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CAN HUMANITY SURVIVE TO A GIANT COMET IMPACT?

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Abstract

It is well known that giant long period comets originating from the Oort's cloud could be the most threatening celestial bodies. The warning time could indeed be very short, five years, and the kinetic energy could be sufficient for global and durable effects on Earth, killing all life forms on the surface. Humans might nevertheless be able to survive decades in underground shelters. Based on a model used to determine the minimum number of people to survive on another planet, a classification of long terms shelters is proposed, taking all needs into consideration and also the double redundancy principle. Accumulation shelters corresponds to shelters with lots of resources but a weak autonomy, and therefore a well-established limited lifetime around thirty years. Borderline shelters correspond to long term shelters with strong autonomous capacities but little margins and high risks of collapse due to misconceptions, underestimations and insufficient testing. Complete shelters correspond to ideal shelters with double redundancy for every system and also for the working capacity. Thanks to a high resilience, they could last decades, eventually saving humanity from extinction. The limits of the shelters are discussed, as well as uncertainties. Given the short warning time, it is impossible to test any shelter, and, as a consequence to avoid errors in the design of a complete shelter. The risk is indeed high that some problems are underestimated and a slow but unstoppable degradation of life conditions would lead to the death of the survivals, whatever the preparation and motivation of the survivals.

1. Introduction

In a recent paper, it was shown that the risk of extinction of humanity due to the impact of a giant comet was of the order of 10^{-6} for the next 100 million years, or 10^{-12} for the next hundred years [23,30]. The Oort cloud is indeed a reservoir of very large comets, many of them with a diameter larger than 100 km, and the instability of their orbits is such that it is relatively common for one of them to approach the inner solar system, and, potentially, be on a collision course with the Earth [3,7,8,9,16, 21, 24, 39, 40]. It is important to note that giant asteroids do not pose as great a threat to the end of humanity, because when they are large, they are quickly spotted and it is possible to predict their approach to the Earth several centuries in advance [5,10,12]. At the present time, none of those that have been recorded are on a collision course. If such a threat were nevertheless to occur in the future, even if it is considered impossible to deviate the asteroid given the inertia of such a massive object [12,13,20,22,31], there would certainly be several decades or even centuries left to attempt the establishment of permanent bases on the Moon and Mars (if this has not already been done), thus avoiding the total annihilation of humanity and terrestrial life in general [6,15,29,33,42]. Giant long-period comets, on the other hand, are detected very late, typically only when they approach the Neptune orbit, about five years before a potential impact [12,13,22]. Such a delay is far too short to attempt to colonize another planet. In this case, the only solution would be to try to survive for a very long period on Earth in underground shelters [1,2,28,30,32]. This is precisely the initial context of the study presented here. The fundamental question is to know if it is possible to survive, and if so,

under what conditions. To better understand the issues and difficulties, we propose to classify the shelters according to a survivability criterion, based on a model presented in a previous study [29]. Section 2 is dedicated to the presentation of the survival context. The survival model is recalled in section 3, as well as the proposed classification of shelters. The lifespan of the shelters is estimated and discussed in section 4 and limitations and approximations of our approach are discussed in the conclusion.

2. Context of survival

Let us assume that a very large comet, at least 100 km in diameter, is about to impact the Earth and that there are only a few years to build underground shelters. The expected impact is much more energetic than the one that killed the dinosaurs 6 million years ago [11,13]. As suggested by several studies, it is assumed that the Earth would become unlivable [18,19, 32, 34, 36]. The immediate effects of a giant impact would be terrific: Giant crater, air blast, earthquakes, tsunamis, etc. However, these effects would be relatively local and if the question is the extinction of humanity, there would be many places on Earth where the immediate effects would not cause the immediate death of life forms. Nevertheless, following these early effects, there would be an astronomical amount of very hot ejecta that would spread all over the Earth, causing fires everywhere, even in the regions opposite the impact. Large regions of the Earth would thus be sterilized, but, once again, there would exist some places on Earth where these events had no or little effects, and where many life forms would survive. But other global effects would follow. All around the globe, temperatures would start to raise and reach at least 100 degrees Celsius, which, in this case, would definitely kill all life forms living on the surface, or very close to the surface, of the Earth. Above 100 degrees, lakes and oceans would start boiling. The atmosphere would be totally occluded for years, and then after a period that could last several decades, a slow and steady cooling would take place, leading to an interminable winter [19]. The threshold of 100 degrees being exceeded, the risk is consequently a complete sterilization and thus the annihilation of all the terrestrial animal and vegetable species, even microscopic, except for some which would be buried deeply or which would live in the depths of the oceans. Humanity would not escape this rule. However, since humanity has reached a high level of technology, with great capacities of adaptation, it is possible to build underground shelters far deep under the surface and to install life support systems to control the temperature, the pressure and the composition of the air, to grow plants allowing to produce food, to install energy systems, industrial systems, habitats, and all that is finally necessary for the long-term survival. Technically, the solutions exist. Given the complexity of such shelters and the short time available before impact, a practical and appropriate implementation of these solutions would certainly raise important issues and only small human groups could benefit. This raises also the problem of selection and the number of people who could access them.

