Charting Response Options for Threatening Near Earth Objects

The 2002 Master of Space Studies Class

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Abstract

The following study presents a multidisciplinary examination of the Near Earth Object hazard. The necessary background knowledge is provided in order to understand and describe a process that charts all the possible responses to all types of NEOs. General space and Earth based options as well as a specific case study are presented. The mission statement under which this report was conducted, was to chart the responses in order to mitigate the hazards of NEOs and thus ensure the survivability of Earth's living heritage.

A literature survey conducted to understand the NEO hazard. First the threat is defined including NEOs origin, composition and their classification. The consequences as well as the probability of the occurrence of impact are examined. Since detection is the first element required to understand the problem, an examination of the techniques used is outlined. This includes a description of how NEO searches are conducted, how the data statistics are handled and finally how a determination of the risk of impact is made. Next examined, are the possible responses that may be designed, including both Space-based and Earth-based responses.

The NEO threat is categorized using the key parameters of warning time, damage potential, response limitations and hit location in order to provide a logical way to chart the possible mitigation options. These options include both space-based options of deflection and destruction as well as Earth-based options of relocation and shelter construction. It is hoped that the multi-faceted charting tree provided will aid in the decision making process and as such, help determine the correct course of action to be discharged. A user friendly software tool has been created as a result of this work that encapsulates this charting process and is also presented.

The general aspects of the space-based responses charted and are presented. With the consideration of the prime elements of warning time and available technological limitations, the possible response actions are outlined. These responses include both deflection and destruction techniques. An examination of the types of space missions to be included as well as the political, organizational, economic, legal, social and ethical questions that these missions would raise is included. Included is a discussion of the mission decision process that could be used.

The general aspects of the Earth-based responses charted and are presented. These include the basic elements of sheltering and relocation of populations both in the short and longer term. Social and political questions regarding the internal management aspects of these shelters are also examined. Finally, a consideration of the psychological aspects regarding the effects of impact is also included.

A specific scenario case of 1997 XF11 is examined. It is assumed that this approximate 2 km diameter asteroid is going to hit the Earth in 26 years. A multi-mission response to this specific threat is described to a system level of detail. A number of software packages, one created as part of this report, are used to develop a first cut description of these missions.Part of the answer to the question of why human kind must develop space skills is answered by an understanding of the NEO impact threat and a realization of what is involved in order to mount the mitigation missions charted within this report. As a insurance policy for the preservation of Earth's human heritage this problem can not be ignored.

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Faculty preface

The MSS program lasts for 11 months in total during which the Team Project (TP) activities amount to roughly a quarter of the allocated sessions in the timetable and make up a similar proportion of the marks in the overall evaluation scheme. Usually the students' experience of previous team projects from the International Space University (ISU) is limited to what's passed on to them by faculty or alumni or written into previous reports on the library shelves. As resident faculty we stay here much longer and thus we get to see the results of several successive projects, both here in the MSS program as well as in the Summer Sessions. That allows us to stand back and make some objective comparisons, so let's use this introduction to highlight some similarities and differences for the MSS02 class report.

First let's look at the similarities. The timing, duration and allocation of periods in the timetable were unchanged from previous years with the broad division into two phases: - TP Part 1: A part of the second module (Nov/Dec), during which students survey the entire field of their chosen theme and produce a comprehensive literature review on the subject, Protecting Earth from the Near Earth Object (NEO) Threat in this case. - TP Part 2: Some sessions in Module 3 (Jan/Feb) in which team members propose ideas for a more focused topic and then select one for later investigation in Module 5. Then, in Module 5 itself after the 3 month placement period, most of the last two months (June/July) are devoted to more detailed, multidisciplinary assessments, in this case on the subject of Charting Options for Response to a NEO Threat. It's good to see how well the Part 1 review has been summarised here and used as the base for the more detailed Part 2 study assessments described in this report.

As always, the students were drawn enthusiastically into the activity - it became very much their activity, their project, a challenge and finally, one hopes, a source of pride. It's always difficult to select an interesting TP topic that hasn't already been subjected to extensive studies elsewhere. This year is certainly no exception in the case of both projects. Clearly their topical interest was known when we picked them more than 18 months ago but who would have guessed there would be as many articles in the popular press and reports in professional journals as we've seen in the last few months. The students are to be congratulated on their efforts to generate fresh ideas and impose their own unique perspectives on such heavily publicised themes.

The most notable difference from earlier MSS programs was that, for the first time, students were offered a free choice between two themes -the NEO Threat and Space Tourism. Compared to previous years this has roughly halved the overall team size, and hence the effort expanded on each project; 21 of the 46 students were involved in the activity described here. From the faculty's viewpoint this has led to clear advantages in terms of the increased levels of enthusiasm and commitment from members of the smaller teams - even if it has increased our own workload in providing advice and evaluations on two parallel projects! The added commitment and ease of interfacing in a smaller team appear to have roughly compensated for the reduced effort on each of the two projects and this report compares very favorably with the outputs from previous MSS classes in terms of scope, depth and quality.

Some element of competition may also have stimulated members of the two parallel activities to give their best but it's good to note that there has also been a healthy degree of collaboration and mutual encouragement between the teams. So should we go even further and offer still more parallel options - maybe, in future years as the class size grows, but for MSS03 at least we'll repeat this year's successful formula.

Another area of difference from recent years, and again this is true of both projects, is that the chosen themes involve very significant considerations of ground-based elements - shelters in the case of the NEO Threat. Partly as a consequence, this report does not go as deep as usual into spacecraft system design but there's still enough attention given to the space sector, notably mission design, to respect the S in ISU's title. Indeed the broader scope was very much a deliberate choice by the team, endorsed by faculty, driven by the fact that general response aspects for the NEO threat have to date received much less attention than detection and, to a lesser extent, mitigation considerations.

The names appearing below are those of full-time Resident Faculty but we should not overlook the valuable support provided by our part-time faculty colleague, Dr Joachim Köppen. We are indebted to him for the encouragement and advice he has offered to the team in the development of the NEO mission software described in this report. This is an original contribution that may well be further developed by Dr Köppen and any members of the team who have been inspired by his enthusiasm and who have the time and interest to continue the collaboration after completing the MSS program. The students have also sought external advice from others (see the list of acknowledgments) to a greater extent than in previous years - and received useful inputs from several experts in the field on their ideas and the content of their draft report.

Further opportunities exist to publicise the work. First, we are pleased to note that a paper describing the NEO team's efforts has been accepted for presentation at the World Space Congress in Houston in October 02. And finally, for our part, we note that ISU has a small consultancy activity on a NEO study funded by the European Space Agency (ESA) that will run for the next few months. In the course of that work we'll be proud to draw attention to the interesting contributions described here by the MSS02 students.

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Student preface

We, the students of the International Space University, Masters of Space Studies Program 2002, Strasbourg, France, present this report as a culmination of 11 months of space studies. We have endeavoured to address our topic of Charting the Response Options for Threatening Near Earth Objects in an interdisciplinary fashion. As a team we come from many different disciplines, backgrounds and cultures but with the one common bond of all being inhabitants of planet Earth.

The approach our team used to tackle the work will hopefully be something similar to how the world as a whole will address a confirmed NEO threat to planet Earth. An international group coming from 9 countries, the 21 members of this team, have worked as a family to produce a report which we hope will be of value to the NEO hazard community.

Many have asked why humans go to space? Why should we spend the time, effort and money to develop our space skills? Within our work to understand this topic we have proven to ourselves why we must. It is not a matter of if the Earth will be hit by another NEO but only a matter of when. We as a generation owe it to future generations to do our fair share to preserve Earth's living heritage.

Our efforts were not without turmoil but persistence and perseverance have payed off. There is no challenge which can not be solved by working as a team. The fruits of our team's labour for which we should all be proud lie within the pages of this report.

We would like to thank all those who so generously contributed there time, effort and skill in helping us to prepare this paper.

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List of acronyms

AIAA	American Institute of Aeronautics and Astronautics
APL	Applied Physics Laboratory
AU	Astronomical Units
CCD	Charged Couple Device
DLR	German Aerospace Center
DOD	Department of Defense
DOE	Department of Energy
ECA	Earth Crossing Asteroid
ECC	Earth Crossing Comet
ESA	European Space Agency
EUNEAS	European Near-Earth Asteroid Search Observatories
EVA	Extra vehicular Activity
FAME	Full-sky Astrometric Mapping Explorer
FEMA	Federal Emergency management Agency
FOV	Field of View
FSU	Former Soviet Union
GAIA	Global Astrometric Interferometer for Astrophysics
GRBE	Swift Gamma Ray Burst Explorer
GUI	Graphical User Interface
IAU	International Astronomical Union
ICJ	International Court of Justice
ISU	International Space University
IMF	International Monetary Fund
INEORG	International NEO Response Guidlines
IO	International Organisation
IR	InfraRed
ISAS	The Institute of space and Astronautical Science
ISDR	International Strategy for Disaster Reduction
ISS	International Space Station
JPL	Jet Propulsion Laboratory
LASCO	Large Angle and Spectrometric Coronagraph
LEO	Law Earth Orbit
LIDAR	Light detection and Ranging
LINEAR	Lincoln Near Earth Asteroid Research
LONEOS	Lowell Observatory for Near-Earth-Object Search
LPC	Long Period Comet
MIT	Massachusetts Institute of Technology
MOID	Minimum Orbit Intersection Distance
MPC	Minor Planet Center
NASA	National Aeronautics and Space Administration
NEA	Near-Earth Asteroids
NEAP	Near Earth Asteroid Prospector
NEAR	Near Earth Asteroid Rendezvous
NEO	Near Earth Opject
NESS	Near Earth Space Surveillance mission
NEST	National Exercise Support Team
OCA	Orange County Astronomers
OECD	Organization of Economic Growth and Development
OECD	Organization of Economic Co-operation and Development

OOSA	Office for Outer Space Affairs
OST	Outer Space Treaty
PHAs	Potentially Hazardous Asteroids
PSA	Public Service Announcements
PTBT	Partial Test-Ban Treaty
PTSD	Post traumatic Stress Disorder
R&D	Research and development
SCAP	Schmidt CCD Asteroid Program
SEDS	Students for the Exploration and Development of Space
SIRTF	Space InfraRed Telescope Facility
SIRTF	The space InfraRed Telescope Facility
SOHO	Solar and Heliospheric Observatory
STA	Japanese Space and Technology
TNT	Trinitrotoluene
TV	Television
UK	United kingdom
UN	United Nation
UNGA	United Nations General Assembly
US	United States
USA	United State of America
USSR	Union of the Soviet Socialist Republic

Introduction

In March and June of 2002 two asteroids, each about a football field in width, passed close by the Earth virtually unnoticed. Had either of these asteroids hit the Earth's surface, the equivalent of a 75 MT explosion (5000 times larger than the bomb which devastated Hiroshima) would have been unleashed, possibly killing thousands or even millions of people.

There is undeniable evidence that the Earth has been impacted by numerous asteroids and comets in the past. Such bodies are commonly referred to as Near Earth Objects (NEOs). Experts estimate a 1 in 1,000 chance of the Earth being struck by a 1km wide NEO in the next century. In the event of a collision with a 2km or wider NEO the event would be a global catastrophe.

It is strange that with 40 years of human space flight and interplanetary space exploration the hazards posed by NEOs have only recently been recognized by the scientific community. Since the threat is significant, it is prudent to more accurately assess the risks and engineer appropriate mitigation measures. There are many pressing problems that must be addressed in order to properly protect the Earth's living heritage from the NEO threat. It has been noted that the current efforts in hazardous NEO detection are inadequate and this issue is receiving attention by scientists and decision makers alike. In order for human kind to protect itself from the devastation that could result, a coordinated and committed global effort is required.

Recognizing this need the multi-faceted issue of response to impacting NEOs was chosen as the topic of this report. It is possible to mitigate against such events and even prevent them, making NEO impacts one of the few natural disasters where this is possible.

The first chapter summarizes the literature review that was done to support this report, explaining the threat and providing details on detection efforts.

Chapter 2 attempts to chart the possible responses based on the key threat parameters such as the warning time and the NEO's size. A tree structure is used as a means to illustrate the decision process that would be followed in order to choose the best response.

Chapter 3 contains a general discussion of the space-based response. The need for a preliminary characterization mission is explained and a classification of the different response options is proposed.

Chapter 4 contains a discussion of the possible Earth-based options. Issues for both short and long term shelters and relocation mitigation are explored.

In Chapter 5 a case study is examined where it is assumed that a specific NEO is going to impact the Earth in 2028. A series of space missions are proposed including characterization, deflection and destruction options.

Finally within the conclusion of this report are presented a series of recommendations as a result of this work.

Chapter 1

Literature Review

1.1 Overview

This chapter is a condensed version of the literature survey of all issues surrounding the NEO threat conducted during an earlier module of the team project. The ideas contained herein have been further considered in the analysis appearing in other sections. The reader could consult the Literature Review produced earlier and/or the following chapters to attain a desired level of precision.

1.2 The threat posed by near-Earth objects

A NEO can be defined as "any asteroid or comet that can come close to the Earth's orbit" [103]. Although the threat caused by the impact of such an object has been increasingly recognised by the international community, both in scientific institutions and by governments, it is not yet well understood. In order to increase the ability to cope effectively with this problem, many important question should be asked: What is the probability of such impacts? What would be the repercussions? Is it possible to detect the threatening NEO before the collision? What means can and should be used to avoid the collision? What about the legal and political issues associated with the response? In this chapter these questions are addressed, presenting not a substantial new contribution to the issue but rather, a literature survey of the work that has already been carried out.

1.2.1 Near-Earth objects

NEOs can be classified into two groups, comets and asteroids. The most common definition of comets is presence of *"cometary activity"* (a bright tail), which requires volatile compounds (especially water ice) near or at the surface of the object [101]. Asteroids are thus all NEOs for which no cometary activity is observable.

Comets

It is generally accepted by the scientific community that comets are made out of the debris that was left over from the solar nebula when it condensed to form the Sun and planets in the solar system. Leftover debris remained in orbit, and separated into two areas where many comets are now found: the Oort Cloud (a spherical shell region outside the orbit of Pluto) and the Kuiper Belt (near the orbit of Neptune). Typically, comets travel around the Sun in the same fashion as the other solar systems components, but in orbits that are typically very elliptical. The planets in their surroundings influence their orbits, as does the gas and dust they they emit, making their orbits are also slightly irregular and hard to predict in the future [50].

In the 1950's, the "dirty snowball" explanation was proposed for comets. Astronomer Fred Whipple stated that a comet had a solid center, usually of a of 1 to 10 km diameter, composed of minerals stuck together with ice (water, ammonia, methane and carbon dioxide). However, comets are now believed to have originated at different distances from the sun and therefore at different temperatures, their composition thus varies greatly[44].

Under normal circumstances, comets only consist of a nucleus. However, when the comet comes into proximity to the Sun, the ice from which it is formed starts to sublimate producing a cloud of gas called the coma. The sublimation also releases the dust and organic particles that were trapped in the ice, and scattering of

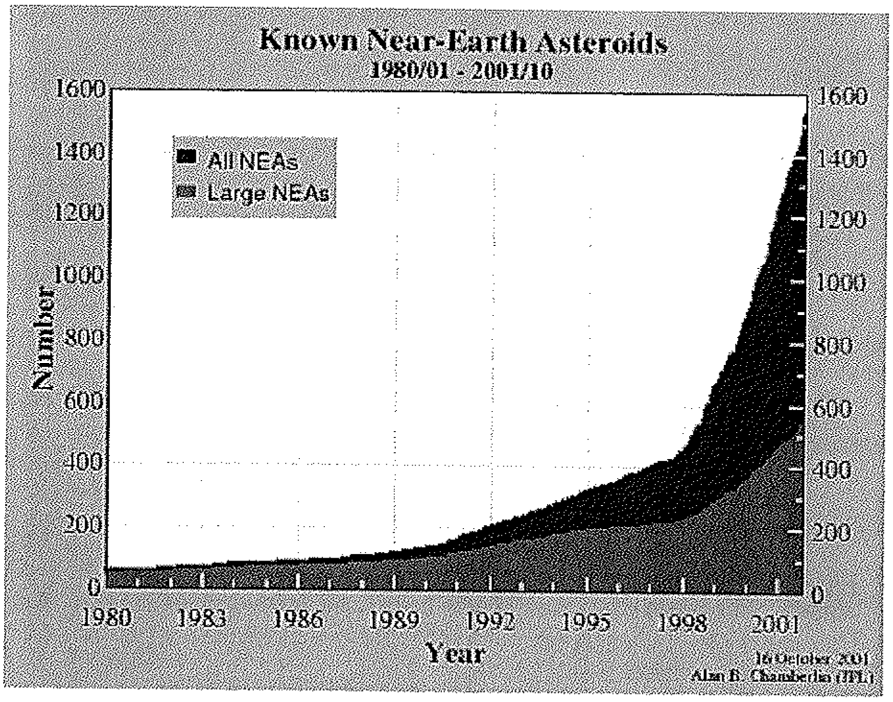

Figure 1.1: Known NEAs versus time [73]
(light shows only NEAs with diameters greater than 1km, dark shows all other known NEAs)

sunlight creates the visible dust tail sometimes observable from Earth, which can stretch huge distances across the sky. Solar wind, (i.e.: the stream of charged particles being blown off the Sun) pushes back the charged particles of the comet, to form a separate ion tail.

Asteroids

Asteroids (sometimes called minor planets or planetoids) are large rocks, from 1 to 1000km across, orbiting the Sun [77]. Most asteroids are positioned in the asteroid belt, which lies between the orbits of Mars and Jupiter (2.1 to 3.3 astronomical units (AU) from the Sun). They often follow orbits much more eccentric than those of the planets and are sometimes tilted by as much as 30 degrees to the plane of Earth's orbit. Another place where one might find asteroids is in the orbit of Jupiter. These asteroids, called Trojan asteroids, can be found on Jupiter's orbit, 60 degrees ahead and behind Jupiter itself, at the so-called Lagrange points. The first person to explain the existence of these asteroids was Lagrange [48, 101, 77].

