of 20Km. Therefore, one can think that the optimal locations for the entire year should be Trezzo sull'Adda (MI), Como, Iseo (BS) and Tirano (SO). While four bases are considered fixed, the fifth one is floating, depending on semestrality. In particular, during cold months (October to March) it is located in the outskirts of Milan city, near Rozzano (MI); during the warm months (April to September), it is positioned on the Garda lake shores, in Salò (BS). In fact, through a more careful observation, it can be noticed how, during warm months, the number of events on the lakes is greater; in particular on east-bound lakes (Iseo and Garda lakes), the number of rescue requests is much higer than during the cold period, due to holidays and vacations.

In conclusion, from the analyses aimed at comapring the total number of served mission with the current and the proposed bases location , it results evident that the current distribution of

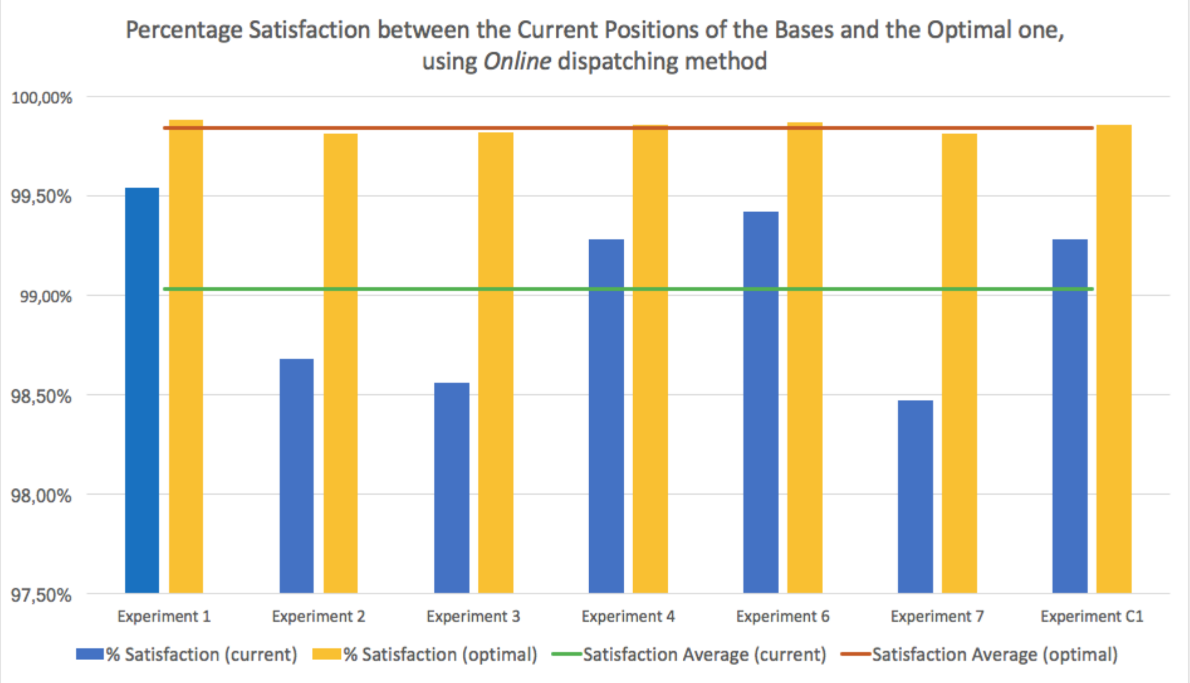


Figure 5.25: Graph showing satisfaction percentage with the proposed optimal locations and the current ones

bases is able to keep the satisfaction percentage above the 98% threshold; this is visible in Figure 5.25, where also the averages are present. That means that experience and historical choices, although not endorsed by a mathematical modelling, were able to locate HEMS bases greatly. Some improvements are, anyway, possible in order to approach the 100% satisfaction threshold and to reduce significantly costs. The above discussed location of the bases, with one floating semestrally, surely allows to improve the efficiency of the Helicopter Emergency Medical Service and, therefore, to minimize the associated costs.

3

CHAPTER 6

CONCLUSIONS AND FUTURE WORKS

> The helicopter symbolizes the victory of ingenuity over common sense.
>
> Montross, Lyn and Prouty, *U.S. Marine Corps Helicopter Experience*

The air ambulance service is the most advanced emergency medical system, peculiar to the more developed countries. The most advanced technology and the state-of-art instruments are concentrated in it, together with dedication and sacrifices of the on-ground and on-board staff, which works in harmony to guarantee a medical coverage all over the territory, 365 days a year. However, this is not sufficient: upstream organization of air ambulance system must run smoothly and efficiently. That is what this thesis work is aimed at, i.e. building a mathematical model able to investigate the optimal HEMS bases location to serve the maximum number of events in the minimum time and then to compare it with the current scenario; moreover, during optimization, a dispatching method (called *predictive*) allows to assign missions to the helicopters of each base, knowing *a priori* all events distribution. Since this method does not match with the one used in reality, downstream of optimization, another dispatching method (called *online*) has been developed. It assigns helicopters to missions chronologically, as they arise. Comparisons between the solutions of these two methods allow to say that the total number of served missions is only slightly different and, therefore, one can make use of the *predictive* dispatching method, with a minimal error. Moreover, there are two mathematical models, the *rigid* and the *flexible* one. The former provides that, as the red code event call is received, a helicopter should be immediately available to serve it; the latter, on the other hand, provides that helicopter time of arrival on site should happen within a fixed threshold from the call receipt. A comparison between two solutions is available on a very-limited timeframe (a week) as shown in experiments A to D. The solutions show small differences in the results of the two models: sometimes base locations are superimposed, often they are near. This endorses the use of the *rigid* model: since results are very similar, the usage of the latter allows to obtain valid results with shorter computational time, therefore for longer periods of time. One can trivially observe that it is not possible to move seasonally HEMS bases, with their staff and helicopters; costs would be prohibitive. In analyzing the semestral experiments, it was found that variations on bases location are slight; this allowed to suggest a strategy for the improvement of HEMS service in Lombardy. Four out of five bases are located near, both during warm months and during cold monts; they are located in Trezzo sull'Adda (MI), in Como, in Iseo (BS) and near Tirano (SO). The fifth base is floating: during the cold months, it is located south-west of Milan city, near Rozzano (MI), whilst during the warm months it is located on the Garda Lake shores, in Salò (BS), probably due to holidays.

What should be evident, from all analyses, is the potentiality of such a tool and in general of mathematical optimization. From experiment results, already widely discussed, it was found that, being autumnal period the less involved, four helicopters are sufficient to guarantee medical coverage and to save about a half million euro. However, it should be pointed out that such data, simulations, and results are referred to year 2015. With the increasing number of requests of the last years, all simulations should be repeated with up-to-date data to confirm or not the results found.

Moreover, from the analyses aimet at comparing the total number of missions served with the current HEMS bases location and the proposed one, it was found that the current bases, although not set in optimal location, are able to cover the great number of the events, keeping the satisfaction percentage always above the 98% threshold. This endorses the current location of HEMS bases, even if some improvement can be anyway applied. What is free from variable factors is the choice of the more suitable helicopter to be used. Basing on considerations and testimonies given by pilots and technicians, it results that, between model AW139 of Leonardo and the model H145 from Airbus Helicopters, the more suitable for HEMS in terms of performances and characteristics is the latter, since it is characterized by much smaller leasing costs, specific consumption, and ignition and shut-off times; and, although it has a lower cruise velocity, on short distances (bases to incident point, incident point to hospital and hospital to base) it is the best choice in any case. The rotor diameter (info available in Appendix A), finally, plays an important role on the helicopter capacity to reach an impervious place: the smaller the rotor, the more suitable the helicopter. Moreover, other considerations not taken into account in this problem, should be considered. The take-off mass is highly different: model H145 from Airbus Helicopters has a smaller take-off mass than its higher category rival. This allows the H145 to be more agile and to transfer less turbulence on patient. In the end, from a technical point of view, H145 presents a neutral attitude while in hovering (while model AW139 has a nose-up attitude), it has skids which allows it to have more stability in case of landing on irregular grounds, it has a retractable hoist and technical halts times are very short (informations from interview with Doc. Giupponi).