Finally, it is not clear how much time has to be spent into the shelters before coming back to the surface. It depends on the energy of the impact which are not fully understood. It is assumed here that the main parameter for survival on the surface (after the first stage in the shelter) is the duration of the impact winter. During that period, which could last decades, an enormous amount of dust and clouds would remain in the atmosphere, blocking the radiations from the Sun, thus preventing any plant growth as well as any use of solar energy systems. The atmosphere might eventually be breathable but without light, food and energy, living outside would probably be as difficult as living in the shelter. At the end of the impact winter, when the sunlight comes back, even if it is very cold, it is possible to grow plants in greenhouses and to use the sun as primary energy source. An important parameter of the survival problem is therefore the length of the period from the impact event to the end of the impact winter. In the following, that period is called the critical period (CP).

3. Long term shelters

3.1 Survival model

We propose to use a model that has been proposed for the determination of the minimum number of people for survival in complete autonomy on another planet [29]. This model is based on an exhaustive list of technical requirements and the counting of the hours of work necessary for all the activities considered essential for survival. These activities are classified in 5 areas (see Figure 1):

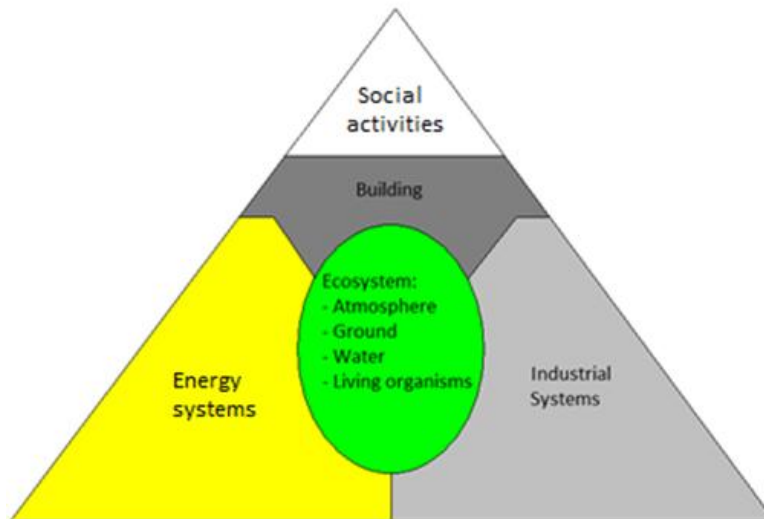


Figure 1. For survival, 5 important domains are highlighted.

d1: Ecosystem management: We refer here to the main activities concerned by designing and maintaining systems for the production of appropriate gases, controlling air composition, pressure and temperature in habitable modules, collecting, and recycling water, controlling life cycles of all living organisms, processing organic wastes, growing plants for agriculture and finally producing and storing food.

d2: Energy production: Many processes depend on the amount of energy that would be available. Important activities are therefore linked to energy production, which includes construction and maintenance of energy systems, whatever their nature, based on electricity, heat, fuels, batteries, etc.

d3: Industry: For long term survival, it is essential to be able to produce new objects in order to repair or replace what has been broken or what has reached end of life. We refer here to the needs of implementing industrial processes, especially in the metallurgy and chemistry domain, for instance extracting, collecting and processing appropriate ores, making construction materials, manufacturing objects, and producing tools for other activities (e.g., agriculture). Industry may also be concerned in the production of glass, ceramics and plastics, as well as clothes and medicine depending on the strategic choices for survival.

d4: Building domain: The shelter will have to be designed and organized for good living conditions and optimization of the work. All activities linked to the architecture, organization (or reorganization), maintenance and construction of rooms, walls, corridors, doors, storage zone, etc. are included here.

d5: Social activities: For survival of the group, it is important to raise children and to educate them. Other fundamental human activities concern health care, organizing the work, solving unexpected problems, and making decisions. Sport, culture and entertainment activities also have to be considered to make sure that the group does not collapse due to psychological trauma.