However, the most dangerous asteroids are those that come near to Earth. Roughly, there are 1,000 of these Near Earth Asteroids (NEAs) of diameter greater than 1km and between 30,000 and 300,000 asteroids greater than 100 m in size [74]. Figure 1.1 summarises the history of NEA discoveries.

NEAs can be divided into 3 categories: the Aten, Apollo and Amor types (see Figure 1.2). The Atens have orbits such that their position is usually between that of the Earth and the sun and are therefore difficult to detect. The Apollos have more elliptical orbits and spend more time outside the Earth orbit, being easier to detect. The Amors stay outside both Earth and Mars orbits and pose a lesser danger [14].

Due to 4 billion years of infrequent but consistent collisions, most asteroids larger than a few kilometers in diameter are expected to have been shattered into gravitationally bound "rubble piles" [103, 101, 77], giving rise to uncertainty about their effects when striking Earth and their deflectibility by man-made space vehicles.

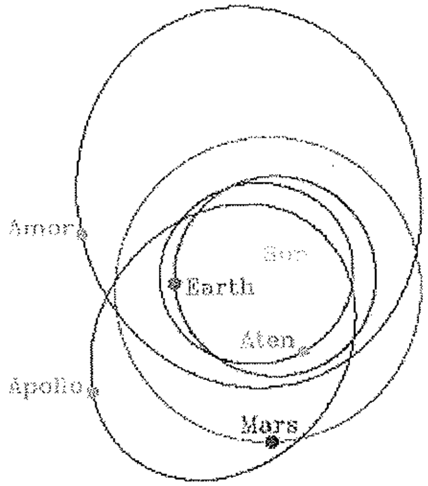

Figure 1.2: Orbits of Atens, Apollo and Amors [14]

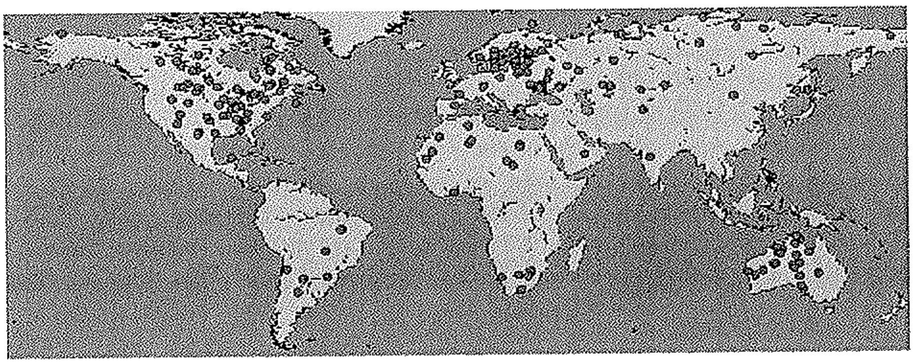

Figure 1.3: Known impact craters on Earth (taken from [82])

1.2.2 Impacts

The impact of a NEO on the Earth, could lead to an incredible amount of catastrophes in a direct or indirect form. The environmental effects depend not only on the characteristics of the body (size, speed, mass, material composition and strength, trajectory), but also on the characteristics of the impact site (land, ice or ocean, latitude, rocks type) and its prevailing climatic conditions (stage of ice age, season). If the NEO impact occurs in the ocean (approximately 70 % of Earth's surface) it will generate a tsunami that will effect coast lines and ships at a regional or global range. For land impacts, rock nearest to the impact is vaporised or melted and farther away it is pulverised and as the shock waves travel away from the impact. After the impact energy is absorbed by the Earth's surface, the ground begins to rebound toward the center of the hemispherical cavity or crater forming a the central peak that is seen in moderate to large sized impact craters [75].

Morrison and Chapman also discussed the effects of an impact on the atmosphere [40, 80]. Big asteroids, such as the one that cased the K/T event, cause global effects. The atmospheric chemistry is changed and submicrometer dust is injected into the stratosphere, darkening the entire planet. For NEOs larger than 4 km in diameter, dust and sulfate levels would be high enough to reduce light levels below the threshold for photosynthesis for several months.

Over 160 impact craters have been identified on Earth, and several new ones are found each year [82] (see Figure 1.3). Thus, there is clear evidence that meteorites and comets impacts have occurred on the Earth and will continue to happen in the future.

Table 1.1: Estimate of death toll from various types of impact. (Adapted from [87])

Asteroid Diameter (m)	Area devastated (sq km)	Annual chance for inhabited regions 1 in ...	Equivalent annual death toll	"Typical" Direct Fatalities	Total fatalities (million)
50	1900	900	1100	200 000	1
100	7200	8000	400	650 000	3
200	29 000	30 000	500	2 000 000	14
500	70 000	180 000	200	4 000 000	35
1 km	200 000	290 000	200	7 000 000	63
2 km	-	1 000 000	1500	-	1500

1.2.3 Human risks

Morrison and Chapman tried to estimate the minimum NEO impact energy to produce a global catastrophe that would lead to the death of 25% of humanity, mainly from collateral effects, such as starvation [80]. This threshold lies near one million megatons, which corresponds to an NEO of several kilometers in diameter. It is however extremely unlikely that Earth will be hit by such a very large NEO, but the chance of an impact by a smaller NEO that would cause a local or regional catastrophe is much greater. Figure 1.1 shows the averaged annual equivalent death toll and other effects for impacts of NEOs 2 km in width and smaller.

These values represent the risk of an inhabited region being within an area of direct devastation - the consequences of that impact depend on the size of the impactor, the population density and numerous other factors. In general, the long term consequences of a large impact are much more severe than those of a smaller one and collateral effects such as global starvation can lead to greater loss of life than the direct effects of the impact.

1.3 Detection

One major step in assessing any NEO hazard is to identify the threatening object and characterise it long enough before the possible impact in order to take the best mitigation measures. This section will discuss the main methods and efforts for NEO detecting NEOs, determining of their physical characteristics and keeping track of them.

1.3.1 Discovery

Many different techniques can be used to discover Earth threatening NEOs They range from the simplest options such as using an amateur telescopes to the advanced methods using Charged Coupled Devices (CCD) devices. Crovisier, J. And Encrenaz, T. (2000) provide a comprehensive overview of current knowledge of the most up-to-date observation techniques [44].

In order to optimise the search for NEOs it is clear that the devices utilised for observations should cover as much sky as possible in the shortest possible time. Therefore, telescopes that cover large swaths are needed. Schmidt telescopes comply with this requirement, being able to simultaneously photograph a field up to 7 degrees with special lenses that compensate for the aberrations produced at angles far away from the center of the image [103]. Despite the strategy chosen, the photographic materials or collector arrays used must be very fine grained in order to detect such small objects [39]. Although photographic methods have accomplished a lot in the past, CCD techniques are the main standard for asteroid and comet observation because of their superiority in many aspects.

Two scanning techniques can be used with CCDs. The simplest one, referred to as the "stare technique", consists of taking fixed images of the sky one by one. Since it is pointless to take a picture for a longer time than it takes a typical object to cross a pixel, the exposure of the images should not exceed 12 s. A normal

CCD needs about 2 minutes to read the information before taking another picture, thus there is less than 10% of actual imaging time per image taken. To overcome this problem, the so-called "scan technique" [51] is used, in which the telescope's drive that compensates for the Earth's rotation is turned off. The objects then drift across the image, but if we read out each column of the CCD at the same speed, we can get a scan of the sky without stopping the observation. Up to 3 images of the same area are taken in order to ensure that only real NEOs are detected and not spurious data such as those caused by cosmic rays or Earth orbiting artificial satellites. Also, taking three images means that the magnitude that can be filtered will be optimised.

1.3.2 Search strategies

In order to make a successful survey of all NEOs, the first step is to take into account the spatial distribution of such objects in the solar system. The Spaceguard survey (which afterwards led to the creation of the Spaceguard Foundation, an international organisation, [6]) provided in 1992 a report devising an optimal search strategy for NEOs. It was shown that the best approach centers the search on opposition, that is, the direction directly opposite to the Sun [104]. Scanning 6000 square degrees of sky would be sufficient perform the task must be considered. Another more recent report dealing with the most optimal distribution of telescopes in order to perform a good search program is the United Kingdom's (UK) Task Force Report [14], which also recommends the use of 3 m telescopes in both hemispheres, but also emphasizes the importance of space-based telescopes, such as GAIA (Global Astrometric Interferometer for Astrophysics) or SIRTF (Space InfraRed Telescope Facility). Space-based telescopes have the advantage of operating without the disturbance caused by the atmosphere, which diminishes and disperses the amount of light received from the sky, as well as totally absorbing some frequency bands (particularly in the IR (InfraRed) band). Obviously space telescopes can also look at a much bigger part of the sky 24 hours a day (and not just the upper half during the night).

1.3.3 Follow-up

Once a possibly threatening NEO is detected, the next step is to calculate its orbit in order to find out whether it will collide with the Earth or not. The usual way to do this is via astrometry. The procedure simply consists of measuring the position sufficiently often for a reliable orbit to be calculated.

The other possibility for follow-up observations is the use of radar. Although radar is not suitable for the detection of NEOs for various reasons (the great distances being dealt with, the enormous Doppler shifts and the impossibility to cover wide areas [103]), they are certainly very useful for accurate follow-up observations when the NEOs are sufficiently close to Earth. The main advantage of radar observation is we can measure not only its angular position but also its speed (thanks to the Doppler effect), its distance, and many of its physical characteristics.

1.3.4 Physical characterisation

The ultimate goals of any focused surveillance program are to determine the orbital distribution, physical characteristics, composition, and origin of NEOs. This major phase of impact hazard research involves not only preliminary characterisation of potentially hazardous bodies, but also statistical characterisation of the observable physical and properties of NEOs, the latter being necessary to quickly place any future identified NEO into a suitable class [41].

The desired physical characterisation of a NEO includes reliable estimates of its size, shape, mineralogical composition and heterogeneity, gas and dust emission, surface texture and internal structure, albedo (i.e. the fraction of the Sun's light that is reflected by the object's surface), spin characteristics, and mass. The meteorites struck the Earth, are often fragments of NEOs, and hence they give some information on specific NEO classes. However, the meteorite record is strongly biased towards the metallic class of NEOs since their fragments can most easily survive passage through the Earth's atmosphere and are distinctive compared to other rocks on the Earth's surface.

Space-based telescopic studies

Infrared observations from space represent a valuable addition to ground based visible characterisation of NEOs by reducing the uncertainty in estimating their size, and consequently their mass [9]. Space-based telescopic studies are needed for interpreting the spectra of NEOs, as they provide the following data for:

1. Physical characterisation - two independent measurements of the visible and infrared emissions of the body allow the derivation of size and albedo.

2. Mineralogical composition - visible and IR spectroscopy enable the identification of the surface molecular compounds of the body, thus inferring the mass, and providing an insight into physical characteristics, which are difficult to study from the ground.

NEO Fly by and rendezvous missions

Much information on NEOs can be learned from concerted telescopic studies. But to remove uncertainties in the mass, composition and structure of NEOs, as well as to gain confidence about mitigation techniques, more in detailed studies are needed [14]. Hence, asteroid and comet rendezvous missions are of great importance to the surveillance programs.

These types of encounter enable precise estimates of the mass of the visited object by measuring the pull of its gravitational field on the spacecraft. Additionally, its shape can be calculated photographically and its chemical composition found by means of spectrometers. A rendezvous mission to a member of each spectral sub-class of NEO would produce data that could be linked to analogous ground-based spectroscopic observations of unvisited objects [14].

1.3.5 Threat assessment and data handling

One of the big problems that arises when trying to detect NEOs is the great amount of data that has to be dealt with. Up to now, a great deal of the data management has been carried on by the astronomers themselves. Although an expert astronomer's criteria is one of the best known ways to determine a real threatening NEO from other sources, there are obvious problems as to the speed in which this can be done.

In an extensive search program such as the Spaceguard, the data handling problem would become critical. Taking into account the amount of sky scanned by the Spacewatch program and the requirements of Spaceguard, it could be stated that the capacities needed for the latter would be about 3000 times bigger than those of Spacewatch [39].The only center that is now dedicated to the collection of NEO data is the Minor Planet Center from the Smithsonian Astrophysical Observatory, which currently employs only 3 full-time staff [28]. This center collects all asteroid and comet observations and computes their orbits [21]. More funding for the MPC (Minor Planet Center) or a similar organisation is urgently needed to ensure that any Earth-threatening NEO will be detected in time.

1.3.6 Current situation

Ground-based observations

International activities In the international arena the Spaceguard Foundation has to be highlighted. The Spaceguard Foundation was officially set-up in Rome on March 26, 1996 to study NEOs due to their potential threat and their scientific interest. The activities promoted by the organisation include the discovery and follow-up observations of NEOs (including the equipment and operation of telescopes), the dissemination of the corresponding scientific information and the general support to NEO research. The foundation is present in the United States of America (USA), Australia, Croatia, Germany, Japan and the United Kingdom.

USA In USA, the National Aeronautics and Space Administration (NASA) is doing most of the NEO detection activities (Spacewatch, NEST (the National Exercise Support Team), the Lowell Observatory for Near Earth Object Search (LONEOS)). NASA has its own NEO search program, the NEO Program Office located at the Jet Propulsion Laboratory in California. It coordinates NASA sponsored efforts to detect, track and characterise potentially hazardous asteroids and comets that could approach Earth [14]. The LINEAR (Lincoln Near Earth Asteroid Research) project at the Massachusetts Institute of Technology (MIT) is having notable success and has detected around 1000 new confirmed NEOs [?]. Also, as discussed in previous sections, radars also play a great role mainly in the physical characterisation of NEOs. Arecibo and Goldstone are the main radio telescopes used as radars that participate in asteroid and comet studies.

European detection activities

EUNEASO EUNEASO (European Near-Earth Asteroid Search Observatories) is an organisation dedicated to research about Asteroids aiming to establish a large search program [12]. Currently, EUNEASO is also developing CCD cameras at the Orange County Astronomers association (OCA), the German Aerospace Center (DLR) and the University of Padua. Computer programs to allow the automatic detection of moving objects on a series of CCD frames are also being developed at the OCA in cooperation with the DLR group.

Japanese detection activities Japanese observation are beneficial for geographical reasons, as telescopes in longitudes away from the ones operational today would be very helpful for follow-up observations. A fast moving object spotted in Hawaii, for example, could be easily lost unless a Japanese telescope took over [86]. A new center partially dedicated to NEO search, the Bisei Center, will be operating soon. The first telescope will have a diameter of 0.5 meters (with plans to upgrading it to 1 m) while the other one will have similar characteristics to the LONEOS telescope .

Australian detection activities The only NEO active search program in the southern hemisphere is the Australian one, which fortunately is operational again after being cancelled in December 1997 due to lack of funding. Important NEO discoveries have been done within this program due to the fact that, being in the southern hemisphere, it looks at different regions of the sky than all other programs. Many follow-up activities have also been successfully undertaken for southbound objects [86].

Chinese detection activities The SCAP (Schmidt CCD Asteroid Program) program of the Beijing Astronomical Observatory (China) uses a 90/60 Schmidt telescope coupled to a 2048 x 2048 Ford CCD. The FOV (Field of View, or amount of square degrees that the telescope is able to see at the same time) is approximately one square degree.

Space based observations

Currently, there are two space based NEO missions, Deep Space 1 and Stardust. These programs are not dedicated to detect new NEOs, but to observe them in detail by doing a fly by. There are also a number of planned missions that will assist the NEO detection effort.

Deep Space 1 Launched on October 1998, Deep Space 1 flew by asteroid Braille only 26 km away from the surface, taking information such as mineral composition of the satellite, size, shape, brightness and changes in solar wind due to the presence of the object. On September 2001 it made another Rendezvous with comet 10P/Borrely.

STARDUST Stardust, a currently flying NASA mission, will be the first probe to ever explore a comet and bring material back from it. Launched on February 1999 from Cape Canaveral, it will collect dust and carbon-based samples from comet Wild2 after meeting it in January 2004 [16].

SOHO Although not designed for this purpose, the sun-orbiting SOHO (SOlar and Heliospheric Observatory) spacecraft has detected more than 100 comets [15], most of them with the LASCO (Large Angle and Spectrometric Coronagraph), which detects them as they pass close to the sun. Built together by NASA and ESA (European Space Agency) and launched in 1995, the main objective of this spacecraft is to observe the sun and the solar wind for scientific purposes.

SIRTF The mission is a space-based telescope that consists of 0.85 meter telescope and three cryogenically-cooled science instruments capable of performing imaging and spectroscopy in the missing gap of wavelength coverage which is not available from the ground-based observatories (the infrared band). The project is planned to launch in July 2002 and will be able to detect the thermal emissions of both asteroids and comets, which lie in the infrared band [22].

GAIA GAIA will be a space observatory in ESA's scientific program. The main objective of this mission is to study the formation of our galaxy, but it will however have a large impact on the discovery and physical characterisation of asteroids. ESA expects GAIA to detect tens of thousands of NEOs. GAIA is scheduled to launch around 2010-2012, and it will be operated for 5 years. The spacecraft will include three optical telescopes of 1.7m of diameter each [13].

SWIFT and FAME Two missions are planned to be launched between 2003 and 2004. Although they are not intended directly for NEO observation, asteroids and comets will be detected as noise to the primary data [17]. The first one (Swift) will primarily study gamma ray bursts and other sources of cosmic gamma rays and the second one (FAME, the Full sky AStrometric Mapping Explorer) will take measurements of approximately 40 million stars in order to construct a large and useful database.