Future Works Being this a new thesis in its arguments and models, there are some extensions that can be made to improve the work. From a *modelling* point of view, the implementation of economical aspects in the objective function can lead to different solutions; a deepening study on costs to open new bases can be also carried out. From the *methodological* point of view, the high number of variables involved in the long-term experiments suggests to try to develop metaheuristics; metaheuristics, differently from heuristics, looks for the global optimum instead of the local one. With this method there are no guarantees to find the optimal solution but surely it can find a feasible result with significantly lower computational efforts and time. Another development could be the matheuristics; the latter is a metaheuristic based on a solution of mathematical problem, treated as a subproblem; for instance, by fixing some binary variables or by adding some constraints to only explore, at each iteration, a neighbourhood of the current solution. This way, the current MILP models developed in this thesis can be exploited also to face big instances.

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APPENDIX A - HELICOPTERS AND TRAINING

The vast majority of HEMS national services endeavor ultimate generation helicopters, like the Leonardo Helicopters AW139 and the Airbus Helicopters H145. But in analysing some countries, other helicopters usages have been discovered. As result, brief technical specifications and personal opinion of engineers and HEMS pilots are reported.

Helicopters

Airbus Helicopters

H125

Operator: China.

Formerly known as EC125 (Figure A.2), the H125 (a.k.a. AS350 B3e) outclasses all other single-engine helicopters for performance, versatility, low maintenance, and low acquisition costs, while excelling in high, hot and extreme environments. It is a member of Airbus' Ecureuil family, which has accumulated more than 32 million flight hours worldwide. In 2005, the AS350 B3 broke the world record for the highest-altitude landing and takeoff, performed on Mount Everest at 8,848 metres (29,029 feet), a title still held today. On 19 May 2013, the AS350 B3 performed the world's highest long-line rescue operation on Lhotse, the world's fourth highest mountain, located in the Himalayas, at 7,800 metres (25,590 feet). When configured for vital life-saving and emergency medical transportation, the H125 can carry up to four people (1 pilot, 1 patient and 2 attendants) plus medical equipment (see figure A.1) [3].

Technical Specs.

1. Max Gross Weight: 2370Kg;
2. Passengers: up to 6;
3. Main Rotor Diameter: 10.69m;
4. Max Cruise Speed: 133kts (= 246Km/h);
5. Service Ceiling: 20000ft (= 6100m) ;
6. Range: 336nm (= 622Km) ;
7. Endurance: 4h 20min .

From: *https://www.airbushelicoptersinc.com/products/H125-specifications.asp*

Figure A.1: Interior sight of a HEMS-configurated H125

Figure A.2: Exterior sight of a HEMS-configurated H125 operating in Austria

H130 T2

Operator: California.

Formerly known as EC130, the single-engine aircraft is retrofitted with the latest aviation safety technology and features a more powerful engine, a spacious cabin with new medical equipment, and a quieter sound signature. EcoStar was selected primarily for its advanced safety features, including an enclosed tail rotor, landing gear that prevents ground resonance, energy absorbing seats throughout and redundant aircraft systems. Its all-in-one digital technology includes features important for the weather, terrain and altitude: synthetic vision, satellite weather, GPS and real-time digital tracking, night-vision and traffic and terrain alert systems. Dimensions are visible in Figure A.3 The large cabin space provides comfort for patients, better patient access for crew and room for new medical equipment: a built-in intercom system for blood pressure, heart and lung sounds; and an Isolette incubator to transport infants (see Figure A.4) [28].

Technical Specs.

1. Max Gross Weight: 2427Kg;
2. Passengers: 6;
3. Main Rotor Diameter: 10.69m;
4. Max Cruise Speed: 130kts (= 240Km/h);
5. Service Ceiling*: 15655ft (= 4770m) ;
6. Range*: 333nm (= 610Km) ;
7. Endurance*: 4h 00min .

* Sea Level, ISA conditions, maximum gross weight, with standard fuel
From: *https://www.airbushelicoptersinc.com/products /H130-specifications.asp*

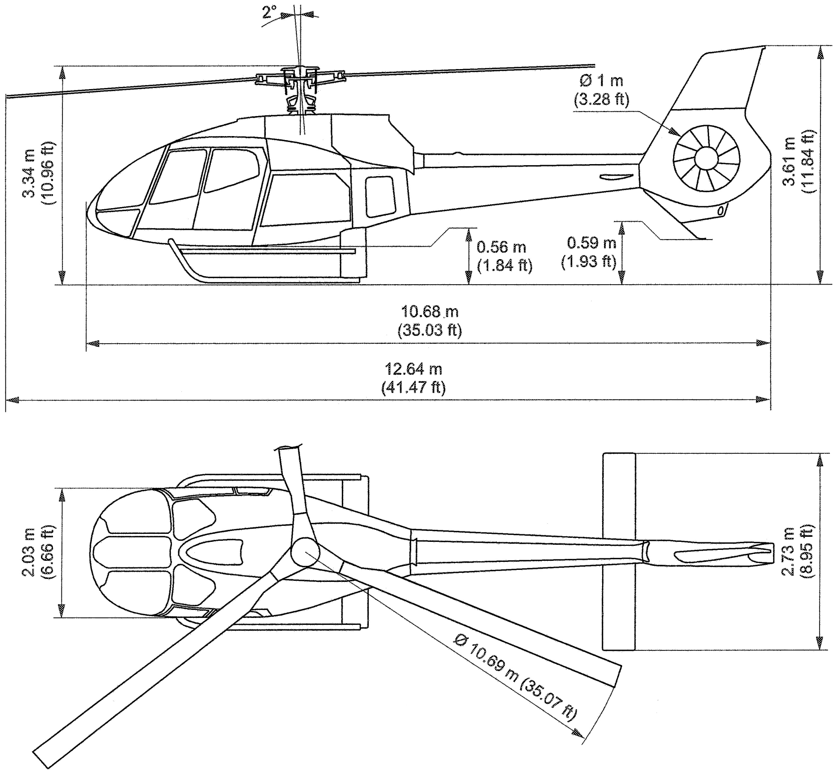

Figure A.3: Technical chart of H130

Figure A.4: Interior sight of a HEMS-configured H130

H135

Operators: Albany,China, Norway, Trentino Alto Adige (Italy).

Formerly known as EC135, it has already been recognized by pilots and technicians as one of the most complete, reliable and powerful machine for mountain rescue ops (see A.5). NVGs used by AIUT Alpin are the ASU Inc M949: they're white phosphorus 3rd generation image intensifiers which allows a 40 degrees visual field of are equipped with lenses that avoid interference with the helicopter's cockpit and service lights. One of the most important factors noted by many, in addition to the new Fenestron design, was the low noise signature of the H135. The H135 was the quietest helicopter in the world, a record it held for over fifteen years. The low noise signature, coupled with the spacious interior that the H135 offered (see dimensions in Figure A.6), made the helicopter an immediate success, initially in the helicopter emergency services arena, then later in para-public, commercial and military service. By 2013, the H135 numbered over one thousand aircraft in service around the world [29].

Technical Specs.

1. Max Gross Weight: 2980Kg;
2. Passengers: 6;
3. Main Rotor Diameter: 10.20m;
4. Max Cruise Speed: 137kts (= 254Km/h);
5. Service Ceiling: 20000ft (= 6096m) ;
6. Range*: 342nm (= Km) ;
7. Endurance*: 3h 30min .