The model is based on the concept of « sharing factor ». It is defined as follows: Given a time requirement per individual A_1 to accomplish an activity for the needs of 1 individual and A_n the time requirement per individual to accomplish the same activity for the needs of n individuals, the sharing factor $S(A, n)$ is mathematically defined by:

$$S(A,n) = A_1 / A_n \quad (1)$$

For instance, if one hammer can be shared by 5 individuals, then there is no need to build more than 1 hammer as long as the number of individuals is between 1 and 5. As a consequence, the time spent per individual to build and maintain hammers is 5 times less for 5 individuals than for one individual. A single person can indeed be assigned to the maintenance of that tool, while the others can do something else. For $n=5$ individuals, the sharing factor is therefore five. For greater values of n , the sharing factor might be more important. For instance, 8 hammers could be sufficient for 100 persons. If this is the case, for $n=100$, the sharing factor would be 12.5. The sharing factor is linked to productivity gains and the sharing of tools and resources as the number of persons increases. Once the sharing factor is known for all activities, it is possible to check if the total time available for working is sufficient to implement these activities. As proposed in [29], equation (2) can be used to check if the required individual annual working time is less than the available individual working time. If not, it means that the group of people is too small to implement all required activities for survival in the shelter. Equation (2) can therefore be used to determine the minimum number of people to run the shelter.

$$\sum_{i=1}^{k_1} \frac{r(a_{1,i})}{s(a_{1,i},n)} + \sum_{i=1}^{k_2} \frac{r(a_{2,i})}{s(a_{2,i},n)} + \sum_{i=1}^{k_3} \frac{r(a_{3,i})}{s(a_{3,i},n)} + \sum_{i=1}^{k_4} \frac{r(a_{4,i})}{s(a_{4,i},n)} + \sum_{i=1}^{k_5} \frac{r(a_{5,i})}{s(a_{5,i},n)} < 2740 \text{ h} \quad (2)$$

Where:

- $r(a_{j,i})$ is the individual annual working time requirement to run activity i in domain d_j .
- $s(a_{j,i}, n)$ is the sharing factor for activity $a_{j,i}$ with n the number of individuals
- k_1 to k_5 are the number of activities for domains d_1 to d_5 .
- 2740 h: available annual working time, taking nights and non-productive people into account (derived from [29]).

3.2 Classification of shelters

Based on the previous model, it is possible to make a classification of shelters. If it is not too long, a possible and viable option would be to store lots of resources and to rely on them for survival, knowing in advance that the lifespan of the shelter would be limited. This is what we call accumulation shelters. For example, it is possible to avoid agricultural production if there is sufficient dehydrated or frozen food. When the CP is over, the colony would have to come back to the surface and agriculture would have to be started straight away in order to produce the necessary food. Such a strategy would be relatively easy to implement, but the success would strongly depend on the evolution of environmental conditions on the surface of Earth. If a long-term autonomy of the shelter is required, this kind of shelter would be inappropriate.

If the shelter is designed for the long-term survival of the group, that is if it is possible to implement all activities required for survival and if equation (2) holds, it does not mean that survival is ensured, because there are many possible reasons for a collapse, see Figure 2 for possible causal chains:

- A possible reason for the collapse is insufficient energy production. As previously explained, there are many processes that depend on the production of huge amounts of energy, for instance the production of oxygen using water electrolysis, or artificial lighting for greenhouses. As there is no solar energy underground, a nuclear power plant could be essential to supply enough energy. However, there would be many technical problems to solve, for instance cooling down the reactor and hot water streams without overheating all the shelter.
- Another reason could be the lack of appropriate resources or tools to implement important industrial processes. For instance, for artificial lighting, huge amounts of LEDs would be required, especially for growing plants. As LEDs have a limited lifetime, the production of new LEDs is essential, but the resources and tools to produce them might not be easily found.
- Obviously, if there is not enough human resources to perform all the work that is required for a long term sustainable survival, the collapse of the shelter is also unavoidable.