NESS NESS (Near Earth Space Survelliance Mission) is a mission from the CSA (Canadian Space Agency) that is just completing its phase A evaluation [20]. It will consist of a small 0.15 m telescope called MOST (Microvariability and Oscillations of Stars) put in a microsatellite and will be dedicated to NEO search (mainly Atens asteroids) and satellite traffic control [19]. Atens asteroids, being inside of the Earth's orbit, are difficult to observe from the ground (because they have to be observed in the daytime). Follow-up observations would also be undertaken by NESS, as its orbital position would allow it to track NEOs for a longer time.

1.3.7 Exploratory missions

The increased interest in the search for NEOs has led to several new planned programs. While some of them are just to fly by NEOs, others are missions to land on them, study their mineral composition and eventually return a sample to Earth. That is because the study of the physical composition of these objects is now a major concern in both ground based and space based programs. The following future missions will bring us the closest understanding of comets and asteroids and their effect on Earth:

CONTOUR (Comet Nucleus TOUR) This take images of at least three comet nuclei with a resolution of 4m, to perform comparative spectral mapping, and to analyze the dust and gases coming from them. This mission is under the supervision of NASA and the Principal Investigator is Cornell University, New York. The mission is scheduled to launch in July 2002 with three planned fly bys; comet Enke in November 2003, comet Schwassmann-Wachmann-3 in June 2006 and Comet d'Arrest in August 2008 [25].

Deep Impact Deep Impact is a mission proposed by the University of Maryland and is the first mission ever designed to penetrate deep into the nucleus of the comet. It is planned to be launched in January 6, 2004, and will reach comet Tempal 1 in July 2005. The spacecraft is designed in two parts, one will fly by the comet and take images during the impact, and the second will separate from the fly by part to impact the comet at a speed of 10 km/s, creating a crater 120 m wide and 25 m deep, the fly by part contains visual inspection components, in both infrared and visual ranges, to take images for the impact and crater in high and medium resolution [25].

Muses-C This mission is led by Japan in association with NASA. The launch is scheduled for November/December 2002, and the mission will gather samples from the surface material of asteroid 1998 SF36 in September 2005 after making a survey for the surface and then landing. It will then return 3 small samples back to Earth in 2007 for analysis [25].

Rosetta Under development by ESA, the objective of this mission is to meet with comet 46 P/Wirtanen in 2011, (launching in 2003). During its journey the spacecraft will fly by two asteroids, Otawara in July 2006 and Siwa two years later. Once the spacecraft reaches the comet 46 P/Wirtanen, the probe that it is carrying will land on the surface of the comet in August 2011, the data will be transmitted to Earth through the main spacecraft [25].

1.3.8 Concluding remarks on NEO detection

The necessary technology for the discovery, follow-up and characterisation of NEOs is generally available. Although several search programs are underway right now, there is not yet a global effort able to guarantee a reasonable lead time before the impact of a threatening object. This is so mainly because of the lack of observations in the southern hemisphere and the fact that follow-up observations are not always done. A satisfactory search program being able to detect most threatening Earth Crossing Asteroids (ECAs) and short-period comets in a reasonable time frame can be undertaken with existing equipment, with the main challenge right now being the coordination of the different search programs.

Present programs actually search in conjunction already more than the 6000 square degrees per month suggested by the Spaceguard survey, but it is not done in a coordinated way and there is a clear lack of observations in the southern hemisphere. For Long Period Comets (LPCs), a permanent survey should be established. Given that their orbits are not restricted to any part of the sky, several 2.5m space telescopes, able to scan in almost any direction, would be advantageous [29]. More data processing centers should be created in order to support the International Astronomical Union (IAU) MPC [29]. The planned observation and rendezvous space missions will be crucial both in detecting a large number of objects and characterizing them. For this reason, there should be soon a substantial advance in our ECA and ECC (Earth Crossing Comet) catalogue, which would include data such as mass, mineral composition and size. This catalogue should greatly increase our chances of predicting objects with threatening trajectories in time and our knowledge of the consequences of an impact [8].

1.4 Response

1.4.1 Brief survey

The response can be simply split into 3 parts, deflection, destruction and protection. It should be noted that the topic of deflecting or destroying a NEO in space is still in the realm of science fiction although many studies have been made to show the technical feasibility. However, there are many steps that can be taken on Earth to mitigate the effects of an impact.

The threat of an asteroid impact is real, even if its likelihood is extremely small. Since it is likely that there will be several decades between the discovery of an impacting NEO, it seems prudent to first find and then track all the large NEOs, before mounting an active mitigation program. Thus, there is actually neither funding nor official program dedicated to the creation of an effective response system. Most works and reports can be classified as theoretical proposals or list of suggestions, and several studies have shown how an Earth threatening asteroid could be diverted from its path. A detailed survey on the subject, requested by ESA, can be found in the doctoral dissertation of Gritzner [54]. Authors of the American Institute of Aeronautics and Astronautics (AIAA) report [29] specify for each mitigation system the technical feasibility, the problems that may be encountered for the development, the maintenance and the cost.

Three important conferences should also be mentioned; the Planetary Defense Workshop (held in Livermore, California, in 1995), and two NEO Interception Workshops (Los Alamos National Laboratory, 1992 and 1993). A compilation of important papers coming from these workshops has been edited by Gehrels [52].

1.4.2 Deflection

The idea of the deflection strategy is to change the orbit of the NEO in order to prevent an impact with Earth. According to Gritzner, it is the only solution in case of a NEO larger than about 100m, because the destruction strategy might worsen the situation [54]. However, the deflection of a NEO years ahead of its impact requires that detection be achieved soon enough and its orbital elements precisely computed. The accuracy of existing NEO detections is often several Earth radii so deflection attempts must deflect the body by at least this amount.

1.4.3 Destruction

The destruction of the NEO body is proposed when there is a very short time left before impact (hours, days or weeks), because any deflection would not be sufficient. However, from a practical standpoint, the choice between the deflection and the destruction is not so easy and there is not always consensus on the most appropriate method. As there are many options for deflection and destruction. They are presented and discussed in the Chapter 3.

1.4.4 Protection

Disaster management

There has been some limited work on the possible response if the collision were inevitable. For instance in the AIAA Report [29], it is states that existing organisations for disaster management are unaware or uneducated about the NEO threat and that national disaster management plans would be insufficient for a NEO impact creating a regional disaster. However, these recommendations are only based on a possible regional disaster but not on a global one. It should also be asked, what can be done to mitigate the effects of a big asteroid impact that could threaten humanity itself?

Evacuation and relocation have to be carried out, but there are very few recommendations for coping with this problem, the United Nations (UN) International Strategy for Disaster Reduction (ISDR) [107], is yet to recognise the NEO threat. Thus, disaster management issues were a key focus of the work presented in Chapter 4.

Extraterrestrial colonies

For truly massive NEO impacts (10 km and greater) shelters on Earth can be lived in for several months or few years at the maximum but not centuries. Survival depends in fact on the degree of self-sufficiency allowed by these shelters. At the same time, efforts should be conducted to transform the Earth into a habitable and safe world again. But is it possible to build such long-term shelters? No documents in the literature that focus on that subject were available. Nevertheless, it is worth noting that a similar problem exists for the Moon, Mars and other planets. The point of view of Steel [103] is interesting:

> "As Greg Canavan has pointed out, the situation is similar to taking out fire insurance for your house: You do so in the hope that you will not need to make a claim.But at the moment, we not only are without insurance, we also are not able to escape from the house.We return again to the survival of our species and our cultures, in that if we had populous, self-contained colonies living in huge oases in space, or on other planets, then we could at least console ourselves with the notion that no single catastrophe could wipe humankind from the face of the universe, even if it could wipe us from the face of the Earth."

There are many studies on the development of Lunar or Martian bases. Lunar associations like Artemis [24] advocate a return to the Moon in order to establish permanent, self-supporting manned lunar bases [34]. There has been some interesting work on the subject. Some technical documents have been written to explain how to build a lunar habitat, to extract lunar resources [109], to obtain oxygen and water, to grow plants, to manufacture solar panels [47], and so on. However, this is only theoretical work without any practical assessment. As for Mars, Robert Zubrin, President of the Mars Society, thinks that it is also possible to settle the red planet in a few decades [110].

1.5 Managerial, legal and political issues

1.5.1 Introduction

Addressed in this section are the managerial, legal and political issues regarding detection, response and recovery . It takes organisation to coordinate the elements of such programmes, and for this reason, organisational structures both in the past and now are examined. The cost of a detection system is not cheap and neither would be the response; so also examined here, are the sources of funding that are currently accessed for the NEO hazard as well as by other natural disasters. Innovative financing schemes to raise the necessary capital are explored since currently funding is far from sufficient. This chapter attempts to put the NEO impact threat into a global context by examining international managerial, legal and political issues under crisis situations. Finally, at a governmental level, policy initiatives are considered as well as legal issues that restrict implementation of the proposed mitigation methods.

It is clear that comprehensive programmes must be implemented by political processes. Things all began to change in 1990 when the House of Representatives, in the United States (US) Congress of that year, during their NASA Multiyear Authorisation Act wrote:

"The Committee believes that it is imperative that the detection rate of Earth-orbit-crossing asteroids must be increased substantially, and that the means to destroy or alter the orbits of asteroids when they threaten collision should be defined and agreed upon internationally."

As a result, the Detection Committee, chaired by Dr. David Morrison, produced the Spaceguard Survey Report in 1992 [104], which recommend the establishment of an international survey program.

Similarly, the UK NEO Task Force [14] was established after a parliamentary initiative by Lord Sainsbury on behalf of the UK Government.

Regarding management of this international project, they suggested several steps starting with a coordinated effort between NASA and the International Union Working Group on NEOs. Within the US, the government agencies that would contribute the most expertise would be NASA, the Department of Energy (DoE) and the Department of Defense (DoD). However, other agencies such as the Federal Emergency Management Agency (FEMA) and the State Department would also make contributions.

The Spaceguard Foundation today is the closest representation of an international NEO program [7].

Thus, a likely starting point for an international organisation to coordinate the NEO effort would seem to be either building upon the Spaceguard Foundation or the IAU Minor Planet Center sites.

The UK NEO Task Force [14] report contains a number of recommendations, on the coordination of all aspects of the subject internationally. They recommended:

"... the Government - together with other governments, the International Astronomical Union and other interested parties - seek ways of putting the governance and funding of the Minor Planet Center on a robust international footing, including the Center's links to executive agencies if a potential threat were found.",

The response by the UK Government contained in the "Government Response to the Task Force on Potentially Hazardous Near Earth Objects" was

"The Government welcomes the work done by the Minor Planet Centre and values its role in coordinating and archiving data on NEOs. NASA is currently pursuing a number of options to provide suitable funding for the Minor Planets Centre and the Government will work together with NASA, the International Astronomical Union, the European Space Agency and other European partners to identify appropriate support to the international effort. In addition, the Government will explore with ESA whether it has plans for similar facilities in Europe."

1.5.2 UN efforts

The UN mainly through its Office for Outer Space Affairs (OOSA) has provided a forum for the discussion of the NEO hazard. In the past it has organised such conferences as the Third UN Conference on the Exploration and Peaceful Uses of Outer Space (UNISPACE III), held in Vienna from 19 to 30 July 1999. Within this conference was discussed the NEO hazard. Within the text of the resolution adopted from this conference was stated the desire "to improve the international coordination of activities related to near Earth objects, harmonizing the worldwide efforts directed at identification, follow-up observation and orbit prediction, while at the same time giving consideration to developing a common strategy that would include future activities related to near Earth objects." [11]

The principle UN body addressing natural disasters, the ISDR [107], is an undertaking to coordinate disasters on a worldwide basis. Unfortunately, this organisation is yet to recognise the NEO threat and focuses exclusively on the well-known Earth-based disasters such as earthquakes, cyclones, floods, infestations and many others. Nevertheless, the four main objectives of the ISDR have many parallels in the NEO problem; increasing public awareness, promoting commitment from public authorities, stimulating interdisciplinary partnerships and improving scientific knowledge.

1.5.3 Financing

For such an international system to work, a solid and assured source of funding must be maintained. To date, there has been little effort in establishing international financial cooperation regarding the NEO problem. The Spaceguard Foundation [23] non-political and non-profit forum. Funding of the organisation is through annual membership fees and contributions by both private and public institutions. The MPC is also a nonprofit organisation, with principal funding coming from subscriptions to the various services it offers.

In the event of the discovery of a real NEO threat, the financial reaction of the international financial community is a serious issue that warrants further attention. There are three principal organs of the UN that deal with financial issues: The World Bank, the International Monetary Fund (IMF) and the Organisation of Economic Growth and Development (OECD). The main mandate of the World Bank is to assist the poorest countries in the world through ongoing projects that fight poverty and establish sustainable economic growth [26] so it is unlikely that the World Bank will provide any funding to the NEO cause since it is specifically focused on problems relating to poverty. The IMF is an international organisation functioning to promote international monetary cooperation [18] to deal with the exchange of money between countries so it too lacks any direct interest for the NEO problem. The OECD comprises 20 member countries that cooperatively develop economic and social policy at an international level [27]. Its work covers economic and social issues including macroeconomics, to trade, education, development and science and innovation. It is thus the correct forum to address the NEO issue and could rally a broad range of resources.

Decision making in a NEO crisis is an important issue so the OECD's decision-making apparatus is examined here. The staff members come from all countries but they serve as international civil servants rather than having national affiliations. There is no policy on the quota of staff coming from different countries, only a policy to employ people with suitable skills and a broad cross-section of nationalities.

1.5.4 Budget competition and communication

With the space research budgets of the main space faring nations being cut, how feasible is research and development for defending the planet Earth against such a low probability event? Embracing nonprofit marketing may be an important step in getting the funding and attention that is required to achieve a better state of readiness. Marketing has recently become common in the Non-Profit sector [98]. Space budgets are tight so one must "sell" the idea, that this project is worth investing in a NEO programme rather than other projects (e.g. Mars exploration, launcher development or manned space-flight). It has now been widely accepted by almost all nonprofit organisations as essential to their success. At a very fundamental level, they recognise that virtually everything they do, especially their major mission, involves influencing the behaviour of others (i.e. the target markets).

Globally, four audiences can be distinguished [93]. The policy makers, the space partners (other agencies and industry), the media and the general public. Future studies are needed to look in more detail at the space audience, how the Earth Impact Prevention project can be promoted to governments and space partners as an attractive investment of a share of the space budget and also to the media and general public. The idea of an asteroid impact seriously worries the general public. This concern has increased with the generally accepted theory that an asteroid hit Earth 65 million years ago, which caused the extinction of the dinosaurs. Also with such films as "Deep Impact" and "Armageddon" any step in protecting the Earth from such catastrophic impacts would not be shunned.

1.5.5 International law related to NEOs

Current status of space law related to NEOs

To date, no specific legal regime has been formulated to mitigate potential damages of asteroids impacts. At present day the most suitable solution for protecting the Earth against NEO threat is building a nuclear shield. When considering that solution two main problems arise; the possibility of carrying out nuclear tests on the Earth and the problem of putting nuclear weapons into outer space. Table 1.3 shows the treaties that are most likely to affect space-based NEO responses.

Termination of a treaty

The Vienna convention on the law of Treaties of 1969 [1] regulates how to deal with treaties. Part V is dedicated to the terms of invalidity, termination and suspension of the operation of a treaty. According to Article 62, a treaty can be terminated in the case of fundamental change of circumstances between the present moment and when the treaty was signed. This would probably be the situation in case of a confirmed NEO treat. Hence, the above treaties could be terminated allowing the construction of a nuclear shield for the Earth. However, powerful new treaties would be needed to oversee such a system.

Table 1.3: International agreements and resolutions affecting mitigation response to NEO threat

Agreement	When	What
Threshold Test Ban Treaty [91]	1963	Prohibits atmospheric testing, even in outer space.
Outer Space Treaty [85]	1967	Prohibits weapon placement in orbit, in space, or on other celestial bodies, including the moon.
Nuclear Non-Proliferation Treaty [2]	1970	Prohibits transfer of weapons or devices.
Agreement Governing the Activities of States on the Moon and Other Celestial Bodies, [4].	1979	Prohibits nuclear weapons in orbit around or on the Moon and other celestial bodies.
Treaties Between the USSR and the USA on Limiting the Yield [3].	1974	Limitation of the yield in single explosions during testing

1.5.6 Current status of space policy related to NEOs

A number of US Senate hearings have been conducted on the topic [28] showing the the NEO issue is starting to influence the policy-making process. The UK NEO Task Force was a direct result of political processes. The Council of Europe is aware of the NEO threat since 1994, and numerous reports [?, ?, ?] have been presented to the Parliamentary Assembly. These reports summarised the scientific evidence for the NEO threat and gave recommendations. All these works have ended with the proclamation of the Resolution 1080 on the 20th of March 1996 [83]. By this resolution, the Council of Europe states its policy guidelines according to NEO threat and invites member states acting according to them. The resolution is organised in six paragraphs. No further discussion on NEO has taken place in Parliamentary Assembly after that resolution. Policy guidelines on NEO have been fixed but no actions for accomplishing these guidelines have been defined. The responsibility of taking initiative is left on member states and ESA.

1.6 Concluding remarks

In the past, it has been individual astronomers who have borne the sole responsibility of watching over the NEO hazard for Earth. Later national and then international organisations were formed to coordinate these efforts but with minimal public funding support. Recent governmental recommendations are recognizing that these efforts should be in the hands of well-funded international organisations capable of efficiently coordinating a truly worldwide effort.

The idea of nonprofit marketing of NEO projects is an important issue for any significant action. One must also look into International Projects and examples of successes and failures, and at current space markets for the trends in space budgets in the next few decades. For the project to be successful we must use a solid marketing strategy to communicate the critical message that the NEO threat is real and that something can be done.