* Sea Level, ISA conditions, maximum gross weight, with standard fuel

From: *https://www.airbushelicoptersinc.com/products /H135-specifications.asp.*

Figure A.5: Exterior sight of a landing german H135 HEMS equipped

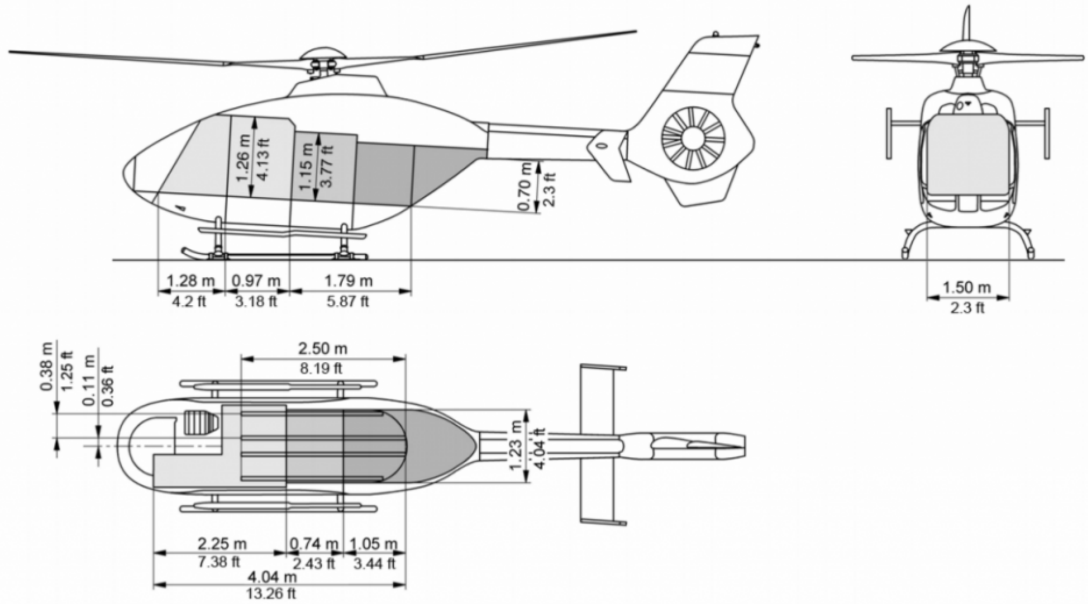

Figure A.6: Technical chart of the H135

H145 T2

Operators: Austria, Japan, Norway, Switzerland; Lombardy, Sardinia.

Formerly known as EC145, the operator's version of the aircraft, which includes about $625,000 of medical equipment (partially visible in Figure A.7), has a unit price of $6.5 million. The EC145 T2 is excellently suited for air rescue missions thanks to its performance capability and the Fenestron. Particularly in night rescue missions, the shrouded tail rotor provides a further measure of safety. "Specifically designed to support HEMS missions and the key points are the safety levels, low emission of noise. It is the first to mount Helionix Cockpit, which release the pilot to its workload and increase significantly the safety"(Wolfgang Schoder, CEO Airbus Helicopters Germany). "It's the perfect helicopter for air ambulance service and for transporting injured people from hospital to hospital" (Steffen Lutz - DRF Luftrettung Director) (see a real emergency situation photographed in Bergamo in Figure A.8) [30].
It can count on a hoist lenght of 60m vs. 30m lenght of AW139 and with respect of the latter, the EC145 is smaller therefore it moves a less air mass and can land almost everywhere counting on a rotor diameter of just 11 meters.

Technical Specs.

1. Max Gross Weight: 3700Kg;
2. Passengers: up to 9;
3. Main Rotor Diameter: 11m;
4. Max Cruise Speed: 143kts (= 265Km/h);
5. Service Ceiling*: 17200ft (= 5240m) ;
6. Range*: 370nm (= 680Km) ;
7. Endurance*: 3h 37min .

* Sea Level, ISA conditions, maximum gross weight, with standard fuel
From:*https://www.airbushelicoptersinc.com/products/H145-specifications.asp*

Figure A.7: Interior sight of the H145 based in Bergamo

Figure A.8: Patient landing from a H145 at Bergamo hospital HEMS base

Leonardo Helicopters

AW139

Operators: Lombardy, Sardinia.

The AW139 is the market leading intermediate twin turbine helicopter, setting the standard against which all intermediate twins are measured. Developed with the latest EASA part 29 certification standards and with a MGW of 6400 Kg and a rotor diameter of almost 14 meters (see Figure A.10 for dimensions,) operators worldwide benefit from unparalleled safety, performance and operational capability. Leonardo AW139 belongs to the Helicopter Division Family of products with AW169 and AW189, which provides training and maintenance savings for mixed-fleet operators. Some but not all of its features are fastest cruise speed and highest power to weight ratio in its category, certified Cat. A Class 1 performance at Maximum Gross Weight (40C at Sea Level), enabling Vertical Take-Off and Landing (VTOL) in confined areas and on uneven terrain. It is the only helicopter in its class to fully satisfy the latest FAR29 and AIROPS regulations, incorporating crashworthiness and survivability features; moreover it has the largest internal volume in its class, with accommodation for 2-4 stretchers (Figure A.9) with up to 5 seats and finally large sliding doors provide unobstructed access to the rapidly reconfigurable, flat-floor cabin for easy loading and unloading of patients on the ground and during hoisting operations.

Technical Specs.

1. Max Gross Weight: 6400Kg (Increased MGW kit: 7000Kg);
2. Passengers: 15;
3. Main Rotor Diameter: 13.80m;
4. Max Cruise Speed: 165kts (= 360Km/h);
5. Service Ceiling: 20000ft (= 6096m);
6. Range*: (with aux fuel) 573nm (= 1071km);
7. Endurance*: (with aux fuel) 5h 13min.

* No reserve.
From: *http://www.leonardocompany.com/-/aw139*

Figure A.9: Interior sight of Leonardo AW139; notice a very large room for patient and medical staff

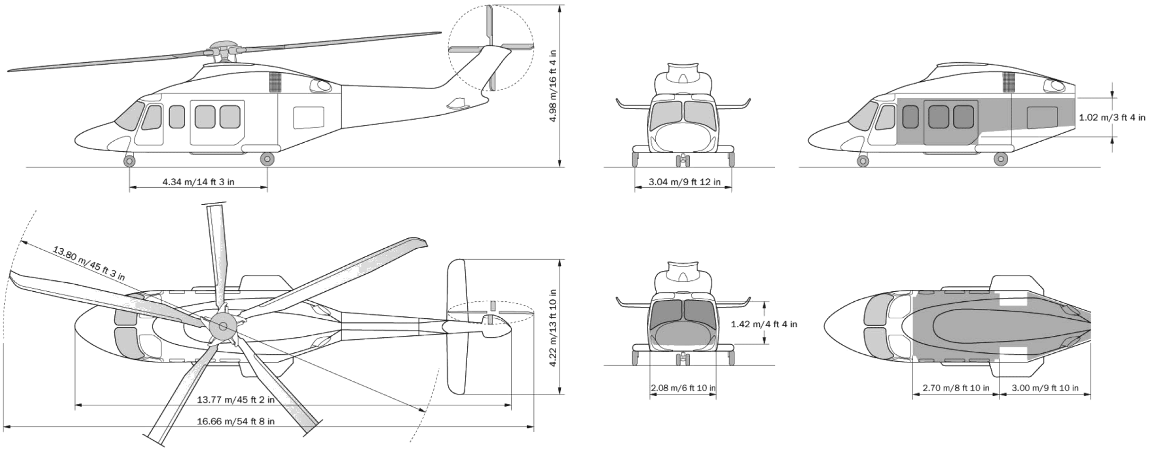

Figure A.10: Technical chart of Leonardo AW139

AW169

Operators: United Kingdom, Maryland (US), Texas (US), Swiss; Lombardy, Lazio, Piemonte, Puglia, Sardinia.