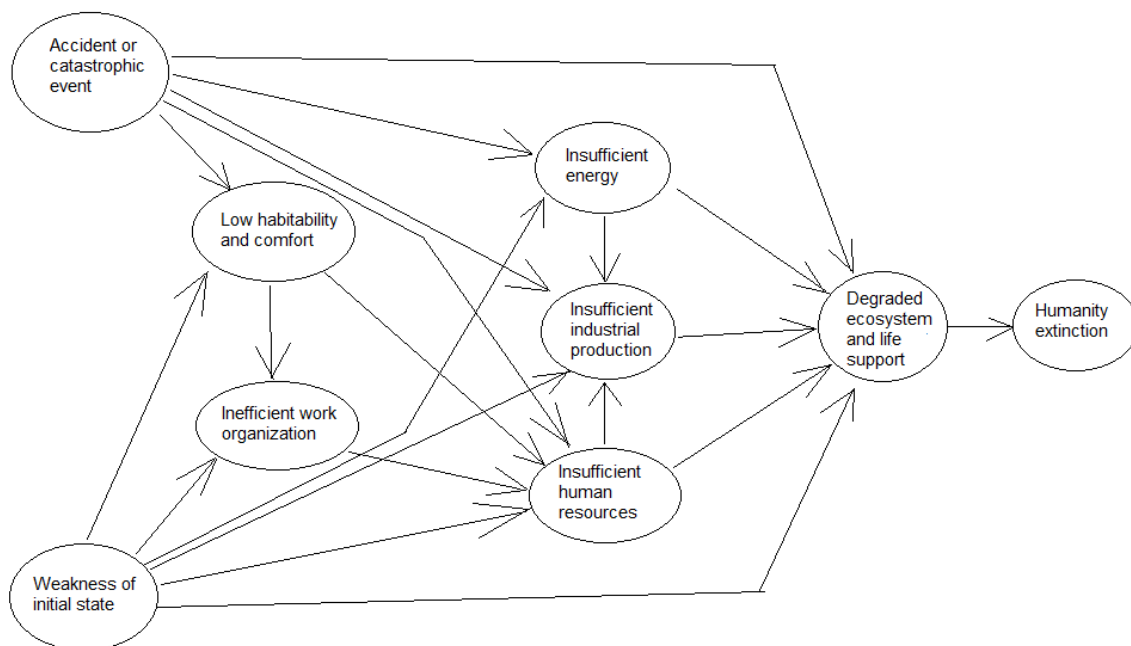


Figure 2. Causal chain of humanity extinction. Many factors could lead more or less directly to a degraded state of the life support systems inside the shelters and finally to the extinction of humanity.

- Importantly, the three previous reasons do not imply an immediate collapse. They only imply a slow but ineluctable degradation of life support inside the shelter, and, finally, the death of all humans.
- Other reasons are more “high level” and linked to human factors. A low habitability and comfort would increase the stress, the fatigue and therefore the efficiency of the workers. The organization of the work could also be an issue, as some people could complain about the workload, the working conditions and want to adapt or change their activity, which might impact the cohesion and efficiency of the group.

- There are also two reasons linked to the context of the shelter: The first is a possible catastrophic event, which might be caused by human errors, human madness, or by unexpected natural disasters. The second is a possible weakness of the initial state, if specific resources were accessible in limited amounts from the start, if the needs were underestimated, if some expertise was missing, or, for example, if there are too many people for a rather small shelter.

Even if the main causes are identified, the probability of failure is difficult to estimate. It is proposed here to distinguish between two categories of shelters depending on risks estimates. In complex domains such as aviation or astronautics, in order to reduce the risks, all systems are tripled (double redundancy). The same approach can be taken here. Once the needs are determined, the systems shall be designed so as to be able to produce 3 times these needs. Furthermore, the systems also are resources of the shelter. Therefore, the industry shall be designed in order to be able to build or repair three times more systems than the minimum required. In addition to a greater resilience to unexpected accidents and breakdowns, the redundancy principle also has the advantage of providing margins in case of errors in the estimation of the needs. As long-term survival is based on complex lifecycles of numerous complex systems, determining the exact list of objects and resources for the initial state is an issue, especially if there is a limited time for testing. By doing so, we can further split the shelters into two categories:

- Borderline shelters may allow long-term survival, but do not respect the double redundancy principle, or it was not possible to determine the exact needs, which would probably be the case if the warning time is less than five years. As a consequence, such shelters would inevitably present a high risk of failure.
- Complete shelters have all the necessary and appropriate parts enabling long-term survival. They must respect the double redundancy principle. Even in that case, long-term survival is not sure, but an important resilience exists. If an important failure occurs for an important system, as there is redundancy, there is no immediate threat to survival. In addition, another backup system exists that allows time to repair or adapt to the situation without being frightened by the loss of the first backup system. Importantly, such shelters must have been tested to make sure that the needs have been correctly determined.