A concurrence of many actors will contribute to an efficient response to a NEO threat. Astronomers are involved in the detection issue. Engineers are involved in the conceptualisation and the fabrication of technologies that enable us to properly respond and mitigate the potential damages of a disastrous occurrence. Sociologists and urbanists will ensure that proper measures are taken for displacing and sheltering exposed population: coastal population in a case of ocean impact creating tsunami; urban population in a case of land impact. But of course, the earlier we detect a potential danger, the better it is to respond in a manner which does not involve the pressure and the immediacy of an emergency, meaning more flexibility in designing reliable courses of action.

The existing Treaties provide the greatest restrictions to a Response system. If we are faced with a major extraterrestrial threat, where the survival of humankind is potentially at risk, we will have to apply general principles, such as, *"self defense"* principle, the *"right to survival"*, the *"right of choice"* for, no specific existing laws will assist in substantiating a response to threat.

Chapter 2

Categorizing the Threat and Response Options

2.1 Concept and methodology

As was seen in Chapter 1, most attention is currently focused on the NEO detection issue, which is obviously the most pressing issue, and hence deserves that attention. Recognizing the nature of ISU, it was decided to find a new field of focus, which can be better served by a broad interdisciplinary study with a forward looking nature. The decision was made to address the issue of responding to future Earth-impacting NEOs. The NEO response work to date has focused almost exclusively on the technology studies of possible space-based strategies. However, there are many issues needing more attention. In particular Earth-based disaster mitigation of NEO impacts is poorly addressed.

As an example, one can imagine that the responses to a small 800 m wide NEO impacting the Pacific Ocean with a two year warning time, and a 3km wide LPC detected for an impact in about 100 years would involved quite different responses. The space missions, and ground preparations for such situations would be vastly different. However, no comprehensive study of the response alternatives has been conducted yet.

Clearly, the issue of responding to NEO threats is very broad, making planning for NEO responses a complex task so the response problem was considered from a general perspective, not overly focusing on specific NEO threat scenarios. Hence, this chapter attempts to chart the categories of NEO threats that are possible, whilst linking them to the appropriate response options in space and on Earth. The objective is to present the full scope of response problem, allowing better understanding the relationship between the NEO threats and the possible reactions.

In addition to classifying the possible NEO threats and responses, the responses were examined from an interdisciplinary perspective. Table 2.1 shows a list of disciplines and main issues that are of concern to NEO response efforts.

2.2 Response decision tree

Considering that there are an infinite number or circumstances by which a NEO might threaten the Earth, it was possible classify responses according to the characteristics of the threats. There are many parameters that define NEO threats since one may consider variations in any of following parameters:

- Warning time
- NEO size and mass
- NEO Orbital parameters (e.g. orbital period, inclination, etc.)
- Impact location
- Certainty of impact

Table 2.1: Interdisciplinary analysis issues

Science	Evaluation and classification of the threat (local/global catastrophes)
	Probability of Impact
	Predictability of impact location
	Classification of the NEO
Engineering	Detection Techniques
	Responses
	Research Test and Simulation of Response Strategies
	Missions to Support Scientific Group
Business & Management	Cost Analysis
	Potential Sources of Funding
	Evaluation of Damages
	Response Programs Management Team
	Evaluation of Current Activities
	Promotion
	International Cooperation
Policy & Law	Evaluation of Current Policy and Law
	Legal Issues of Mitigation and Response
	Technological Issues
	Political Awareness and Acceptance of the NEO Threat and the need to Respond
Social and & Ethical	Cultural and Religious Concerns
	Socio-Political Climate
	Legal and Ethical Problems Connected with Response Methods

- NEO orbital class (e.g. Atens, Apollo, Amor, Trans-Neptunian, LPC)
- NEO composition
- Spin state of the NEO

Each of these parameters classifies the response activities in different ways so they should all be considered in the problem. However, to make the work concise, parameters were sought that could separate the NEO threats according to the possible responses. For example, a small NEO of about 500m coming towards the Earth should be deflected if possible, whereas heavy NEOs rule this out. If the warning time is longer than a few decades, there is sufficient time for large mitigation strategies to be organised, whereas if the warning time is short, only emergency evacuation is possible.

The concept of a decision tree was applied to break down the problem into manageable sub-categories. Each branch of the tree corresponded to a class of NEO threat scenarios for which response options would be similar. Thus, for any threat scenario, the reader of the tree can rapidly follow the corresponding branches to determine what responses are appropriate. When using the tree, the reader should proceed to read the relevant section of this report to which it refers.

In addition to the parameters listed above, which reflect purely intrinsic properties of the NEOs (e.g. spin, mass, composition), there are also two generic parameters that might require expert scientific advice to determine such as deflectability and destructibility. The second branch point of the tree is this type since it allowed significant simplification of the classification problem.

The right hand column of 2.1 shows the typical responses to each case in a simplified way. There are obviously cases for which these simplified responses are not appropriate (e.g. a small high inclination LPC detected with a very short warning time). However, it was felt that the tree covered the most dangerous cases and the most likely cases.

2.3 Threat classification parameters

The branches of the the Threat Classification Tree are described in the following sub-sections:

Warning time

At least two 100 m wide asteroids made close approaches to the Earth in the first half of this year (2002). On June 15, the asteroid 2002 MN passed just 120,000 km from Earth and on March 8 asteroid 2002 EM7 passed 463,000 km from Earth [65]. Both these bodies were detected as they passed the earth, if they were on a collision path there would have been little or no warning time. Clearly, the category of short warning time is urgently needing attention.

The classification of 'Short' is intended for threats with less than one year of warning time. Such scenarios, exclude the development of new space missions, allowing only ground-based responses. When the warning time is only a few days or even hours, there are still many opportunities for Earth-based responses but space-based strategies are impossible (since no space-based mitigation system is in place today).

If the warning time is in the scale of decades, there are many opportunities for both space-based and Earth-based mitigation efforts. The category named 'Medium' encompasses the warning time frame from 2 to 30 years, presenting the possibility of new space missions with exisiting technology.

The 'Long' warning time category encompasses all NEO impact scenarios with the impact occurring more than 30 years in the future. Only speculative guesses can be made of the mitigation technologies that will be available at that time so the proposed responses for these NEOs are in the realms of science fiction. Furthermore, when the warning time is over a few hundred years, the certainty of impact is hard to predict due to uncertainty in the orbital perturbations caused by the lack of knowledge about the body (e.g. albedo) . In fact, the most hazardous known asteroid, 1950 DA, has a 1 in 300 chance of impacting the earth in the year 2880 according to NASA [67]. The lack of public attention for that case demonstrates that people and governments are unlikely to have significant reactions to impacts predicted to occur more than a few centuries in the future.

Damage potential

This refers to the effects that the NEO would have if it impacts the earth. It is largely dependent on the size and mass of the NEO, however, impact speed and location are also influences. To avoid complication this

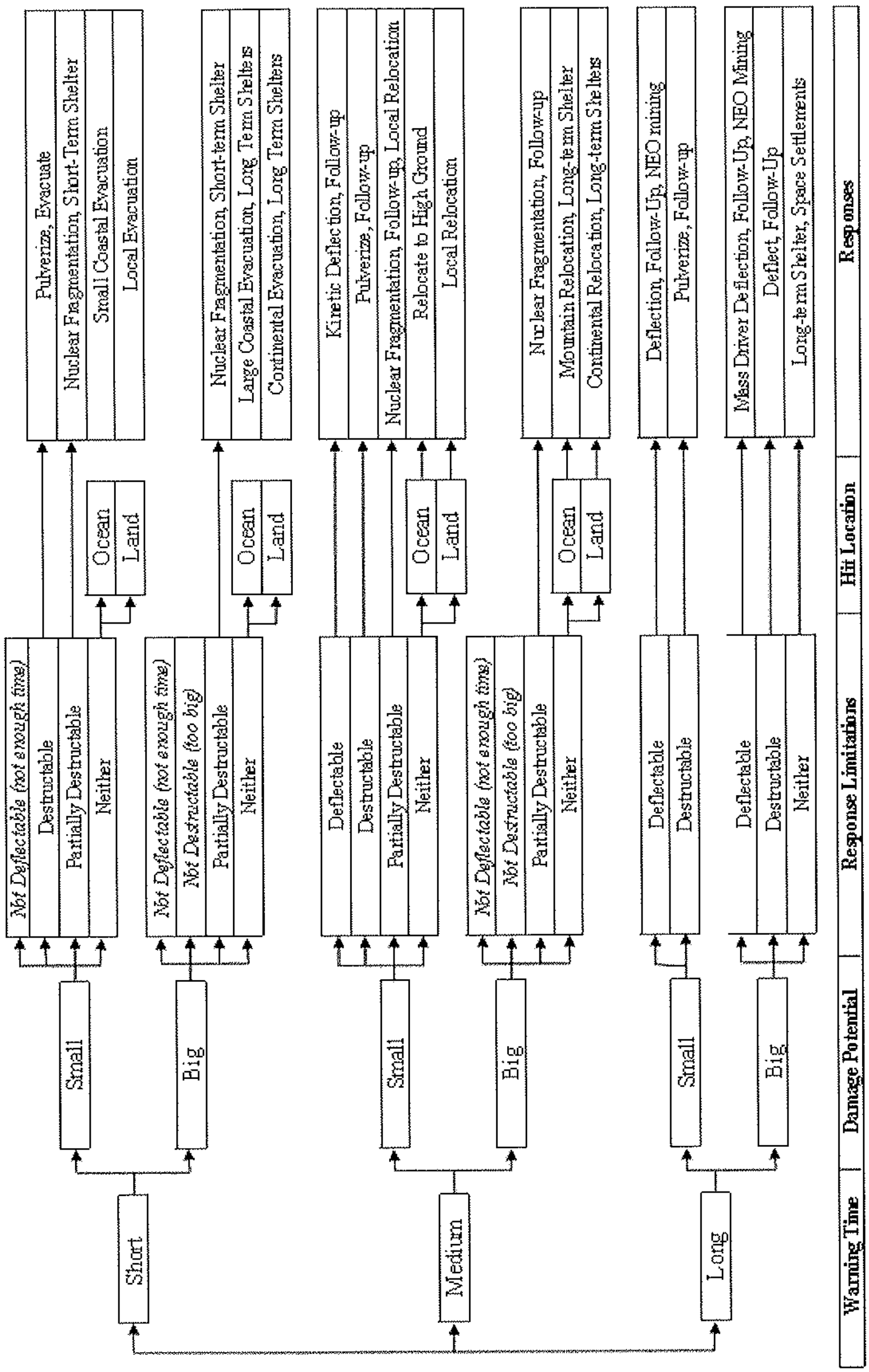

Figure 2.1: Classification tree of NEO Threats

category was divided into only two categories. The 'Large' category includes all NEOs larger than 2 km since these objects would require global response efforts to mitigate since very large disasters (see Table 4.1.

The 'Small' category is intended to include any NEO threats that would be of local or regional significance. It is generally thought that such NEOs can successfully deflected or destroyed with modern technology if there is sufficient warning time. Excluded are the very small NEOs that would burn up in the Earth's atmosphere (less than 30 m), since these little or no response.

Response limitations

The branches at this point of the tree primarily distinguish between the different types of space-based responses.

The category named 'Deflectable' is for NEOs that are small enough or with long enough warning time to enable deflection of the body with sufficient ΔV to prevent its impact with Earth. The accessibility of the object should also be taken into account. When possible, this category is the most desirable response since it doesn't effect the Earth.

'Destructable' is a possibility for objects that are not deflectible. In some cases the NEO is held together too weakly to be able to absorb the energy transfer required for deflection. There are some cases were 'Partially Destructable' is a possibility. Fragmenting the NEO into many smaller fragments by nuclear blasts may reduce the scale of disaster on Earth, although it also risks spreading the effects (including nuclear fallout) over a wider area.

Finally, 'Neither' is included for the cases where the NEO is neither destructable nor deflectable.

Since the alternative branches at this level of the tree take into account many complex relations between the parameters that make up the threat, determining the appropriate branch for a given threat scenario would normally require complex mathematical modeling of the NEO's orbit, its composition, and the space vehicles that would be involved in the response. Some special software taking into account these complexities was developed as part of this project.

Hit location

If a NEO strikes the Earth's surface, there are numerous response alternatives. However, the two most important distinctions are between 'Ocean' impacts and 'Land' impacts. The most devastating effect of an ocean impact would be the Tsunami (see Section 1.2.2), which would damage coastal regions in the region or around the world. On the other hand, a land impact of a similar size would lead to more debris and dust being ejected into the atmosphere, perhaps causing more severe climatic changes. In both cases, large numbers of people would need to relocate away from the affected areas.

Accurate prediction of the impact location is not always possible since it depends on accurate orbital parameters for the NEO. In some cases, there will be insufficient data to determine whether the NEO will hit the land or the ocean (long warning times, incomplete orbital observations, etc.). Also, there is a possibility of a dispersed impact zone including both ocean and land regions. The comet Shoemaker-Levy [64] was observed to disperse due to gravitational forces before impacting with Jupiter. Furthermore, the presence of the Earth's atmosphere may also lead to dispersion of the body over a wide area.

2.4 Response decision graph

An alternative method to visualise the numerous response alternatives is by separating them in the two-dimensions of warning time and NEO size. Figure 2.2 displays all the alternatives. The curve dividing the top and bottom of this graph represents the limit of space-based responses. Below this curve, there is too little time to build a sufficiently powerful deflection or destruction system so only Earth-based responses such as evacuation and sheltering are possible. The shaded regions on the graph indicate the response that is the most likely to be appropriate, however there is undoubtedly some overlap between the possible responses.

2.4.1 Response alternatives

The responses outlined in both the Threat Classification Tree and the Decision Options Graph are described in the following sub-sections. For each response activity, links to the relevant sections within this document are provided.

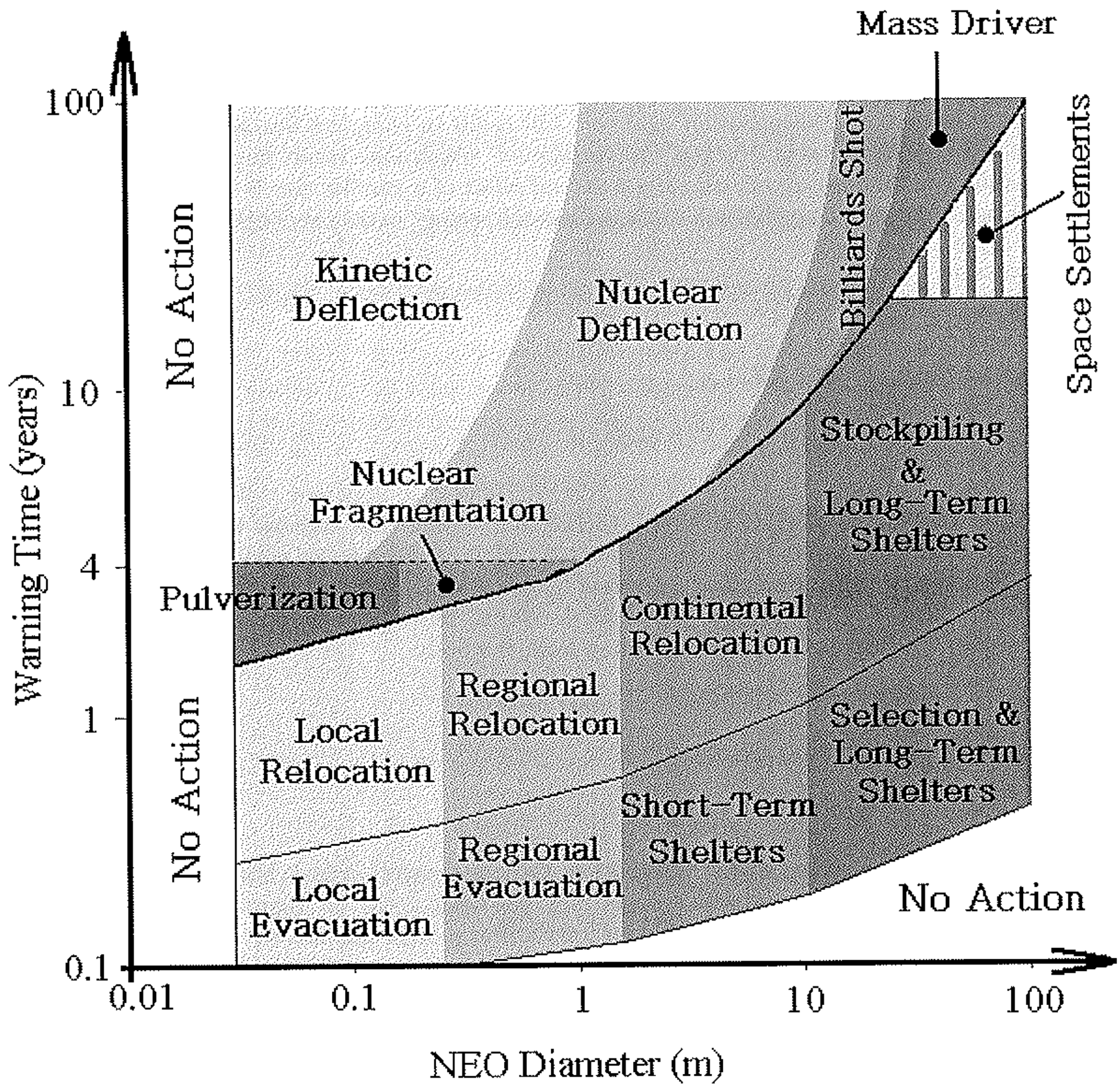

Figure 2.2: Graph of decision options

Follow-up

This refers to observations of a NEO intended to refine its orbital parameters or to characterise it more precisely. This activity is not mentioned in Figure 2.2 since it is assumed that it will be performed in any threat scenario.