Designed around the patient's needs, the AW169 is ideally suited to life-saving primary and secondary missions and rescue services. The aircraft exceeds the most demanding market and regulatory requirements, including the most recent FAA and EASA Part 29 standards for performance and safety. Pilots benefit from an advanced open-architecture avionics suite with fully digital glass cockpit and excellent external visibility for optimised situational awareness and minimised workload. Operators benefit from a large, rapidly reconfigurable cabin, with constant-height cross section and easy access for adaptability to a variety of missions. The AW169 is easily adaptable, rapidly reconfigurable and uniquely designed around the patient needs, ensuring that air medical professionals can be there when it counts, providing the best care. Features whose pilots would benefit from AW169 are the largest cabin in its class with flat floor and constant cross-section height for maximum versatility; accommodation for 2 wheeled stretchers longitudinally and transversally (see Figure A.12); easy access to the entire patient body from both sides of the cabin, accommodation for a full suite of advanced life support equipment, its well-lit, comfortable operating environment and very large (1.60 m) sliding doors (for helicopter dimension see Figure A.11) for easy patient entry and egress.

Technical Specs.

1. Max Gross Weight: 4600Kg (Increased MGW kit: 4800Kg) ;
2. Passengers: 11 (1 stretcher + up to 7 medical attendants or 2 stretcher + up to 5 medical attendants);
3. Main Rotor Diameter: 12.20m;
4. Max Cruise Speed: 143kts (= 266Km/h);
5. Service Ceiling: 15000ft (= 4600m) ;
6. Range*: 440nm (= 820Km) ;
7. Endurance*: 4h 20min .

* At 5,000 ft, no reserve, standard fuel system.
From: *http://www.leonardocompany.com/-/aw-169*

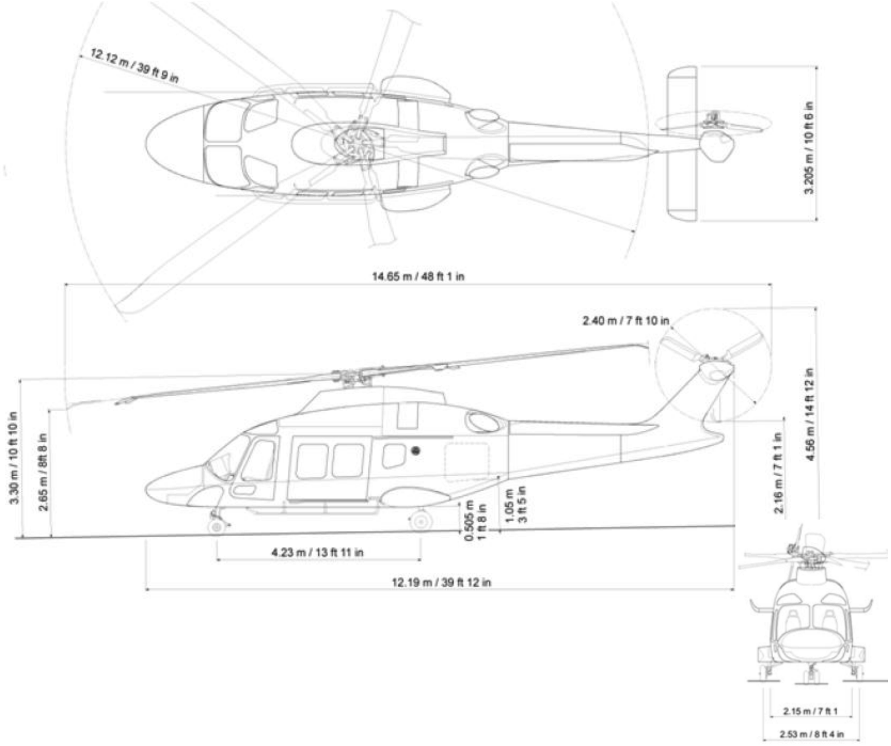

Figure A.11: Technical chart of Leonardo AW169

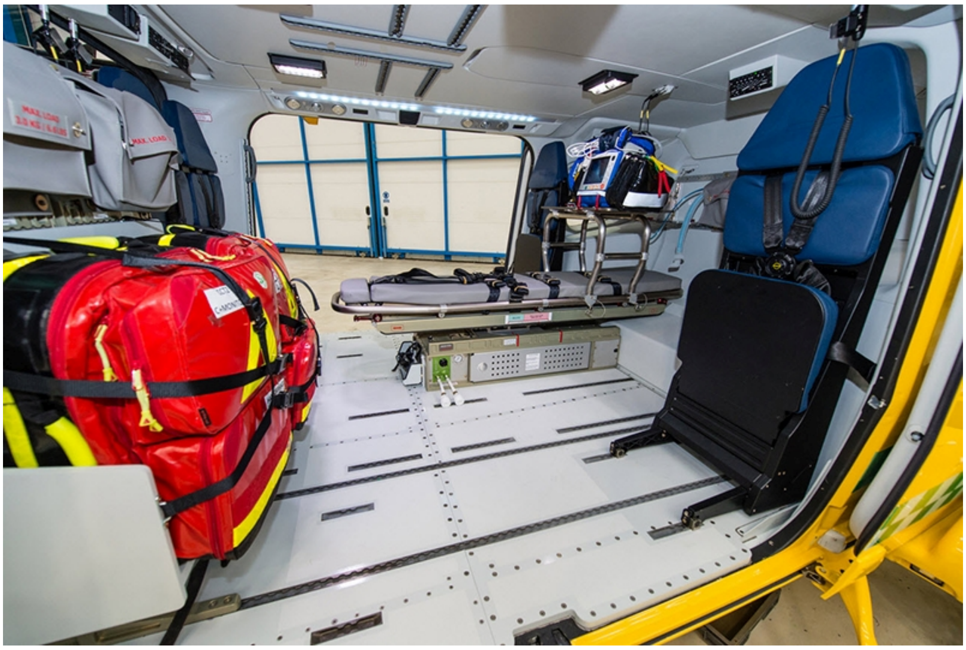

Figure A.12: Interior sight of Leonardo AW169; although smaller than AW139, there is anyway enough room for patient, medical staff and two pilots

Bell Helicopters

B429

Operators: United Kingdom, Sweden.

The Bell 429 GlobalRanger also offers exceptional flight performance with a fully integrated glass cockpit, advanced drive system and best-in-class WAAS navigation and IFR capability. Additional safety features include a collective mounted throttle, damage tolerant hub and rotor system, and energy attenuating seats. It is the first helicopter certified through the MSG-3 process, resulting in reduced maintenance costs for operators. The Bell 429 also features a spacious cabin and extra large 60 inch side doors (see Figure A.13), as well as Instrument Flight Rules (IFR) capability certified for single or dual pilot operations. In late October 2014, the Federal Aviation Administration (FAA) has rejected the appeal of Bell Helicopter relative to the increase of 500 pounds of the maximum weight of the Bell 429. This was the second rejection by the highest US authority: in 2012 the same request of the Canadian section of the American manufacturer had been rejected. The Bell 429, therefore, will not benefit in the United States of exemptions on the maximum weight, which will remain fixed at 7,000 pounds (3,175 kg). The Canadian authorities and a total of 18 International Institutions, including Australia, Brazil, China, India, Indonesia, Israel, Mexico, already gave the green light to the weight increase of the helicopter (technical chart available in Figure A.14). In the meanwhile, the Sweden HEMS missions are performed by an EC-145 [31].

Technical Specs.

1. Max Gross Weight: 3175Kg;
2. Passengers: 7;
3. Main Rotor Diameter: 10.97m;
4. Max Cruise Speed: 150kts (= 278Km/h);
5. Service Ceiling*: 11290ft (= 3440m) ;
6. Range**: 411nm (= 761Km) ;
7. Endurance**: 4h 30min .