4. Shelters lifespans

4.1 Accumulation shelters

Accumulation shelters are based on accumulation of resources. Though the amount of resources would be enormous, this kind of shelter could certainly be built in five years, which is the warning time. This period would be rather short but as humanity would concentrate on this objective, with all industrial and human resources, this constraint does not seem unsurmountable. The maximum lifespan depends on the amount of resources and also on the ability to maintain their exploitability. The most critical resources are food, water, air and energy. Water stored in bottles may be conserved two years. However, even after that period, it is possible to boil it and drink it without health issues. There is therefore no limit of usage. Dry or frozen food can also be stored a very long time. For instance, a study from Kondo et al suggests that rice was eatable 30 years after storage in a environment [17]. Though the food might lose some of its nutritive properties (especially vitamins), it could probably be exploited after several decades of storage, especially if it is frozen at low pressure. In order to keep the atmosphere breathable, it is necessary to store oxygen, and also to remove carbon dioxide and any harmful contaminants. To this end, as performed in the International Space Station, the air can be controlled and cleaned using pumps and

appropriate filters, which can be replaced on demand, provided that a large number has been stored. Concerning energy, for an underground shelter, the best option is probably a nuclear reactor that could provide electricity to all systems. However, there are important issues to exploit such a system underground. The main one is the evacuation of the heat and the control of temperatures. If the surface of the Earth becomes very hot, it might be easier to transfer that heat into the ground, using for instance huge water reservoirs (which would be required anyway for water needs) as well as pipes and pumps for heat dissipation. Most nuclear power plants have an initial operating lifetime of approximately 30 years [25]. After that period, important revisions and maintenance operations have to be carried out to extend their use and it is not clear what spare parts have to be stored. All in all, provided that no important errors have been made for the storage of the huge amount of resources, systems, spare parts and tools (including drugs, objects for hygiene, clothes, etc.), in first order estimation, thirty years seems to be the maximum lifespan of this kind of shelter. After that period, it would be imperative to reach the surface. Survival would be possible only if the CP has ended.

Though accumulation shelters have a limited lifespan, the most important advantage is to simplify the management of systems and the needs for experts in different fields. As there are nevertheless complex systems such as nuclear power plants, the minimum number of people could be relatively low, on the order of one hundred [29]. The maximum could also be very easily to calculate, based on the amount of critical resources such as food or life support elements.

4.2 Borderline shelters

As there are numerous complex systems (life support systems, energy systems, industrial systems, human systems), it is very difficult to estimate the lifespan of borderline shelters. An interesting strategy would be to accumulate many resources as for accumulation shelters and to add many other tools and resources to be able to recycle as much as possible, to repair the defected parts and to survive longer. Similarly, this kind of shelter could be built in five years. However, such a short period suggest that many approximations will be made and numerous misconceptions or underestimations will certainly be observed due to the lack of time for testing and understanding the exact needs. At some point, some resources might therefore become insufficient and the degradation of the shelter would be observed, slowly but surely, according to one or several causes suggested Figure 2, until the end of its habitability. As accumulation shelters have a lifetime of approximately 30 years, borderline shelters would last longer, perhaps on the order of 100 years, but not much longer.

In order to run the numerous complex systems of the shelter, it would be important to determine the required skills and to predict the turnover in all domains, considering the education of children and caring for the elderly. This problem has already been addressed in a previous study [29]. The minimum number for a Mars settlement was only 110, but it is far too less in this case for several reasons: First, the volume of the shelter cannot be easily extended, which prevents any development. Second, the use of a nuclear power plant has an important impact on the complexity of the shelter, and therefore on the number of people assigned to the energy domain. And third, the double redundancy principle was not considered in [29]. As a consequence, thousands of people would certainly be needed to run such shelters, with important constraints on the pyramid of age and skills.