- 1.3.4: Characterisation Overview
- 3.3: Characterisation Options
- 5.2: Characterisation Mission for 1997 XF11

Destruct

This refers to attempts to break the object into many pieces. If the object is divided into pieces smaller than 50 m, the method is defined as 'Pulverisation' and this will result in complete burning up in the atmosphere. Another alternative for destruction is 'Nuclear Fragmentation' which may result in pieces greater than 50 m. The other main option is 'Billiards Shot' whereby a second NEO of a smaller size is deflected to intercept the threatening NEO, with the resulting collision releasing enough energy to destroy both objects.

- 3.5: Pulverisation
- 3.6: Billiards Shot
- 5.4: Destruction Plan for 1997 XF11

Deflect

This refers to attempts to change the orbit of the NEO such that it does not collide with the earth. The option of 'Kinetic Deflection' involves launching a rocket from Earth that collides with the NEO, imparting enough momentum to alter its orbit. 'Nuclear Deflection' involves detonating nuclear blasts on or near the body. 'Chemical Propulsion' involves docking a conventional chemical rocket to the NEO and firing it to apply a change to its orbit. 'Mass Driver' refers to yet to be developed technology that may use the material of the NEO as propellant, by accelerating that material away from the body.

- 3.4.1: Chemical Propulsion, kinetic deflection, mass driver
- 3.5: Nuclear Deflection

Shelter

The 'Shelter' response category refers to any attempts to provide protection from the effects of a NEO impact on Earth. Depending on the size of the NEO, there may be 'Long-Term' or 'Short-Term' sheltering. Long-term shelters are envisioned to sustain human life on Earth after a large impact has substantially changes the atmosphere and climate. This is in some ways analogous to life on other planets. Short-term shelters encompass all attempts to mitigate against the direct effects of the NEOs impact such as blast wave, earthquakes, fires, landing ejecta, etc.

- 4.2: Short-Term Shelters
- 4.3: Long-Term Shelters

Evacuate and relocate

The term "evacuation" encompasses all emergency efforts to move people from the area prior to an impact. Depending on the size of the impact, the time scale for evacuations would be hours to weeks. Since the NEO may impact in different locations and with different magnitudes, the cases of 'Local Evacuation', 'Coastal Evacuation', 'Regional Evacuation' and Continental Evacuation' are all considered. The concept "relocation" refers to a broader effort to save not only humans but wildlife, cultural heritage, etc. and to establish a temporary or permanent habitat for them. The time scale for relocation is assumed to be enough for planning (weeks to decades).

- 4.2.2: Local, regional and coastal evacuation and relocation.
- 4.3.2 Continental evacuation and relocation

Stockpiling

This refers to all activities intended to collect and store resources that are necessary to sustain life for prolonged periods of low food production. It is a support activity for long-term sheltering, and the geographic distribution of food production and consumption before and after the impact must be taken into account. It is only applicable when many months or years of warning time are available.

- 4.2.4: Stockpiling

NEO mining

In the event of a very long warning time, it is envisioned that technology will have time to advance to a level whereby the threatening object can be used for the benefit of mankind through mining. This is also a merely science fiction concept at the present day, and has therefore not been considered.

2.5 Concluding remarks

The following chapters of this report will go into more detail in the important cases presented in the Threat Classification Tree (Figure 2.1) and the Response Decision Graph (Figure 2.2). Chapter 3 covers the options available for space-based mitigation including characterisation, deflection and destruction, and Chapter 4 covers the activities on the ground such as evacuation, relocation, sheltering. Finally, Chapter 5 is presents a detailed case study to an assumed NEO threat that encompasses both Earth-based and space-based responses.

Due to the complexity of the NEO threat, there is a strong need for more clarity and structure in the international NEO community. Thus, it is recommended to establish a new International Organisation as an organ of the UN that would be tasked with planning response strategies for mitigating the NEO threat, and coordinating response activities on an international level if a threatening NEO is ever discovered.

It was envisioned that this methodology might be the first thing that decision-makers consult for when they are told that a serious NEO threat has been detected, and more importantly enable them to comprehensively address the problem before any threat occurs. Furthermore, by providing a broad outline of the complex problems involved, the NEO community can better divide up their work in relation to preparing response activities at international, national and local levels.

The classifications of the threat and response options presented in this chapter were intended to better focus research and funding on NEO response planning at an international level, in order to achieve a better balance of funding attention to the most critical areas. In this light, it is proposed that this work could form the first draft of a reference document named 'International NEO Response Guidelines (or 'INEORG') that could assist such an organisation.

Chapter 3

Space-based Responses

3.1 Introduction

In Chapter 2, an overview of the most promising options for mitigation has been presented without going into great depth. This chapter focuses on the space-based part of the mitigation. The decision process that determines the appropriate response has been examined. As a part of this team project, an algorithm has also been implemented in a software tool with a user-friendly Graphical User Interface (GUI) to help designing the mission. The algorithm follows the concepts that are presented in this chapter. It starts with the assessment of the threat and continues with the timing and the determination of the appropriate mitigation strategy. A simulation is included to show the evolution of the trajectories at any time. Any object of the solar system can be visualised, provided that its orbital parameters are set.

The global decision process is summarised in Figure 3.1. Before designing any mission, the threat should be identified. As already stated in Chapter 2, if the NEO is smaller than 30m, it is going to burn in the atmosphere and there is no need for a space mission. Moreover, if the warning time is too short, typically in the order of one year or less, whatever the size of the NEO, there is no time for a space mission. In the decision process, the assessment of the threat is determined by the answers to the questions when and what. It is assumed in this chapter that the threat is justified and that there is enough time for a space mission.

Different aspects of the mitigation are examined. The presentation and classification of the different responses are the main parts of the chapter, but the ethics and some general organisational issues have also been considered and discussed, as well as the use of nuclear weapons.

3.2 Timing the interception

Timing the interception is an important step in the decision process. It helps a lot in understanding what can be done and what cannot. The warning time is the main driving parameter of the timing, but it is not the only one.

3.2.1 Definitions

In order to classify and discuss the different responses, some terms need to be defined:

- Warning time: This is the time between the detection of the NEO and the predicted impact on Earth.
- Preparation time: This is the time between the detection and the launch.
- Travel time: This is the time between the launch and the arrival of the interceptor in the neighborhood of the NEO.
- Action time: This is the time between the arrival of the interceptor and the predicted impact on Earth. The significance of this parameter is explained in the next sections. Short action time means less than five years.

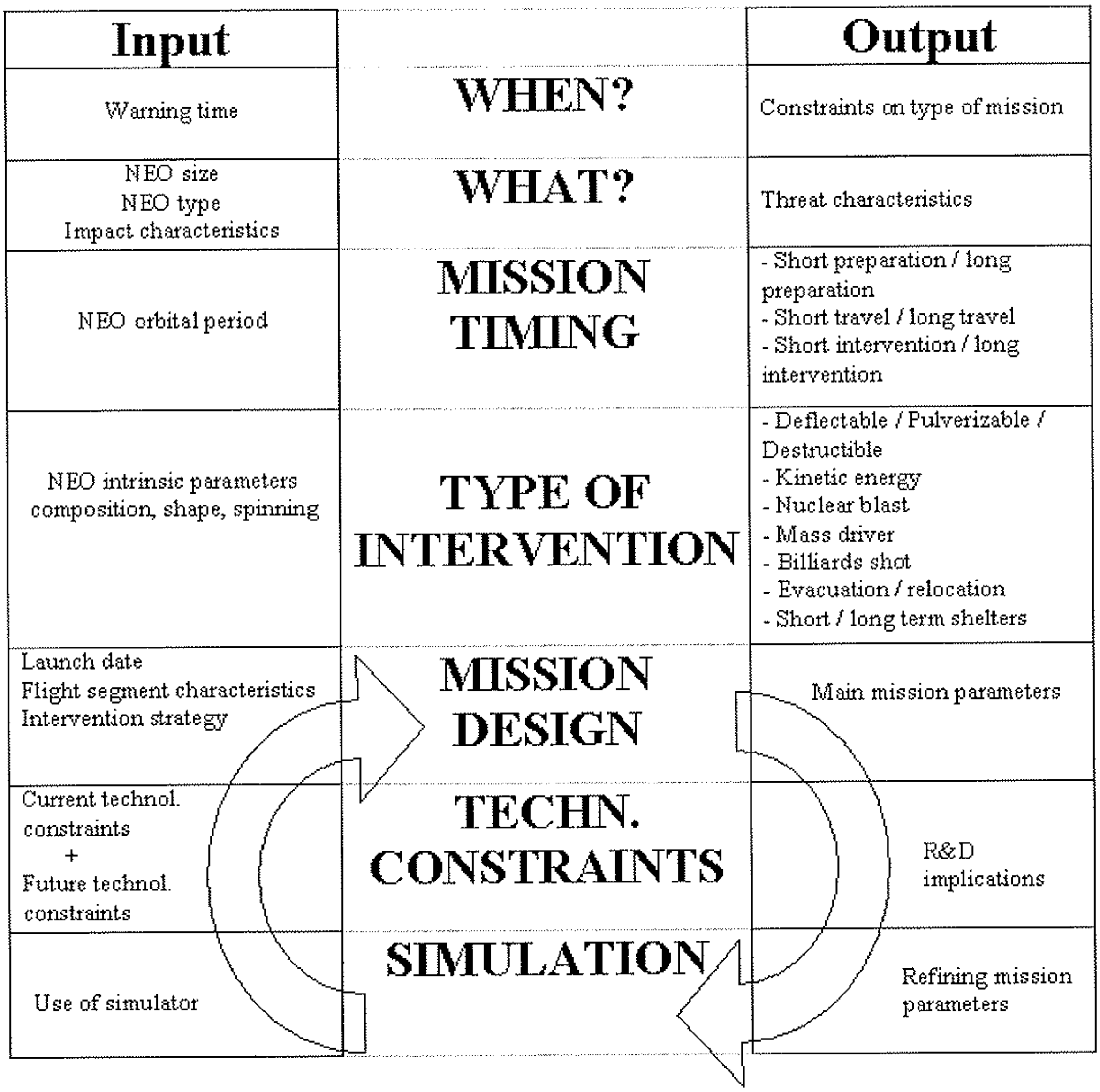

Figure 3.1: The decision process that has been implemented to determine the response.

3.2.2 Assumptions

In addition, the following assumptions have been made:

- The minimum preparation time is 1 year. Such a short preparation might be necessary in some cases, but at the expense of design and testing. A long preparation time is two years and more.
- A short travel time is defined as 1 year and a long one is in the range 1 to 5. In order to discuss the general case, it is assumed that the interceptor can reach the NEO within one year while it is entering the inner part of the solar system.

3.2.3 Mission classification as a function of the timing

The period of the NEO is the second main parameter in regards to the timing of space-based responses. From the warning time and the period, the key elements of the timing can be roughly inferred. The preparation, travel and action times can be short or long and can be used to classify the different timings, see Figure 3.2. A list of 8 cases arise:

1. *Short preparation, short travel, short action.* This situation occurs when the warning time is shorter than two years. There is only time to build the interceptor, launch it and intercept the NEO a few days or weeks before impact.
2. *Short preparation, short travel, long action.* If the NEO is a long period comet that has just being discovered one period before the predicted impact, there is a unique chance to intercept it before it comes back to its far aphelion. However, there is a short time to prepare and launch the interceptor. The action time, on the other hand, would be very long.
3. *Short preparation, long travel, short action.* This case corresponds to the threat of a big NEO, which would be hardly deflected. The sooner the interception, the better would be the mitigation. However, if the NEO is far from Earth or if the accessibility is an issue, the interception might require a long travel in the solar system to reach it on time.
4. *Short preparation, long travel, long action.* This situation is similar to the second, but the comet might not be easily accessible. A long travel in the solar system would be required to reach it before it is too far from the sun. Gravity assist maneuvers might allow complex interplanetary navigation.
5. *Long preparation, short travel, short action.* This case occurs when there are strong constraints on the launch window, for instance if the inclination of the NEO on the ecliptic is high, making it difficult to reach it. It is also the case of long period NEOs with late detection. There is some time for preparation but the time and position for launch might be strongly constrained, thus allowing late interceptions only.
6. *Long preparation, short travel, long action.* This is probably the easiest situation. A NEO is detected long in advance, a short travel is possible to reach it and there is still time for a long action or other missions.
7. *Long preparation, long travel, short action.* This case is typically a variation of the second. If the long period comet cannot be reached before the last orbit, the interception has to be undertaken in the last years before the predicted impact. The preparation would be long, not because of any particular need, but because waiting is the only solution. Then if it is required to intercept as soon as possible, a long interplanetary travel could be decided to reach the NEO as far as possible from the Earth, for instance at Jupiter's orbit.
8. *Long preparation, long travel, long action.* If the warning time is long but the accessibility is difficult, a long travel might be required to reach the NEO. It could be for instance the case of a NEO with high inclination. In order to reach it, the gravitational assist of Jupiter might be used, thus explaining the long duration of the travel.

If the preparation time is long enough and the accessibility of the NEO is not too hard, a specific mission can be undertaken to characterise the NEO.

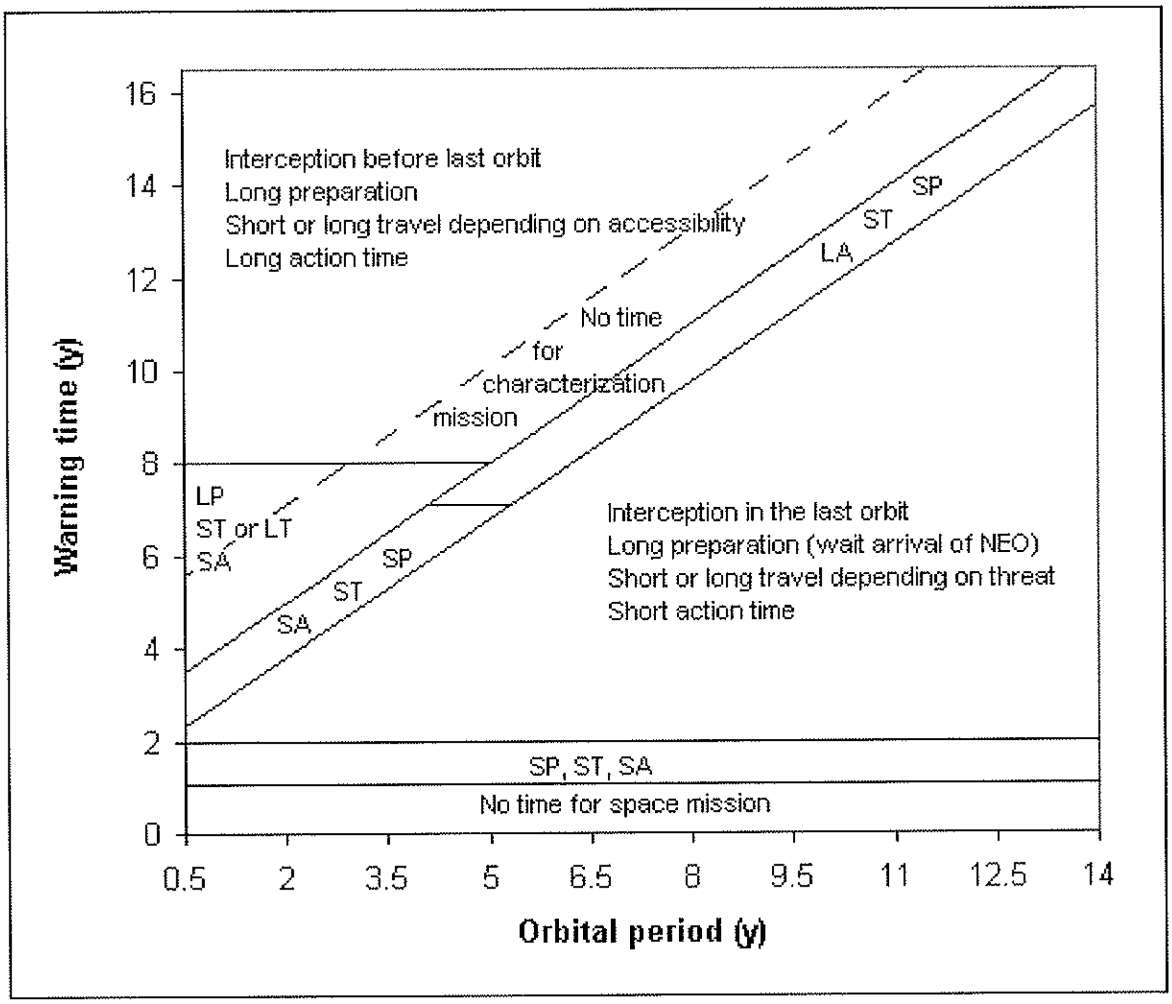

Figure 3.2: Mission timing according to the warning time and the orbital period of the NEO (L=long, S=short, P=preparation, T=travel and A=action).

3.3 Characterisation of the NEO

3.3.1 Search for information

If or when a threatening NEO is detected, the earliest response steps will be to study the object in more detail to determine whether it will really hit the Earth, the effects of the impact and how best to mitigate the disaster. Reliable studies would be of extreme importance. After follow-up observations to more accurately determine its orbit, the studies will rapidly shift into detailed characterisation of the threatening body. This will give crucial information to those people responsible for responding to disaster both in space and on Earth. The following list of properties form the most important information that is needed from such follow-up and characterisation studies:

- Accurate orbit determination
- Spectral class
- Mineralogical composition
- Mass and size (and hence density)
- Shape
- Internal structure

Although there are many thousands of NEOs well-determined orbits, only a few of these objects have been studied in enough detail to determine their geological and shape characteristics. As a result, there is very limited data to allow comparisons between spectral class information we can observe from Earth with important physical properties of the bodies.