* At MGW.
** Max GW, ISA, Std fuel – no reserve, at 4000 ft / 1219 m.
From: *http://www.bellflight.com/commercial/bell-429*

Figure A.13: Interior sight of Bell 429

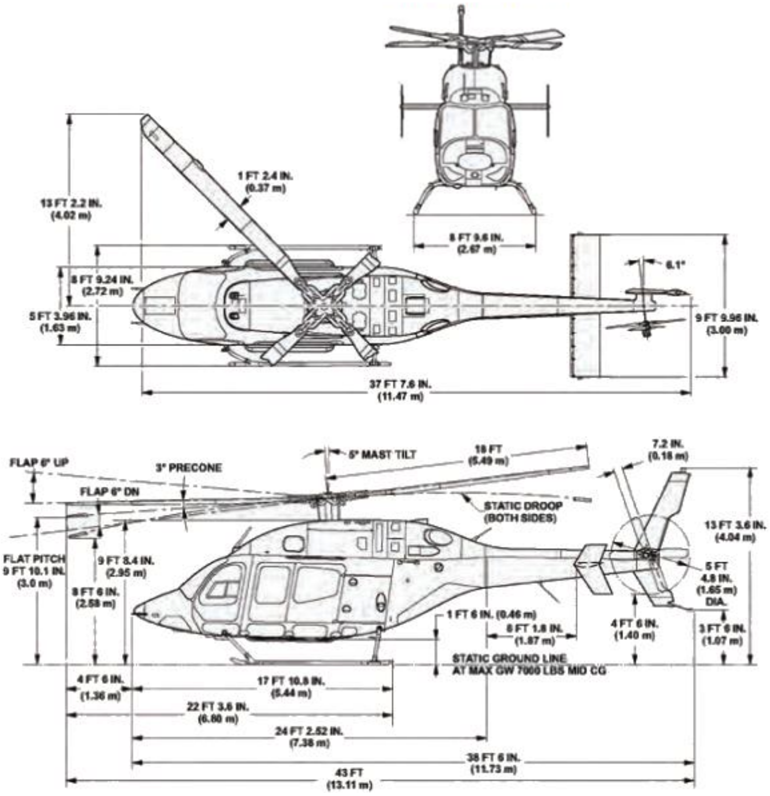

Figure A.14: Technical chart of Bell 429

Training Staff On New Helicopters

From a study of Galazkowski et al. *[25]*

The main aim of the government program for replacing the fleet of Emergency Medical Service (EMS) helicopters in Poland (PMAR: Polish Medical Air Rescue) was to fulfill the duties resulting from European flight regulations which specify the technical requirements for the aircraft used by EMS operators in European Union countries, which were no longer met by Mi-2 plus helicopters. The second aim was to increase the operation capabilities of the Helicopter Emergency Medical Service (HEMS) in the area of performing aviation tasks using the new type of helicopter, the EC135. To ensure the maximum level of safety during the missions performed both in the transition period and in the course of later operations, the management of the company started preparing a strategy of training HEMS crews for the new type of helicopter. Such a strategy involves the technical aspects of the pilot's work, the manual for which is obtained when purchasing a new helicopter and implementing its use. The basic challenge that had to be met while developing the training strategy was – paradoxically – the extremely rich experience of HEMS crews, which comprised hundreds and even thousands of work hours.The EC135 has been designed for the needs of medical rescue services. It is equipped with the necessary medical devices for saving human life and health and a new system of loading the patient on board. Modern solutions in the main rotor and its decreased diameter make it possible for the machine to land in more difficult terrain, both during the day and at night. Modern aviation means using multi-function display screens in the cockpit. In this situation, experienced HEMS pilots and crew members were forced to abandon the fixed work patterns acquired over many years and learn new procedures. The main factors determining the safety of an aircraft carrier are worked out by considering the number of accidents and their causes: accidents involving Mi-2 helicopters over the period 2006–2009 were analyzed.

Analysis showed that human-related and technological factors constituted the basic causes of flight incidents and should, therefore, be particularly emphasized in the training strategy. Most unintended incidents, particularly aviation accidents, stem from a combination of a series of contributing events and circumstances called an error chain [33]. In conclusion, five point have to be stressed for reducing risks and optimizing staff training and they are:

1. Adopting an appropriate strategy of training PMAR crews to work on the new type of aircraft led to reaching the objectives, both in the quantitative and qualitative aspects and to completing them in the time that had been planned;

2. Preparing HEMS crews with no loss of health or life and without flight incidents which would damage equipment reached an appropriate level for performing operational tasks using the new type of helicopter both during the day and at night;

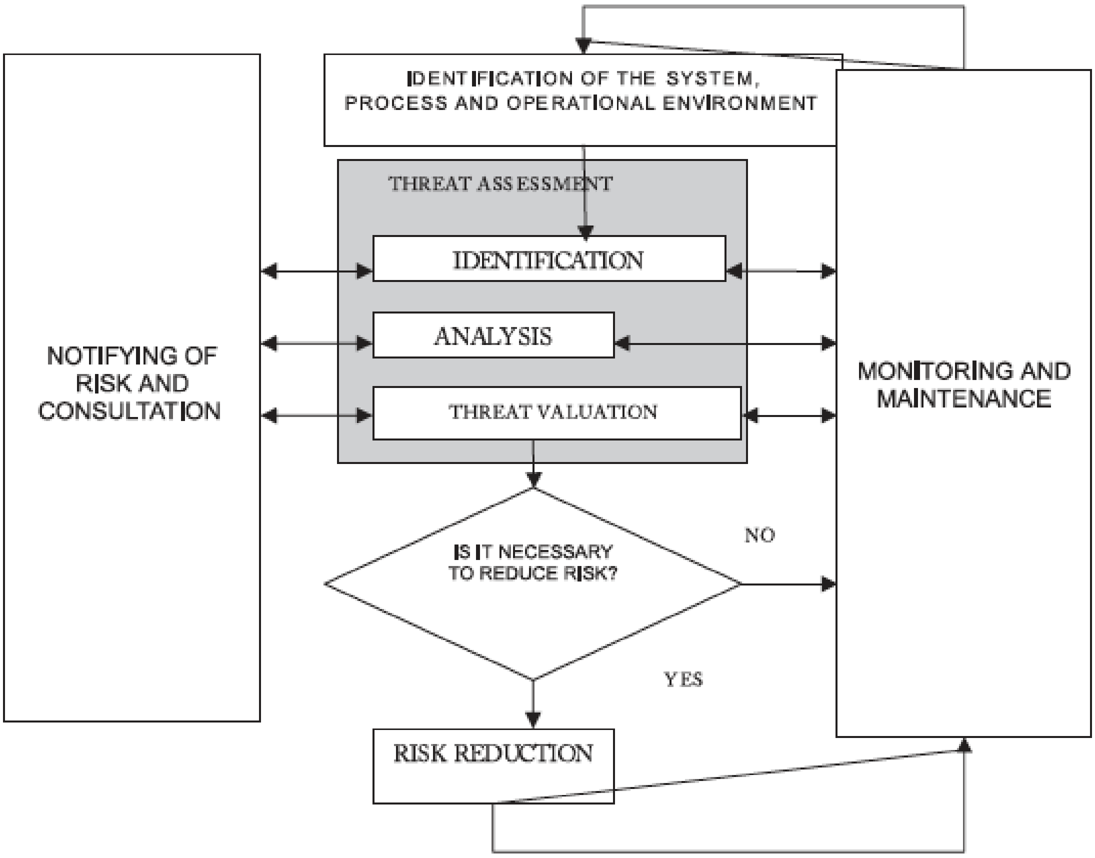

Figure A.15: Algorithm of risk management process.