4.3 Complete shelters

Complete shelters are similar in conception to borderline shelters. Theoretically, however, this kind of shelter could last forever. It should have been tested before to determine with highest precision all the necessary resources and all the chemical and industrial processes that would be implemented to achieve self-sufficiency and resilience. Testing means long period of times or at least accelerated aging. Another important issue is to determine the required skills and the appropriate organization in terms of work, health, family, education, justice, etc. As accumulation shelters have a lifespan of three decades, a good understanding of the problems probably requires the same period of time for testing the resilience. Once again, the probability of survival would never be 1, but it could be greater than the probability of failure and, provided that CP is not infinite, humans would have an opportunity to settle the surface of the Earth once again.

4.4 Survival probability

The survival probability can be modelled using different mathematical functions. For illustration, it is proposed here to use the Weibull law, which is often used for the survival of living organisms [41].

$$P(t) = e^{-(t/\gamma)^k} \quad (3)$$

See Figure 3 for illustration. The fitting parameters γ and k have been set empirically in order to obtain approximately a probability of 0.5 for the average lifespan and a probability of 0.9 for the period with reasonable trust. The average lifespan is 30 years for accumulation shelters with a trust period of 20 years. The average lifespan is 100 years for borderline shelters with only 70 years for the trust period (high uncertainties). It is more than 400 years for complete shelters as they are supposed to be reliable for extended periods of time.

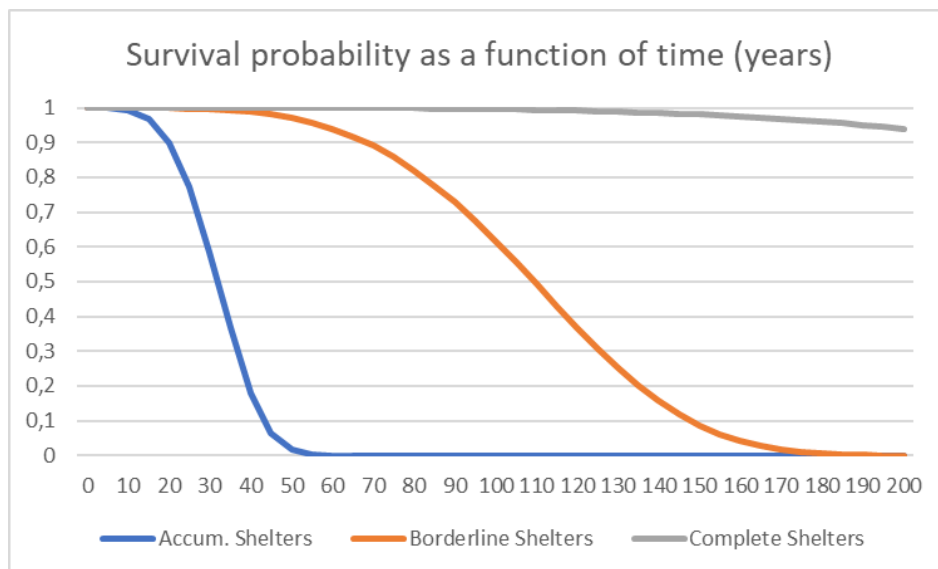


Figure 3. Illustration of the survival probability using different categories of shelters. The following parameters have been used for the Weibull function: ($k=4$; $\lambda=35$) for accumulation shelters, ($k=4$; $\lambda=120$) for borderline shelters and ($k=4$; $\lambda=400$) for complete shelters.

5. Conclusion

A method has been proposed to determine the category of shelter and its resilience for long-term survival. The triple redundancy principle allows some margins and suggests that survival of humanity after the impact of a giant comet could be possible with a Complete Shelter. For the production of energy, a nuclear power plant might be the solution, but it would be very difficult to build such a plant in the very limited time before the impact. It would probably also be required to add industrial systems to produce iron, glass, plastics, etc., but as the size of the shelter would be rather limited, so would be the amount of available resources. Recycling resources could be a solution, but it could be very difficult to determine in advance the recycling rate and the processes that have to be implemented. In other words, it might be almost impossible to determine the exact specifications of a Complete Shelter, especially given the short time available before impact, without time for tests and simulations. Within such constraints, only accumulation shelters (based on accumulation of resources) or borderline shelters (unperfect complete shelters) could be built. In addition, the requirements of such shelters could be unpractical, for instance if calculations suggest the excavation of several cubic kilometers of rocks and the construction of a huge underground city for a group of one million people. Complementary studies are required to better understand the limitations and provide a better estimate of the risk of extinction [4,35,38]. A possible approach is to consider the causal links presented Figure 2 as the causal links of a Bayesian tree and to try to estimate conditional probabilities.

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