Accurate knowledge of the NEO's properties is essential for planning almost all response activities. The mass and size of the object (and hence its density) are the major influences on our ability to deflect it and on the effects when it hits the Earth. The overall configuration of the NEO may be of many types such as double, bifurcated, spherical, irregular, binary or with satellites. Highly irregularly shaped and small NEOs are hard to land on, making space-based mitigation attempts more complex. Determination of a NEO internal structure and consistency is necessary for planning deflection and destruction missions. Also, if it collides with the Earth for which there are three major possibilities that depend on its internal structure and composition; disintegration in atmosphere, explosion in atmosphere, and impact on surface of Earth. Studies of its surface geology would include mineralogy, water and other volatiles, metals, chemical composition, distribution of compositional units, magnetic field, etc.. These would be of high importance for developing scientific models of the body's response to nuclear explosions that are envisioned. Knowledge of its structural weaknesses (in the form of cracks or mineralogical concentrations) could inhibit or assist mitigation activities. Specification of the spin state, including pole orientation and precession is important since fast spinning NEOs are more difficult to land on and spin has other important implications for planning space missions to the NEO such as available sunlight for power generation and illumination, and also for communications with Earth or other spacecraft. These properties need to be determined by a combination of Earth and space-based studies, which are discussed in the following sections.

3.3.2 Limitations of ground-based studies

The available technologies today can detect the size and the shape of asteroids from the ground to a level of accuracy that is enough for many purposes. Earth-based observations with the largest, most powerful telescopes and radars can provide improved estimates of size, shape, spin-state, and composition. A more detailed assessment of the surface and interior conditions such as physical, chemical and mineralogical properties of NEOs is provided by studies of meteorites. However, meteorites studies are strongly biased towards the metallic NEOs since they are the most likely to survive the passage through the Earth's atmosphere. There is almost no meteorite information from the non-metallic types that make up the majority of the NEO population.

During the following years, ground-based observations will have an ongoing focus but will play a secondary support role to the various space-based and Earth-based mitigation activities. To ensure good support of both the early and ongoing observations, it is recommended to have them coordinated and funded by the same international body that is overseeing the response planning.

Table 3.1: Some existing and planned characterisation missions.

Mission	Institution	Dates	Target NEO	Science goals
NEAR	John Hopkins University, APL	1996-1998	Mathilde, Eros	Mapping chemical composition, shape, size, density and magnetic field
Deep Space	NASA JPL	1998-1999	Braille	Mineral composition, shape, size and brightness
Muses-C	ISAS, NASA	2002-2007	1998 SF36	Sample return, imaging, composition, LIDAR
Deep Impact	NASA JPL	2004-2005	Tempel 1	Impactor Study
NEAP	SpaceDev Inc.	Unknown	Nereus	Science, entertainment
Stardust	NASA JPL	1999-2004	Wild2	Sample return mission
CONTOUR	NASA	2002-2008	Enke, Schwassmann-Wachmann and d'Arrest	Nuclei spectral mapping, analyze the dust and gasses.
Rosetta	DLR ESA	2003-2008	Otawara, Siwa and Wirtanen	In-situ analysis on Wirtanen

3.3.3 Space missions for NEO characterisation

Since ground-based characterisation and follow-up studies of NEOs are limited in the types of science data they can provide, there is a clearly a need for space missions to characterise the threatening NEO. In addition to confirming the Earth-based size and spin observations, such missions will give detailed data about its surface features (craters, boulders, cracks, topology, etc.) of the NEO. Once the spin, size and surface features of the NEO are known it will be possible to determine whether a lander can be sent to its surface. Devices can be included on the characterisation spacecraft for collecting samples from the NEO's surface (or maybe its subsurface). Distributed data collectors can perform analysis of the surface materials at multiple locations around the NEO and act as network stations for seismic studies of the interior and targeting points for subsequent missions. An instrumented penetrator similar to that developed for Beagle 2 (UK Mars mission) would enable subsurface studies. Since the tasks are complex and cannot be easily automated, there is an intriguing possibility of sending a manned mission. This concept is expanded in the characterisation mission of the case study in Chapter 5.

The orbit of the NEO will have a strong influence on the possibilities for characterisation missions. Long period orbits will allow long mission development but may require a deep space rendezvous which could pose difficulties for propulsion and energy since solar radiation is weaker. Depending on the propulsion system and trajectory, arrival might take anywhere from a few months to quite a few years, with fly-by speeds of a few to 20 km/s or more. More energy and time would generally be required to match its heliocentric orbit in order to rendezvous or land on the object.

It must be kept in mind that between 18 to 24 months are required to develop high quality fly-by missions (regardless of financial resources), and even longer for lander and sample return missions. So for threat scenarios with short warning time, these missions are not an option.

A brief survey of existing NEO characterisation missions are presented in Table 3.1.

3.3.4 Characterisation payloads

The development of science instruments for space flight is a time consuming and difficult task that can only be carried out by a limited number of institutions in the world. It would be imperative for these organisations to drop all other projects and devote their time and expertise to working on the necessary instruments for a comprehensive set of characterisation missions. Care would be needed to be taken to coordinate international efforts to reduce duplication of effort and to commission the instruments of the types that are in the competence of the various organisations. Table 3.2 was created to enable a trade-off of different instruments that would be considered.

Regarding the determination of the interior composition, seismic studies are good for determining the distribution of bulk material properties (density and elasticity) however the only way to be sure of the composition

Table 3.2: Science instruments for NEO characterisation missions.

	Physical characteristics	Usage of Data	Mission Type
Imager	High resolution images of surface, including craters, boulders, etc.	Size, shape and structure, reconstruction of geological evolution, spacecraft guidance.	All
IR Spectrometer	IR spectra, surface temperature measurements	Prediction of mineralogical composition	All
UV Spectrometer	UV spectra	Prediction of mineralogical composition	All
Gamma-ray, X-ray spectrometer	High energy particle spectra, map abundances of specific elements	Atomic composition	All
Alpha particle spectrometer	Map Detect presence of radioactive gasses such as radon and polonium	Atomic composition, age determination	All
Neutron spectrometer	Map abundance of hydrogen atoms	Predict chance of airburt, possible propellant	Rendezvous
Magnetometer	Localized magnetic field vectors, estimate distribution of ferrous minerals	Estimate effects of blasts/impacts, determine feasibility of NEO mining	Rendezvous or lander
Electron reflectometer	Map magnetic field on surface	Ferrous composition of surface	Fly-by or rendezvous
LIDAR	Scan of reflected light beam, 3D map of surface	Choosing explosion/impactor locations	Rendezvous
Mass spectrometer	Ion mass spectra for localized atomic mass fractions	Estimate effects of blasts/impacts	Lander
Impactor	Map energy transfer during impact, seismic response of NEO, propagation of thermal wave through core	Better theories for impacts: fragmentation, heat transfer, energy transformations	All (multiple stations needed for seismic analysis
Seismograph	Seismic analylsis, map density and elasticity of core	Better prediction of deflection & destruction efforts	Lander with multiple stations
Drilling	Core samples, analyized with any of the above instruments	Better prediction of deflection & destruction efforts	Lander with specially developed micro-gravity drilling equipment
Sample Collector	Surface (or near to surface) samples, analyzed with any above instruments or returned to Earth	Better prediction of deflection & destruction efforts	Lander

would to be do extract sample by core drills or expose then by impactors. In some case, examining the ejecta from existing large impact craters would also give information about subsurface composition.

3.4 Selecting the appropriate response

In Chapter 2, a graph has been presented to determine an appropriate response according to the size of the NEO and the warning time. However, it is simple and does not take into account important parameters like the orbital parameters of the NEO or its composition and structure. Now let us go into more details and make a deeper analysis.

3.4.1 List of possible options

In order to mitigate the threat, many options may be considered using existing technologies[55]. The main ones, already presented in Chapter 2, are listed below:

1. Kinetic deflection: A massive spacecraft is sent to intercept the NEO. Since high velocities can be achieved, the resulting kinetic energy makes it possible to deflect it.

2. Nuclear deflection: Nuclear explosions triggered at a distance, on the surface or below provoke the ejection or rocks from the NEO, which in turn reacts by slowly moving in the opposite direction.

3. Nuclear destruction: In some cases, the explosion might cause the fragmentation or even the pulverisation of the NEO.

4. Mass driver: If the action time is significant, it is possible to land a device that would regularly eject some matter from the asteroid and therefore slowly deflect it from its original trajectory[78].

5. Billiards shot: This option consists of deflecting a small asteroid and put it on a collision course with the big threatening NEO.

Others ideas have been proposed like pushing the NEO using rocket engines, but the required amount of propellant that has to be sent in space is much too high with respect to the current launching capabilities.

3.4.2 Energy as a driving parameter

The appropriate strategy depends on the energy required to deflect or destroy the NEO, the timing and the technological constraints. As it is shown in Figure 3.3, the required energy is an important issue.

The first important observation is that typical chemical explosives like TriNitroToluene (TNT) are less efficient than kinetic impacts or nuclear explosives. It is the reason why this option has not been included in the list.

Ahrens and Harris have worked on the deflection of NEOs [30]. According to them, if the action time is in the order of 10 years, a few cm/s are needed to deflect the NEO. The corresponding energy is plotted in the same Figure for different values of the diameter. The second important observation is that even if it were possible to obtain 100% efficiency in the process of impacting the NEO with a massive spacecraft, the kinetic energy option is appropriate only for small NEOs (a few hundreds of meters in diameter at the maximum).

The nuclear option is the only one that can cope with the deflection of bigger objects. The graph suggests that the deflection would be easy. However, it is not possible to convert all the energy of the blast into kinetic energy for the NEO. Only a few percent (5% for surface blasts according to Solem [100]) would be effectively converted, the rest going to the heat, the compression and the ejection of rocks in all directions.

Solem performed simulations to determine the maximum energy of nuclear blasts that could be used to deflect the NEO without fragmenting it into several pieces[100]. His results have been added to Figure 3.3. He intentionally neglected several parameters and assumed that NEOs are aggregations of smaller parts linked by gravity. It is questionable whether his assumptions are valid. As a first approximation, however, it is interesting to observe that NEOs bigger than 1 km in diameter might be hardly destroyed by nuclear weapons. The composition and the structure of the NEO may nevertheless strongly change the limiting size for the destruction. Finally, according to Solem, for an asteroid measuring above 3 km in diameter, only deflection is a possible usable option. Between 3 and 3 1/2 km, he recommends to deflect it using a stand-off nuclear explosion

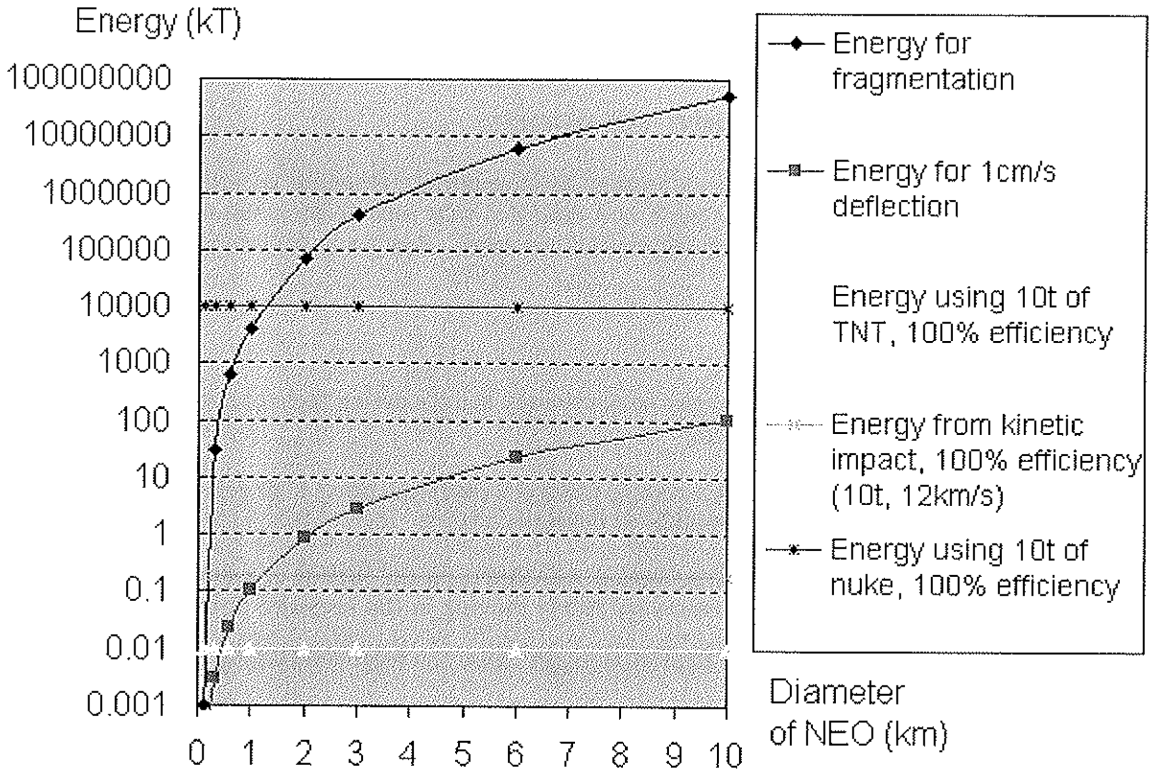

Figure 3.3: Energy is the main driver of the problem (1kT=4.18E12 J).

with detonation at a distance, to avoid any possible fragmentation. Under 0.5 km, the author recommends it be pulverised.

3.4.3 Deflection and destruction capabilities

Though several theoretical studies have been undertaken, there is a lack of experimentation. The numbers are therefore approximate and the determination of the best strategy is unsure. In order to classify the different options, we propose to define the concepts of deflectability, destructibility and pulverisation capability.

- Given the difference in velocity that is required to deflect the NEO from its collision course, a NEO is called deflectable if its composition, structure, size and shape allow a mean of deflection that does not break it into pieces. The composition means the chemical content while the structure is related to the existence of agglomerates.
- A NEO is called destructable if its composition, structure, size and shape allow a mean to break it into several pieces, which are most probably not on a collision course with Earth anymore.
- A pulverisation capability exists if a NEO is destructable and all the resulting parts are smaller than 10 m in width.

3.4.4 Classification of responses

The different options can be classified according to the deflection and destruction capabilities and to the action time. The result is presented in Figure 3.4. It is very similar to the classification presented in Chapter 2. However, since the warning time is not necessarily proportional to the action time, it is a misleading concept in the case of space-based responses. The action time, which depends on the warning time and the orbital period of the NEO is more appropriate for the classification. As it has been defined in the previous section, short action times are shorter than 5 years. Below this limit, it is assumed that the billiards shot option is not applicable. The following classes can be distinguished:

- *Short action time, pulverisation*: If the action time is very short (about 2 years) and the NEO is small a deflection process might break the object into dangerous pieces. Pulverisation is therefore preferred. The use of nuclear weapons is appropriate if the pulverisation capability exists. Most NEOs smaller than 300 m in diameter are concerned. If the composition is nickel-iron, the capability is reduced.

- *Short action time, deflectable*: Compact NEOs up to 10 km in diameter are concerned. If the kinetic deflection option is possible (NEOs typically smaller than 1km), it should be preferred to the nuclear option.

- *Short action time, not deflectable but destructable without pulverisation capability*: This situation occurs when the action time is too short for a deflection, while destruction is a possible option. The nature of the NEO might be important in this case. If the NEO is a rubble pile the deflection becomes more difficult, while the destruction is easier. A fracture in a relatively big NEO might also be advantageously exploited.

- *Short action time, not deflectable, not destructable*: Only partial destructions are possible if the NEO is big and the action time does not allow deflection. Earth-based mitigations have to be considered.

- *Long action time, deflectable*: When the action time is long, destructible NEOs are always deflectable. The latter option is preferred. If the NEO is not too big, typically less than 10 km in diameter, the kinetic deflection or the nuclear one are appropriate.

- *Long action time, not deflectable, comet*: The mass driver option is appropriate if 2 conditions are fulfilled: 1)The preparation time is greater than 2 years; 2)The action time is greater than 10 years (this number comes from the work of Melosh[78].

- *Long action time, not deflectable, not a comet*: Very big NEOs are concerned. Time permitting, the billiards shot option might be the only one to provide a huge amount of energy to deflect or destroy the NEO. If the NEO is larger than hundreds of kilometers in diameter, any space mission is probably useless.

3.5 Nuclear weapons

3.5.1 Options of nuclear blasts

There has been some debate to determine the most suitable way to use nuclear weapons. Ahren and Harris and later Solem defined three modes of engagement[56], [94]. The first one consists of an explosion by a standoff device at some distance from the object. The second mode of engagement is a collision on or very near the surface of the object. The third one is caused by a penetrator device, which buries the explosive at an optimum depth. The different methods are compared according to the efficiency of the energy transfer and the probability of breaking the celestial body into several pieces, which may still remain on a collision course with the Earth.

- *Stand-off device:* Though the kinetic energy transfer is not optimum, Solem shows that the fracture problem can be much mitigated. The neutron flux of the nuclear explosion would be efficient in the sense that a large amount of its energy will be captured by the first 20 centimeters of the surface. After the explosion, some highly ionised debris would blow-off a thin layer of the asteroid surface and the impulse will be spread over a large area.

- *Surface-burst device:* In that case, the blow-off fraction will be about 35 times greater than the previous one. The problem is that the explosion concentrates the energy in a small area. A crater is formed and fractures may occur. Another problem is to time the detonation with sufficient accuracy. Since the velocity of the interceptor is high and the exact position of the surface is approximate, it might be difficult to obtain a surface explosion, unless it is directly linked to the impact.