3. The correctly performed potential risk analysis, preparing an appropriate number of qualified aircraft instructors, and using a flight simulator at each stage of the training, ensured a high level of the courses, and proved that there is no need to change the syllabus;

4. The strategy to extend the scope of courses to include external EMS units, in particular the State Fire Service and the Mountain Volunteer Search and Rescue Service, raised the safety level and limited crew stress when performing landings in unknown areas and at night;

5. The necessary, uninterrupted process of hiring new pilots, paramedics, and drawing conclusions from the courses and from the crews' fieldwork led to a change in attitude and to awarding a particularly important status in the training to issues connected with human resource management. Now, courses preparing Aeromedical Crew Resource Management (ACRM) instructors include pilots, paramedics, and doctors.

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APPENDIX B - TRAUMA RELATED DISPATCH CRITERIA

- **Mechanism of Injury**
  - High-speed (>40 mph; >65 km/h) moving vehicle accident;
  - Multiple casualty incident;
  - Motor vehicle collision with significant vehicle deformity;
  - Frontal collision on hardened roads outside urban area;
  - Frontal collision on hardened roads outside urban area;
  - Significant compartment intrusion on patient side or on opposite side;
  - Significant displacement of front or rear axle;
  - Lengthy extrication and significant injury/entrapment;
  - Overwhelmed with debris, including head and/or chest;
  - Vehicle turnover;
  - Fatality on high-speed roads;
  - Death, same compartment;
  - Patient ejected from vehicle;
  - Thrown from motorcycle > 20 mph;
  - Pedestrian struck > 20 mph;
  - Explosion;
  - Electricity or lightning accident;
  - Fire in confined space, or inhalational injury;
  - Logging/farm/industrial accident;
  - Exposure to hazardous materials;
  - Fall from height;
  - Diving accident;
  - (Near) drowning;

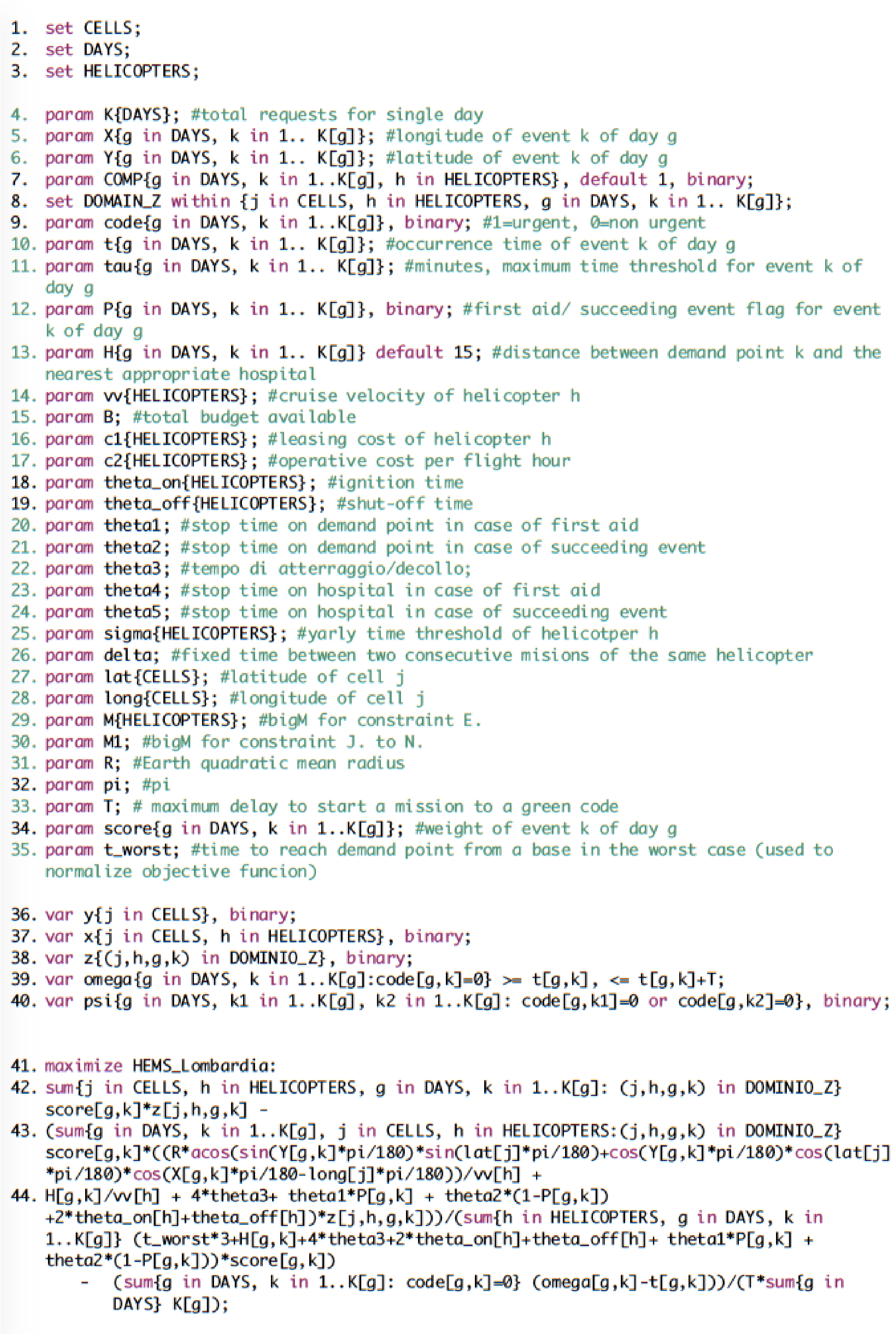
- **Patient characteristics - anatomy**
  - Penetrating injury to head, neck, chest, abdomen, or groin;
  - Blunt injury with significant involvement of head, neck, chest, abdomen, or pelvis;
  - Skull fracture/severe facial and eye injuries;
  - Flail chest or pneumothorax;
  - Two or more proximal long bone fractures, or open long bone fractures;
  - Potential injury to spinal cord or column;
  - Major proximal amputation or degloving injury;
  - Amputation or near-amputation in case of emergent evaluation for reimplantation;
  - Fracture or dislocation with vascular compromise;
  - Burns of significant body surface area or relevant body regions;
  - Multiple system injury;
- **Patient characteristics - physiologic parameters**
  - Low or high respiratory rate, risk of airway obstruction, or other signs of respiratory distress;
  - Low systolic blood pressure, tachycardia, or pulse character;
  - (Posttraumatic) cardiac arrest;
  - Low CRAMS score;
  - Low Glasgow Coma Scale score;
  - Low (Revised) Trauma Score;
  - Age <5 or >55 years;
  - Known cardiac or respiratory disease/cardiovascular instability;
  - Known pregnancy;
- **Others**
  - Medical control approval;
  - Paramedic judgment/intuition;
  - Anticipated need for ATLS procedures;
  - (Expectation of) prolonged transport time/prehospital time;
  - Inaccessible road/area;
  - Heavy traffic conditions;

- Understaffing of ground units in a region/local resources overwhelmed;

However, there are no organisations that solely use this group of criteria for dispatching their HEMS. Literature data revealed that criteria that are based upon MOI have a specificity varying between 72 and 97%, implying that the overtriage rate will be acceptable. Due to a poor sensitivity between 0 and 73%, however, the undertriage rate will be high. As a consequence, the majority of patients who would benefit from HEMS would be missed (and deprived of potentially life-saving treatment by a trauma team at the accident scene) when only using these criteria for HEMS dispatch. The current study shows that dispatch criteria related to MOI and patient characteristics are frequently applied throughout Europe. Consequently, unacceptably high overtriage rates are at risk in almost every HEMS providing country in Europe. Although overtriage does not directly reduce patient safety, it results in overutilisation of limited financial and human resources and augmented risks. The criterion "Low Glasgow coma scale" is an important criterion because it is a good indicator of the injury severity of a patient. It was to be expected that low GCS would the most used physiology criteria, as it is most likely the most appropriate indicator of patient status. [50] found a sensitivity of 98% and a specificity of 96% which suggest a high appropriateness of this criterion for HEMS dispatch. Reliability is however influenced by the experience of the personnel at the scene. As said, citeria from the subgroup "Patient Characteristics—Co-morbidities and Age" were not being used in Italy but not even in Luxembourg, Finland and Slovakia. [80] found a sensitivity of 56% and a specificity of 45% for dispatch criteria from the subgroup "Patient Characteristics— Co-morbidities and Age". Using these criteria will therefore lead to both under- and overtriage.

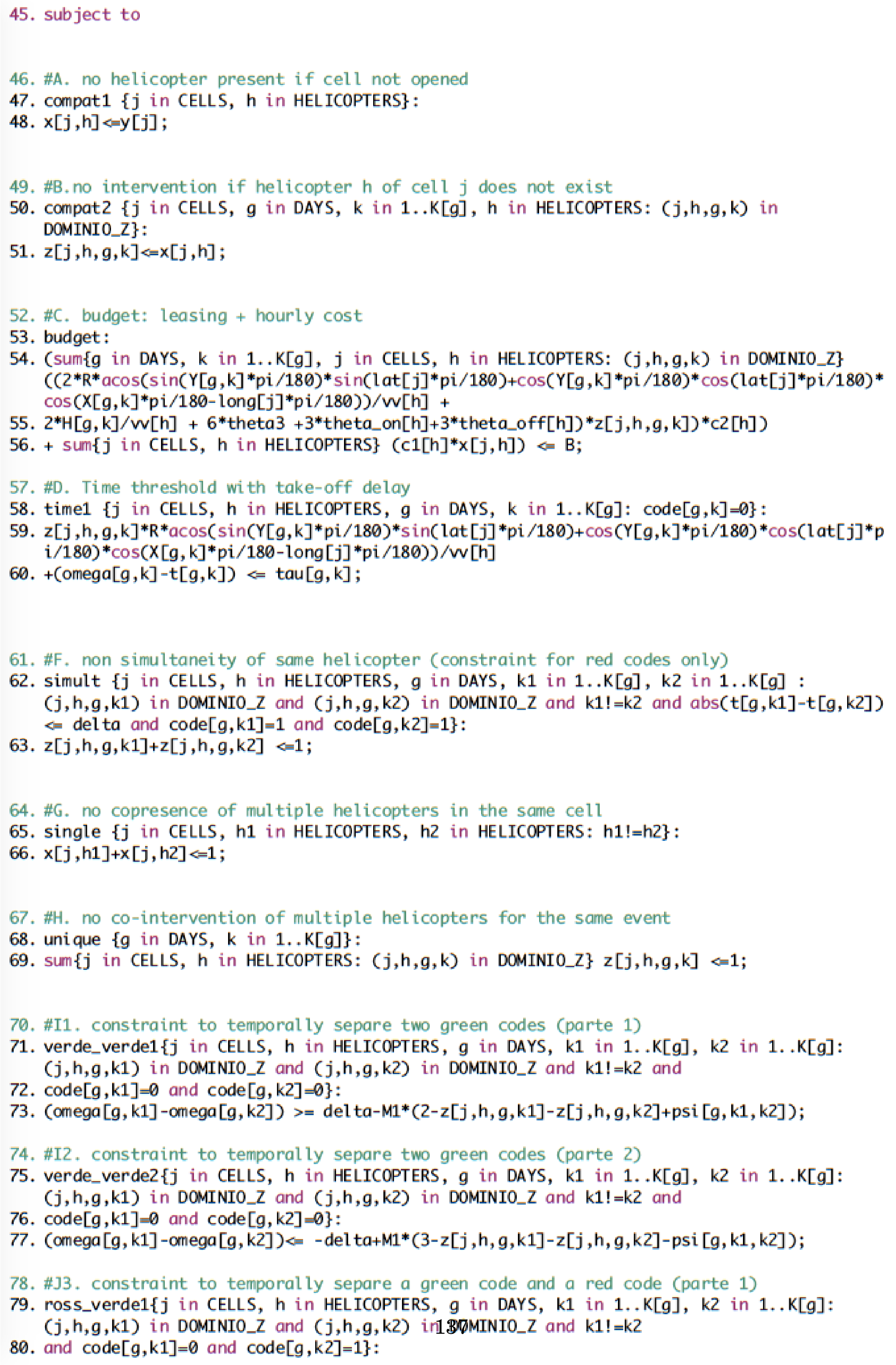
APPENDIX C - AMPL MODELS

Ahe mathematical model is reported in this appendix. As widely said throughout the thesis, there are two different models, the *rigid* and the *flexible* one. The two differ in the way the red code events are handled. The *rigid* model consider a red code served if, at call receipt, a helicopter immediately start its mission; therefore no delay on mission start is allowable and demand point has to be reached within a fixed time threshold from the call receipt. If there is no immediately available helicopter, the mission is considered rejected. *Flexible* model, on the other hand, is able to delay the mission start of a red code provided that the demand point can be reached within the threshold. Figures C.1, C.2 and C.3 shows the AMPL algorithm of the *rigid* model. *Flexible* algorithm is not shown for sake of brevity.