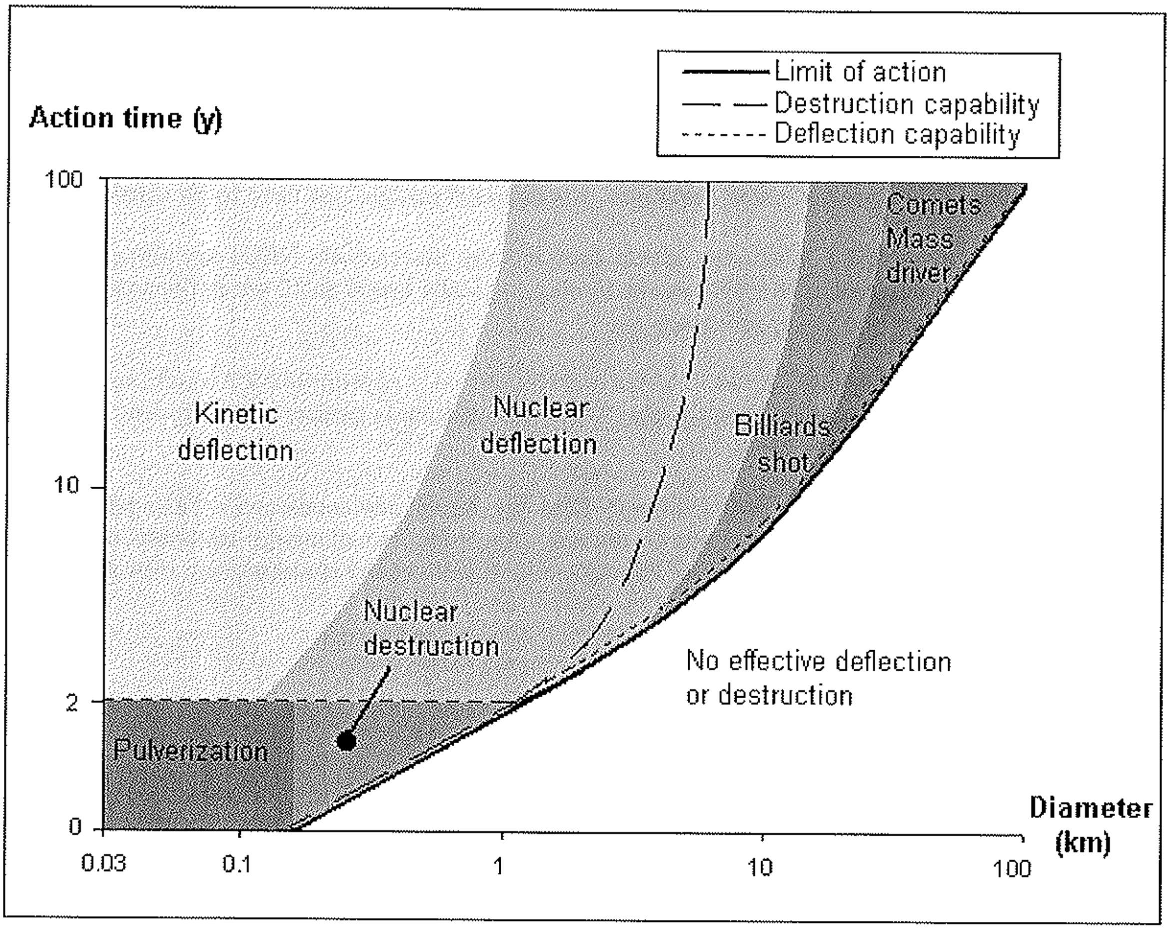

Figure 3.4: Classification of space responses according to the action time and the diameter of the NEO.

- *Penetrator device:* Though more energy is transferred to the object, analytic studies have shown that a deep explosion does not provide more deflection than a surface burst. Moreover, the protection of the explosive and its detonator is required while the interceptor is penetrating into the celestial body. In case of Nickel-Iron NEO, the penetration would be very difficult. This problem is discussed in the next section.

The preferred option is the first one because the probability of fragmentation is very low and it is important to avoid it. However, if the action time is short and the deflection capability is unsure, the destruction of the NEO is the best option (provided that it is destructible). In this case, a blast in close proximity to the surface is appropriate to maximise the energy transfer.

3.5.2 Deep penetration

The focus here is on the physical aspect of the penetration of the explosive into the asteroid. Chistov et al propose a nuclear explosive deep penetration method to maximise the energy transfer to the asteroid [42]. It is suggested that the use of kinetic-energy means instead of preliminary impacts to place a nuclear warhead a few meters below the surface. Numerical simulations to assess the feasibility of the method are presented. The results of this assessment show that the rocket can penetrate more than three meters into the asteroid without any observable disturbance of the conic section. Finally, if the interception is rather close to the Earth, the advantage of placing the nuclear charge below the surface is that the effects of the nuclear explosion on the atmosphere are lessened. This last point is important because there are many studies (for instance [108]) showing that a nuclear explosion in the magnetosphere will significantly alter the configuration of the Earth's atmosphere.

3.5.3 Legal issues

Using nuclear weapons for the deflection or destruction of an asteroid brings a lot of attention to the articles mentioned in both the Outer Space Treaty (OST)[?] and the Partial Test Ban Treaty (PTBT)[92].

As article IV of OST mentions not to place nuclear weapons into or around the Earth in any manner, the PTBT mentions that no test shall be undertaken for any type of nuclear explosions on territories of under control or jurisdiction of any of the parties.

An amending or a new resolution is therefore needed to allow the use of nuclear weapons for the exclusive deflection or destruction of an asteroid on a collision course with the Earth.

"Some time in the future, maybe 20 years, maybe 200 years, using nuclear explosions will become common, and it will be very hard to show people why we shied away from it," says Mr. Teller[105].

3.6 Destruction by billiards shot

3.6.1 Principles

The feasibility of the billiards shot option has been examined. The idea, illustrated in Figure 3.5, was first introduced in 1992 in a workshop dedicated to the interception of NEOs[37]:

Billiards shot: The orbit of a small NEO will be changed in this concept in order to achieve a collision with the (larger) NEO being on a collision course with Earth. This method would be capable to deflect even 10km-class NEOs. But this requires very accurate astrodynamical capability and the impacting NEO has to be available for this maneuver, i.e. we need a deflection system that provides enough ΔV for this.

In 1992, very few small NEOs were known. In fact, 99% of NEOs smaller than 200 m in diameter have been discovered during the last 5 years. The feasibility was therefore doubtful and no case-study has been performed. Since then, simulations have been done to assess the destructibility of a NEO [31]. The work of Solem can also be cited here, since it does not really matter what strikes the NEO[100]. The general concept is to provide energy and to examine the consequence for different types of NEOs.

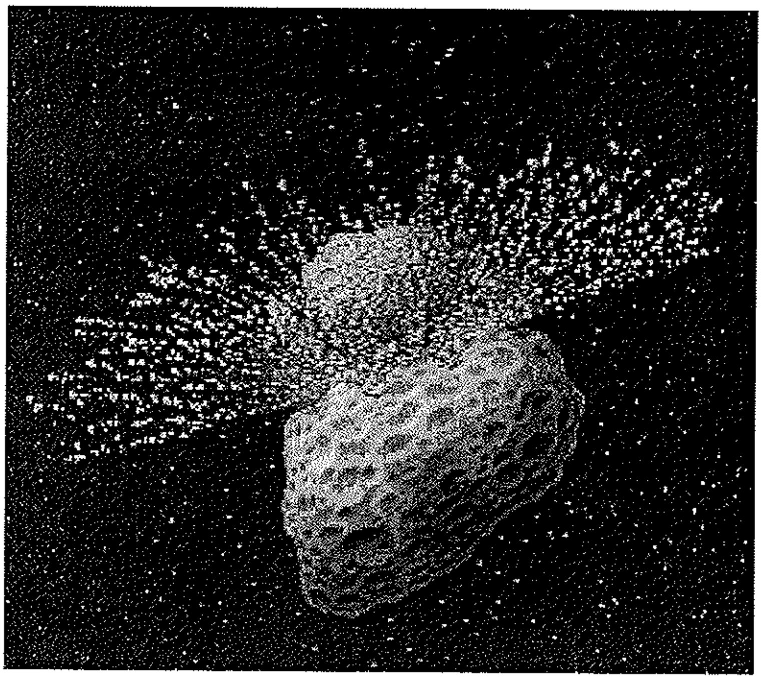

Figure 3.5: Illustration of the "billiards shot" strategy (Courtesy of SEDS, University of Arizona).

3.6.2 Assessing the feasibility

The impact between the striker and the target can be elastic or inelastic. In practice, the collision would probably be something in between and part of the kinetic energy would be transformed in heat and in velocity of ejected rocks. Let us consider both cases separately. In the following, m_1, v_1, and m_2, v_2 are, respectively, the mass and the velocity of the target and the striker before the collision and ΔV is the difference between the velocity of the target after and before the collision. In order to simplify the equations, a perfectly aligned collision is assumed.

Elastic collision:

In case of an elastic collision, the 2 bodies collide and then go away from each other. Provided that m_2 is much smaller than m_1, it can be easily demonstrated that ΔV is proportional to the ratio of the masses. The exact equation is given below.

$$\Delta V = \frac{2(m_2/m_1)(v_2 - v_1)}{(1 + m_2/m_1)}$$

This result is very important. Since v_2-v_1 is of the order of several km/s, it means that ΔV values as high as several m/s can be achieved. This is to be compared to nuclear blasts, which only provide some cm/s. For instance, as a first approximation, if the striker is 10 times smaller in diameter and if the impact theoretically occurs 100 days after deflection, the threatening body would be deflected by 8600 km (more than 1 radius of the Earth) and therefore miss the Earth.

Inelastic collision:

In case of an inelastic collision, the 2 bodies collide and remain together. A similar equation can be obtained to determine the difference of velocity after the collision. It is given below.

$$\Delta V = \frac{(m_2/m_1)(v_2 - v_1)}{(1 + m_2/m_1)}$$

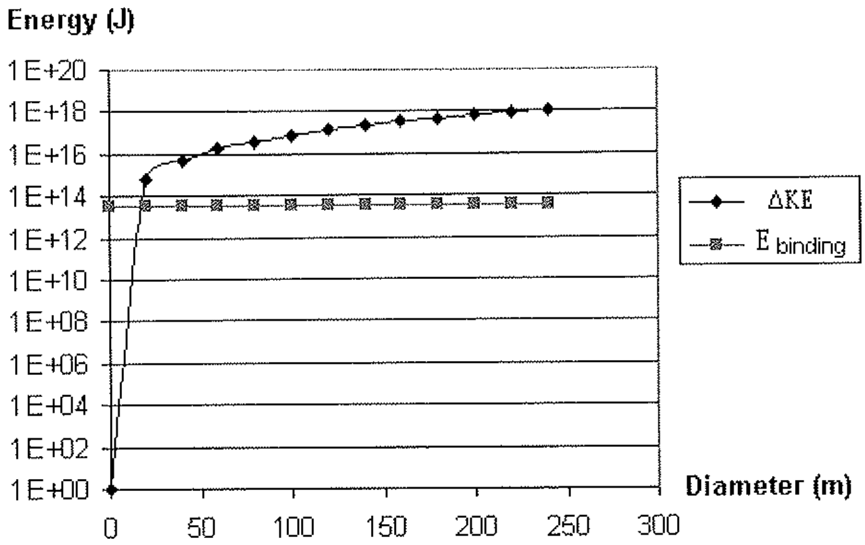

Figure 3.6: Comparison between the binding energy and the kinetic loss.

However, in this case, there is a reduction in the total kinetic energy after the collision. Of course, the total energy of the system must remain constant. This loss of kinetic energy is therefore converted into heat, compression and fragmentation. It is given by the following equation:

$$\Delta KE = (m_2/2)(v_2 - v_1)^2$$

An important problem has to be addressed. Is there any chance that the bigger asteroid is going to be destroyed? The previous equation can help to solve that problem. Let us assume that the main binding force is gravitational, hence electromagnetic binding forces are neglected: The body is considered to be a set of atoms that remain together only by means of the gravitational forces. Then as a first approximation, the energy required to pulverise the asteroid can be derived. The formula is given below, G being the gravitational constant and R the radius of the asteroid.

$$E_{binding} = \frac{G(m_1 + m_2)^2}{R}$$

Therefore, if the loss of kinetic energy is totally absorbed in the fragmentation process, the asteroid would be destroyed, or at least broken into several pieces if the following condition is fulfilled:

$$(m_2/2)(v_2 - v_1)^2 > \frac{G(m_1 + m_2)^2}{R}$$

Let us consider an example. Let us assume that the diameter of the target NEO is 2.5 km (the mass can be directly inferred by assuming a spherical shape and a typical density) and the difference between the velocities is of the order of 10 km/s. The two expressions can now be calculated for a range of masses of the striker NEO. The result is presented in Figure 3.6. As can be observed, the binding energy is low compared to the reduction of kinetic energy. It means that strikers as small as 10 m in diameter might destroy the big one if the collision is inelastic. If the collision is 90% more elastic than inelastic, the reduction of kinetic energy is ten times smaller but still well above the binding energy using strikers of similar size.

In conclusion, the billiards shot option seems feasible. The threatening NEO can be either deflected or destroyed by another smaller NEO, which can be more easily deflected. However, this option is possible only if an appropriate NEO is found for the strike. In addition, it is questionable whether current astrodynamical capabilities are sufficient to ensure the collision of the two NEOs.

3.7 Technological issues

In some cases, space missions might require new developments in terms of facilities, technologies, tests and simulations. Here is a list of possible issues:

- *New launcher*: The kinetic deflection option might be possible only if heavier spacecraft are available. Furthermore, a manned characterisation mission requires heavy payloads. Time permitted, a new launcher might therefore be built. 80 to 100 tons payload capability can easily be achieved after 3 to 5 years development. Low Earth orbit assembly is also possible to increase the total mass of the spacecraft up to 200 tons.

- *Nuclear thermal rockets*: The use of nuclear engines is actually considered by NASA for manned interplanetary missions. Such engines enable faster travels, which might be required if the accessibility of the NEO is difficult, for instance out of the ecliptic, or if the action time is directly linked to the travel time.

- *Repetitive launches*: Multiple launches might be required in a short time. Several launching facilities all over the world can be used, but this could not be sufficient. There is usually a delay of 1 to 2 weeks minimum before the next launch on the same launch pad. Decreasing this delay to a few days could be an issue. This need might occur if there is no time to build a new big launcher. Several launchers are therefore sent instead of one, but the number of spacecraft that can be sent in a short delay might be a critical problem. Another solution consists of building new launching facilities.

- *Experimental data to refine the models*: There are theories and tools for the simulation of impacts, nuclear blasts, crater formation and destruction of a celestial body but they are not accurate and uncertainties are high. In case of long warning time and uncertainty on the expected result, other NEO missions and real tests might help to refine the models.

- *Emergency system*: Emergency systems for warning time shorter than one year may have to be considered. Kryukov and Gribova propose a sophisticated system for anti-asteroid defense[72]. Their method is clearly appropriate for the complete destruction of 1km size and less objects, even if it is fractured into several pieces. The projectiles are sent into outer space with high velocity and the detonation is provoked by high-speed impacts on the surface of the NEO. This system would work if the NEO is not too far from the Earth, at a maximum distance of one million kilometers. Moreover, in order to be able to send the explosive charge in any direction of the sky, they propose to deploy the ballistic system on a moving platform in the ocean.

Specific developments are also required for the mass driver option. The concept is simple, but there is a lack of experimentation and the technologies have to be tested before being used.

3.8 Organisational and ethical issues

3.8.1 Ethics

One of the first ethical questions to be answered is, does society have the responsibility to prepare mitigation methods to address the NEO impact hazard? There would be some who would say we should let nature take its course. After all, if it were not for an asteroid hitting the Earth in the past we as humans probably would not be here today. The counter position would be to do all we can. We owe it to ourselves and following generations to be prepared to deal with this hazard. It is after all one of the few natural hazards we can conceivably do something about.

But what if our means of mitigation could not be totally successful. How interesting would be the situation if it was proposed that partial destruction was the only possible mitigation response. And, by performing this breakup of the object several countries would receive minor damage rather one country receiving major damage.

What about the whole nuclear question? Is it ethical to use nuclear means for mitigation. If it is the only device available, in a time of crisis it would be hard to argue against its use. As we have seen the deaths from even a small asteroid can be very large. Refer to Table 3.3. The argument of the lesser evil might be used to justify their use. At least it would be using a horrible weapon for a good purpose.

Table 3.3: Estimate of death toll from various types of impact. Adapted from [87]

Asteroid Diameter (m)	Area devastated (sq km)	Annual chance for inhabited regions 1 in ...	Equivalent annual death toll	"Typical" Direct Fatalities	Total fatalities (million)
50	1900	900	1100	200 000	1
100	7200	8000	400	650 000	3
200	29 000	30 000	500	2 000 000	14
500	70 000	180 000	200	4 000 000	35
1 km	200 000	290 000	200	7 000 000	63
2 km	-	1 000 000	1500	-	1500

"By far the biggest disadvantage to nuclear detonations is the political and social ramifications of developing such a large, accurately targetable, highly reliable nuclear weapon. This might infringe on several treaties, and a launch failure could cause extreme amounts of destruction." [53] The prevention of miss-use should be agreed to before work begins.

3.8.2 Organisational issues

In the case of a real NEO threat, the response should be undertaken under the framework of UN: "Governments often respond quickly to crisis but are less well suited to remaining prepared for extended periods."[81]. It would be hoped that in such a time of international crisis the Nations of the World would work together to tackle the problem and overcome all the difficulties.