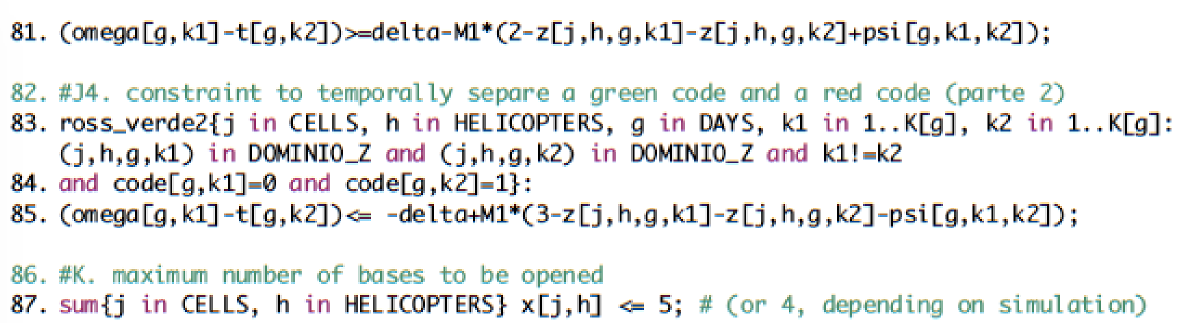
```
set CELLS;
set DAYS;
set HELICOPTERS;

param K{DAYS}; #total requests for single day
param X{g in DAYS, k in 1.. K[g]}; #longitude of event k of day g
param Y{g in DAYS, k in 1.. K[g]}; #latitude of event k of day g
param COMP{g in DAYS, k in 1..K[g], h in HELICOPTERS}, default 1, binary;
set DOMAIN_Z within {j in CELLS, h in HELICOPTERS, g in DAYS, k in 1.. K[g]};
param code{g in DAYS, k in 1..K[g]}, binary; #1=urgent, 0=non urgent
param t{g in DAYS, k in 1.. K[g]}; #occurrence time of event k of day g
param tau{g in DAYS, k in 1.. K[g]}; #minutes, maximum time threshold for event k of
day g
param P{g in DAYS, k in 1.. K[g]}, binary; #first aid/ succeeding event flag for event
k of day g
param H{g in DAYS, k in 1.. K[g]} default 15; #distance between demand point k and the
nearest appropriate hospital
param vv{HELICOPTERS}; #cruise velocity of helicopter h
param B; #total budget available
param c1{HELICOPTERS}; #leasing cost of helicopter h
param c2{HELICOPTERS}; #operative cost per flight hour
param theta_on{HELICOPTERS}; #ignition time
param theta_off{HELICOPTERS}; #shut-off time
param theta1; #stop time on demand point in case of first aid
param theta2; #stop time on demand point in case of succeeding event
param theta3; #tempo di atterraggio/decollo;
param theta4; #stop time on hospital in case of first aid
param theta5; #stop time on hospital in case of succeeding event
param sigma{HELICOPTERS}; #yarly time threshold of helicotper h
param delta; #fixed time between two consecutive misions of the same helicopter
param lat{CELLS}; #latitude of cell j
param long{CELLS}; #longitude of cell j
param M{HELICOPTERS}; #bigM for constraint E.
param M1; #bigM for constraint J. to N.
param R; #Earth quadratic mean radius
param pi; #pi
param T; # maximum delay to start a mission to a green code
param score{g in DAYS, k in 1..K[g]}; #weight of event k of day g
param t_worst; #time to reach demand point from a base in the worst case (used to
normalize objective funcion)

var y{j in CELLS}, binary;
var x{j in CELLS, h in HELICOPTERS}, binary;
var z{(j,h,g,k) in DOMINIO_Z}, binary;
var omega{g in DAYS, k in 1..K[g]:code[g,k]=0} >= t[g,k], <= t[g,k]+T;
var psi{g in DAYS, k1 in 1..K[g], k2 in 1..K[g]: code[g,k1]=0 or code[g,k2]=0}, binary;


maximize HEMS_Lombardia:
sum{j in CELLS, h in HELICOPTERS, g in DAYS, k in 1..K[g]: (j,h,g,k) in DOMINIO_Z}
score[g,k]*z[j,h,g,k] -
(sum{g in DAYS, k in 1..K[g], j in CELLS, h in HELICOPTERS:(j,h,g,k) in DOMINIO_Z}
score[g,k]*((R*acos(sin(Y[g,k]*pi/180)*sin(lat[j]*pi/180)+cos(Y[g,k]*pi/180)*cos(lat[j]
*pi/180)*cos(X[g,k]*pi/180-long[j]*pi/180))/vv[h] +
H[g,k]/vv[h] + 4*theta3+ theta1*P[g,k] + theta2*(1-P[g,k])
+2*theta_on[h]+theta_off[h])*z[j,h,g,k]))/(sum{h in HELICOPTERS, g in DAYS, k in
1..K[g]} (t_worst*3+H[g,k]+4*theta3+2*theta_on[h]+theta_off[h]+ theta1*P[g,k] +
theta2*(1-P[g,k]))*score[g,k])
    -  (sum{g in DAYS, k in 1..K[g]: code[g,k]=0} (omega[g,k]-t[g,k]))/(T*sum{g in
       DAYS} K[g]);
```

Figure C.1: *Rigid* model AMPL algorithm



```
subject to


#A. no helicopter present if cell not opened
compat1 {j in CELLS, h in HELICOPTERS}:
x[j,h]<=y[j];


#B.no intervention if helicopter h of cell j does not exist
compat2 {j in CELLS, g in DAYS, k in 1..K[g], h in HELICOPTERS: (j,h,g,k) in
DOMINIO_Z}:
z[j,h,g,k]<=x[j,h];


#C. budget: leasing + hourly cost
budget:
(sum{g in DAYS, k in 1..K[g], j in CELLS, h in HELICOPTERS: (j,h,g,k) in DOMINIO_Z}
((2*R*acos(sin(Y[g,k]*pi/180)*sin(lat[j]*pi/180)+cos(Y[g,k]*pi/180)*cos(lat[j]*pi/180)*
cos(X[g,k]*pi/180-long[j]*pi/180))/vv[h] +
2*H[g,k]/vv[h] + 6*theta3 +3*theta_on[h]+3*theta_off[h])*z[j,h,g,k])*c2[h])
+ sum{j in CELLS, h in HELICOPTERS} (c1[h]*x[j,h]) <= B;

#D. Time threshold with take-off delay
time1 {j in CELLS, h in HELICOPTERS, g in DAYS, k in 1..K[g]: code[g,k]=0}:
z[j,h,g,k]*R*acos(sin(Y[g,k]*pi/180)*sin(lat[j]*pi/180)+cos(Y[g,k]*pi/180)*cos(lat[j]*p
i/180)*cos(X[g,k]*pi/180-long[j]*pi/180))/vv[h]
+(omega[g,k]-t[g,k]) <= tau[g,k];



#F. non simultaneity of same helicopter (constraint for red codes only)
simult {j in CELLS, h in HELICOPTERS, g in DAYS, k1 in 1..K[g], k2 in 1..K[g] :
(j,h,g,k1) in DOMINIO_Z and (j,h,g,k2) in DOMINIO_Z and k1!=k2 and abs(t[g,k1]-t[g,k2])
<= delta and code[g,k1]=1 and code[g,k2]=1}:
z[j,h,g,k1]+z[j,h,g,k2] <=1;


#G. no copresence of multiple helicopters in the same cell
single {j in CELLS, h1 in HELICOPTERS, h2 in HELICOPTERS: h1!=h2}:
x[j,h1]+x[j,h2]<=1;


#H. no co-intervention of multiple helicopters for the same event
unique {g in DAYS, k in 1..K[g]}:
sum{j in CELLS, h in HELICOPTERS: (j,h,g,k) in DOMINIO_Z} z[j,h,g,k] <=1;


#I1. constraint to temporally separe two green codes (parte 1)
verde_verde1{j in CELLS, h in HELICOPTERS, g in DAYS, k1 in 1..K[g], k2 in 1..K[g]:
(j,h,g,k1) in DOMINIO_Z and (j,h,g,k2) in DOMINIO_Z and k1!=k2 and
code[g,k1]=0 and code[g,k2]=0}:
(omega[g,k1]-omega[g,k2]) >= delta-M1*(2-z[j,h,g,k1]-z[j,h,g,k2]+psi[g,k1,k2]);

#I2. constraint to temporally separe two green codes (parte 2)
verde_verde2{j in CELLS, h in HELICOPTERS, g in DAYS, k1 in 1..K[g], k2 in 1..K[g]:
(j,h,g,k1) in DOMINIO_Z and (j,h,g,k2) in DOMINIO_Z and k1!=k2 and
code[g,k1]=0 and code[g,k2]=0}:
(omega[g,k1]-omega[g,k2])<= -delta+M1*(3-z[j,h,g,k1]-z[j,h,g,k2]-psi[g,k1,k2]);

#J3. constraint to temporally separe a green code and a red code (parte 1)
ross_verde1{j in CELLS, h in HELICOPTERS, g in DAYS, k1 in 1..K[g], k2 in 1..K[g]:
(j,h,g,k1) in DOMINIO_Z and (j,h,g,k2) in DOMINIO_Z and k1!=k2
and code[g,k1]=0 and code[g,k2]=1}:
```

Figure C.2: *Rigid* model AMPL algorithm



```
(omega[g,k1]-t[g,k2])>=delta-M1*(2-z[j,h,g,k1]-z[j,h,g,k2]+psi[g,k1,k2]);

#J4. constraint to temporally separe a green code and a red code (parte 2)
ross_verde2{j in CELLS, h in HELICOPTERS, g in DAYS, k1 in 1..K[g], k2 in 1..K[g]:
(j,h,g,k1) in DOMINIO_Z and (j,h,g,k2) in DOMINIO_Z and k1!=k2
and code[g,k1]=0 and code[g,k2]=1}:
(omega[g,k1]-t[g,k2])<= -delta+M1*(3-z[j,h,g,k1]-z[j,h,g,k2]-psi[g,k1,k2]);

#K. maximum number of bases to be opened
sum{j in CELLS, h in HELICOPTERS} x[j,h] <= 5; # (or 4, depending on simulation)
```

Figure C.3: *Rigid* model AMPL algorithm