Until now, decision making and money investment regarding a NEO threat has been deferred since most NEO researchers believe that in all likelihood there will be sufficient warning time before impact to develop an interception system if it is needed. The limited amount of funding that can be raised for NEO mitigation in no threat time is the main driver for adopting this policy: "From the standpoint of allocation of society's resources, an uncertain threat calls for adaptive policies, delaying potentially costly action but informing later decision by investing in uncertainty-reduction measures. In the context of the NEO impact hazard, this means avoiding the costs of standing organisational structures and capital expenditures until a threat materialises, while continuing modest support for surveys and inexpensive studies of mitigation options." [81]

Nevertheless, often delaying things in the short term results in things being more costly in the long run. Thus considering the possibility of a short-term threat it would be essential to raise some prior efforts in managerial matters: "In an organisational sense, planning for adaptivity entails establishing a chain of responsibility prior to the materialisation of an emergency - that is, a shadow institution." [81]. Furthermore, some prior investments in preliminary tests could bring down substantially the price of the response: "An adaptive planning approach could also accommodate the short warning scenario associated with long-period comets, requiring that a relatively low-cost generic interception system be built and tested, then shelved." [81]

3.9 Concluding remarks

This work gave a new depth of coverage to the wide range of response issues, better focusing further work on NEO response planning at an international and interdisciplinary level. Also, it could be considered as a first draft of the International response handbook, which would be the first point of reference for an international organisation tasked with coordinating response if a threatening NEO is ever discovered.

The key points to remember are the followings:

- Characterisation mission is important to ensure the success of the deflection or the destruction mission.
- Deflection is suggested when there is enough time (several years) to prepare the interceptors.

- Destruction is more appropriate when the detected asteroid or comet is already very close to the Earth or if the deflection mission fails.
- The direct impact of a massive spacecraft can deflect a NEO, provided that it is small enough and the action time is long.
- Nuclear weapons have to be used if the NEO is big.
- The billiards shot option is theoretically feasible but probably very difficult in practice.
- An important issue is to improve our knowledge on NEOs by performing real tests using different interceptions strategies.
- Technological, legal, and organisational issues have to be considered as soon as possible, preferably before the threat is identified.

Chapter 4

Earth Based Responses

4.1 Introduction

4.1.1 Overview

The purpose of this chapter is to study the scenario in which it would be impossible to destroy or deflect the threatening NEO. As has been described in Chapter 2 and specifically in figure 2.1 this could happen due to different reasons. A space interception mission could be made impossible if the warning time were too short or if the size of the NEO were too big. Even if a space mission were attempted, there would always be the possibility of total or partial failure.

Once the likelihood of impact of a NEO with a particular region of the Earth is established, the most obvious step is to plan the evacuation of the population from that zone. Currently there are very few procedures for coping with this problem, and none at an international level. The UN ISDR [107], is yet to recognise the NEO threat, although it has procedures to deal with large scale disasters on an international level. Furthermore there no internationally agreed link between the NEO detection community who would give the warning of an impact and these disaster response authorities. Thus, the time delay between confirmation of a detection and the decision makers in government being aware of the threat is probably of the order of days or weeks.

The construction of shelters to protect the population is a last resource that would have to be attempted in these cases. Even in the other cases, in which a space mission is the main response option, a shelter plan would still certainly be developed as a contingency plan.

4.1.2 Cases considered

The management of the international response would depend heavily on the size of the impact, as would the purpose, technology and size of the shelter network. Thus, a distinction has been made between long term and short term issues. Looking at the Table 4.1 it can be seen that, depending on the size of the object (and other parameters) the effect on the Earth's biosphere would be very different.

The first part (short term) refers to the case in which the effects of the impact would not last for a long period of time. For NEOs smaller than two kilometers the consequences would mainly be restricted to certain areas and the dangers that would require sheltering (the impact itself and the consequent earthquakes, hurricanes, tsunamis, debris fallout and mud flows) would only be present for a few weeks. It is for these reasons that the complexity of the shelters in this case would not be very high and their main objective would be to protect the entire population of a certain region for a short period of time. Referring to figure 2.1, this would be the correct approach both in the case of small NEOs or fragments of broken bigger NEOs. A parallel effort in this scenario would be to relocate the population from the most endangered areas so the technical, political and economic considerations of such a complex population migration are also considered.

The second part (long term) refers to the worst possible case, an impact of a NEO 10 km in size or larger, for which the consequences of the impact would be devastating on a global scale. Apart from the effects mentioned before, the ozone layer would be destroyed, the atmosphere might stop being breathable, there would be a global greenhouse effect for centuries, and photosynthesis would be interrupted for many years, leading to massive animal and plant extinctions like the K/T boundary event. In this scenario the shelters

Table 4.1: Global effects of a NEO impact. (Adapted from [102] and [106])

Asteroid Diameter	1 km	2 km	5 km	10 km
Kinetic Energy (millions of megatons of TNT)	0.1	1	10	100
Average impact interval (years)	200,000	500,000	10 million	100 million
Crater Diameter - rim to rim	24 km	46 km	100 km	200 km
Dust and debris fallout cover the ground and cause severe mudflows. (Months)	300 km	400 km	1100 km	4000 km
Area for firestorm ignition due to radiation from ballistic re-entry of ejecta (within hours)	Local	Local (600 km radius)	Regional (5000 km radius)	Global
Earthquakes, hurricanes and tsunami (hours to months)	Regional	Regional	Global	Global
Dark skies and cooling from dust, soot and oxides of sulfur	Regional freezing for weeks. Moderate global effects for weeks	Skies darker than darkest cloud cover. Global drop of 8C for weeks then moderate global effects for months (no summer)	Severe global effects, day becomes night for months.	Very severe global effects. Day becomes night for months. Freezing conditions away from coastlines.
Acid Rain, pyrotoxins (poisons from fires) and heavy metals.	Regional for months	Regional for months	Global for months	Global for years
Ozone destruction (hazard from UV radiation)	Partial global destruction for years	Severe global destruction for years	Total global destruction for years	Total global destruction for decades Global
Greenhouse heating from water and CO2	Negligible	Minor for years	Moderate for decades	Major for centuries
Plant growth and extinctions.	Disrupted for months. Some global crop failures.	Disrupted for years. Some regional extinction. Global crops failures.	Photosynthesis stops for months. Decades for plants to recover. Major regional extinctions.	Hundreds of years. Global mass extinctions

Table 4.2: Estimate of the risk of an inhabited region being within an area of direct devastation (Adapted from: [87].)

Asteroid Diameter (m)	Annual Probability	Average Interval (Years)	Chance in 50 years 1 in ...
50	1.1E-3	900	18
100	1.3E-4	8000	160
200	3.4E-5	30 000	600
500	5.6E-6	180 000	3600
1000	3.4E-6	290 000	5800
All	1.3E-3	800	16

might have to be inhabited for decades before the Earth's surface becomes habitable again. Their technological and organisational requirements are certainly very different than in the prior case and require almost fully self-sustainable independent habitats.

As can be imagined, the ethical, social, cultural and psychological implications of an event of this magnitude are overwhelming so the issue of providing psychological support for large populations was also considered. Finally, a section is dedicated to the technology developments that would come from the shelter building efforts. As will be seen, many of the aspects of shelter building (life support systems, for example) have important applications in space and non space fields.

4.2 Short term scenario

4.2.1 Effects

This section tries to identify the adequate response actions involved with the impact of a small NEO (smaller than 1 km wide). In this case, the consequences involved would not include the sheltering of the population for a long period of time, but just the evacuation of the most endangered areas and the protection in shelters for two weeks at the most. The effects of such an impact would mostly affect less than a 300km radius (see figure 4.1). This area may have little of no population, indeed nobody was killed during the Tungunska Event [5]. But if the asteroid strikes a big city, it could affect an area which may contain hundreds of million of people. If the impact destroyed one or larger cities in developed countries, there would be an inevitable global economic depression and efforts to integrate refugees may be hampered by the weak economic environment. International financial assistance by the IMF [18]would be needed may take different forms including immediate support in assessing the disaster's impact and in developing a recovery strategy. Thus, it is recommended that the IMF be part of any new international body tasked with the issue of responding to NEO disasters.

A main objective of the any NEO disaster planning would be to protect the population from the post-impact effects such as dust and debris projected in the atmosphere and the regional earthquakes and fires. The different strategies for this scenario depend, among other things, on the warning time given before the impact. The focus here is set on short warning times, which would preclude any preventive measures other than evacuation and emergency shelter building. This combination of a short warning time and a short period of shelter habitation makes the use of existing facilities (such as nuclear shelters, for example) possible and recommended. Among these, one must make the distinction between private and public shelters.

4.2.2 Relocation and evacuation issues

Table 4.2 shows that there is a significant annual risk of one of the world's inhabited regions being within the area of impact devastation. This suggests that the creation of emergency response plans to deal with evacuation for imminent NEO impacts should be implemented, and a communication link between the NEO detection community and the world's disaster response agencies is needed.

The specific procedure should be based on the probability of an impact happening, the magnitude of the impact, the duration until the impact and its location. An impact of any scale is bound to do more damage near ground zero, or along the coast of the body of water that is impacted, than elsewhere, so evacuation (and other localised mitigation steps, if there is time) can always help. Near ground zero, and elsewhere steps could be taken similar to precautions taken to mitigate the disaster effects of table 4.1. For example, in earthquake zones the the integrity of structures should be enhanced. In forested areas the susceptibility to fire should be lessened by backburning, and unimportant infrastructure assets should be protected from electromagnetic pulses that can damage electrical equipment.

In general, the evacuated zone should be quite larger than the expected damage zone, taking into account the uncertainty of exact impact location. Furthermore, the warning time might not be the real time lapse between NEO discovery and impact date. Indeed, even if a deflection or destruction project were to be carried out, its partial failure could require evacuation. The warning time would be, in this case, shorter than the time between the NEO threat identification and the NEO impact.

Of course, relocation should also be planned together with a shelter programs. The total evacuation of an area may not be possible when the warning time is short, some of the local people would prefer to stay in the affected zone, or there the NEOs may be expected to fragment over a wide area.

If one or more large cities need to be relocated, there would certainly be cultural/societal stresses in the areas taking many refuges. Relocating the refugees far enough away to keep their population below an acceptable level in host communities may be impossible in some regions of the world, which are poor and have a poorly developed road network. If cross-border migration is needed, countries with strong anti-refugee policies would not be able to control the influx and would be forced to accept extra people. On the other hand, large countries could house the relocated people entirely within their own borders, unless the NEO impacts on the highest density cities. Great care should be taken to avoid disease spreading.

4.2.3 Types of shelters

Public shelters

In the event the we are considering (relatively small impact with a short warning time), it would not be necessary to develop many new infrastructures, as it would be possible to rely instead on the reorganisation or reprioritisation of existing facilities such as schools, sports complexes and existing underground shelters including atomic bomb shelters and storm shelters. Schools and sports complexes are already planned for use in several countries for contingency purposes (e.g. France). If they are not damaged, schools can be very useful in these situations, since they can be used for shelters and/or as headquarters because they are generally close to high-density areas and since they have many integrated facilities. Main governmental infrastructures can be used as well if modified since they are generally located in the centre of the social life in towns and cities. Military bases, as well as police and fire stations, could also be used . One should also consider the use of the existing nuclear shelters for the elites, such as State Mount Weather, in Virginia (USA), which is a virtual underground city [68].

Deciding how to divide the population amongst all the shelters could easily be done according to the repartition of the children in the schools in order to keep families together. At a higher level, the distribution of the population could be done at the city level. Each city would then have the responsibility to host all their citisens.

Depending on the area, another alternative approach is to use natural or existing man-made structures such as caves, mines and underground subway tunnels. Mines and caves represent a good potential source of large scale emergency shelters. In Switzerland, for instance, there is a tunnel system with blast doors, ventilation, emergency power generation, sanitary stored beds and supplies. In the United States, the Bureau of Mines compiled an underground mines inventory which identifies approximately 35 million individual shelter spaces that could be created in U.S. mines. It is estimated that 2 to 3 million spaces could be created in tunnels, 4 million spaces in caves, and a potential for up to 100 million spaces in mines (60-70 million in limestone mines, 20-30 million in salt mines, and 5 million spaces in gypsum and sandstone mines.) [76]. This type of underground shelters have the advantage of withstanding atmospheric and surface hazards fairly well. They would be fairly immune to blast effects, falling debris, and fire storms, but would experience sizeable earthquake activity after impact. This could result in cave-ins, so these facilities should have the necessary equipment to be able to dig or blast the blocked entry. Another problem is that many poisonous gases are heavier than air, and may gravitate to underground structures. Also since they may be open structures, they may not be immune to the effects of flooding or tsunamis.

Private shelters

Earth sheltered residences or underground homes have the potential of becoming acceptable shelters that will survive the blast effects of a NEO impact. These homes may require some modifications, but would provide good protection against radiation, blast and heat. Some of these modifications would include : conventional reinforced concrete, concrete blocks, steel reinforced concrete domes and barrel vaults, metal culvert, used fuel tanks, pre-made fibreglass and wood framed shelters [60]. The most important consideration when building this type of shelter is which envelope system or structural shell is the best suited to the special case of interest.

Planning for future shelter needs could be done by passing a new set of laws that would require individuals to build their new houses with new imposed standards of construction. Each house would need an isolated room with access to water, an emergency kit with medicines and a survival guide and some of the modifications just described. In this way it would be possible to have private shelters within individual houses. This mandatory implementation of construction standards would need to be supported by a legal framework that would require old houses to make some adjustments, preferably with some governmental financial support. This framework would also apply to public and communitarian buildings with dedicated rooms in the basements and places adapted to host the residents.

The main problem when considering the construction of private shelters, though, is that there would most likely be a lack of tools, materials, space, determination, physical strength or time. Most unprepared urban citisens would have to use basement and other shelters in existing structures. In any case, it would have to be guaranteed that every shelter has the necessary strength, adequate ventilation, cooling, food and hygiene. A very simple and inexpensive option would be to use fuel steel tank shelters [60]. They are easy to purchase, they can provide electromagnetic pulse shielding and can be made watertight in areas where a light water table exists. Their main problems are their confined space and shape distortion. Another option is to use pre-made fibreglasses, which have the advantage of coming completely internally outfitted from the factory with all life support systems (air filtration, water storage, entry way, sewage system, power....)[60]. They can be used where high water level exists. The problem is that these structures are expensive, confined in space and not useful for communitary applications. They have a minimum personal privacy and only one entrance.

The most effective type of private shelters would be well-equipped basement shelters. There would be a possibility to use an existing structure by using the family room, recreation room or storage room as the shelter. The advantage would be that it is close and easy to get inside and all necessary supplies are there at short notice. This type of shelter can also provide protection from thermal effect. But the main problem for basement shelters is that there is no blast protection if the house collapses due to overpressure and destroys the shelter. A solution could be the use of a subterranean exit leading away from the house to avoid getting trapped. However, whenever underground solutions are considered one must take into account the risk of carbon monoxide poisoning.

4.2.4 Shelter building and preparation for the impact.

Once the NEO impact threat is identified and recognised, the following steps and considerations should be followed to make an adequate preparation both for the building of shelters and the evacuation of the population.

Selection of shelter site.

The shelter site should meet the following requirements [76]:

- It should be above water table.
- The soil should not be water saturated.
- It should be in a clearing away from tree roots.
- Ideally, the site should be on granular soil such as sand and gravel (no clay, peat and silt).
- The site should be easily excavated to a depth of 2.5 m. (Large boulders, limestone, solid rock formations could make excavation very difficult).

- Availability of water
- Good drainage
- Big depth of bedrock
- Easy access
- Earthquake resistant

Stockpiling

The chances of surviving a NEO impact would be improved by stocking the following low-cost supplies before a serious crisis: Water containers, compact, non perishable food (milk powder, vegetable oil, sugar), disinfectant water, sanitation containers, medicines (any special medications needed by family members, first aid kit and a tube ointment), light (long burning candles sufficient for several nights, expedient lamp, flashlight, extra batteries) and a transistor radio with extra batteries.

In a general global context, it would also be an imperative task to make worldwide stockpiles of non-perishable food and medicine. During many years preceding the impact, world economic should be oriented toward production, not only for refugees, but also for the international community who would have to face drastic changes in production due to economic and political chaos and long-term climatic changes. After the impact, the international community would have to face a globally drastic decrease of primary resource if the NEO were large or the impacted zone were highly productive. Economic crashes would probably occur. This means that there should be international cooperation and agreement on aid and supply provisioning. The international community should create international laws and rules to facilitate the management during such global crisis with effective means of enforcing laws (such as international armed forces or drastic economic penalties). All governments would have to face political chaos and drastic changes even if the affected zones were not highly populated, rich or with high agricultural production.

Protection against fires and carbon monoxide

Fires and their consequences would be a major danger resulting from a NEO impact on the Earth. Heat radiation would set fire to easily ignitable materials (dry newspapers, thin dark fabrics, dry leaves and grass) in about the same extensive areas over which the blast would cause moderate damage to frame houses. The blast wave and high-speed blast winds would blow out many flames. The number of fires started by heat radiation in areas where the blast is not so severe could be reduced by whitewashing the insides of windowpanes and by removing flammable materials from places in and around houses where heat radiation could reach them. Also, occupants of shelters in some homes only slightly damaged by the blast could move quickly to extinguish small fires and throw out smoldering upholstered articles before the depositing of fallout. Unless forests or brushy areas are dry, it would be difficult to start even scattered fires. Dangerous mass fires would be unlikely except in blast areas where the heat radiation would be very intense. However, people building a shelter would do well to select a site at least as far away from trees as the height of the tallest tree that could fall. If an undamaged building is burning, people inside might be killed by carbon monoxide, toxic smoke, or fiery-hot air.

Light

Numerous disasters have proved that many people can remain calm for several days in total darkness. However, some panic reactions are to be expected in the case of long confinement in a blocked dark shelter.

Even in communities outside areas of blast, fire, or fallout, electric lights dependent on the public power system probably would fail. The destruction of power stations and transmission lines would knock out most of the public power. Flashlights and candles along with matches in a waterproof container could provide minimum light for more than a very few days. Lit candles and other fires should be placed near the shelter opening through which air is leaving the shelter, to avoid buildup of slight amounts of carbon monoxide and other noxious gases. Gasoline and kerosene lamps should not be taken inside a shelter, as they produce gases that can cause headaches or even death. If such lamps are knocked over (by blast winds rushing into shelters over extensive areas, from example) the results would be disastrous.