Digital Currency Design for Sustainable Active Debris Removal in Space

Kenji Saito, Shinji Hatta, and Toshiya Hanada

***Abstract*— Orbital debris (OD) remains as an obstacle to further space development. While efforts are ongoing to avoid newly launched objects becoming debris, the number of debris would still continue to grow because of collisions. Active debris removal (ADR) is an effective measure, but building a sustainable economic model for ADR remains as a difficult problem. We propose that the cost of removal can be paid by circulating digital currency tokens on a blockchain platform whose values may decrease and/or increase over time, issued by global cooperation (a consortium) of parties interested in space development, in exchange with proofs of ADR. The tokens pay their cost by themselves through contributions by the token holders, who are likely to be benefited by removal of debris. This scheme imposes virtually no cost to the consortium. We have generalized this concept as proof of disposal, which, we believe, provides a more accountable foundation for solving social problems with digital currency than many Initial Coin or Cryptoasset Offering in practice today. We evaluated the feasibility of our proposal through a simulation. We conclude that dynamic estimation of the economic values of each ADR and automated pricing of tokens that represent the OD being removed are indeed possible. Actual prototyping of the proposed digital currency system is ongoing.**

***Index Terms*— Blockchain, cryptocurrency, digital currency, environmental remediation, orbital debris (OD), social problem.**

I. Introduction

ORBITAL debris is a threat to active spacecraft and satellites. Efforts are ongoing to ensure that newly launched objects will be properly disposed from their orbits after their missions post mission disposal. However, the number of debris would still continue to grow even under ideal conditions of no new launches, no debris release, or no explosions, because of collisions among existing orbital objects including debris themselves. Therefore, for further development of space, it is mandatory for us to conduct active debris removal (ADR). However, building a sustainable economic model for ADR remains as a difficult problem.

We see that a possible solution may be to design an economic medium, learning from history.

Local currencies issued by local governments have been experimented in the past, in order to make use of underutilized resources in the region, especially in times of depression. Well-known cases include experiments in Wörgl, Austria, in 1932, which made use of "stamp scrip" as a form of money whose value depreciates, which helped the local government to invest on public works at virtually no cost. This design may be a hint for us to implement works of public interest with limited budget.

The first author of this paper has extensively worked on possibilities of implementing and utilizing such currencies as digital media that can be used on the Internet.

Fig. 1 shows the effects of depreciating (reduction over time) currency tokens [1]. While it helps to reduce the debt of the token issuer, a game theoretic analysis showed that depreciating currency is likely to accelerate people's spending. Being digital, such media can easily be reversed to obtain opposite effects. Fig. 2 shows the effects of amplifying (multiplication over time) currency tokens [2]. An analysis showed that this type of currency decelerates people's spending. Applications of such currencies have also been studied, for example, for postcatastrophic disaster recovery [3].

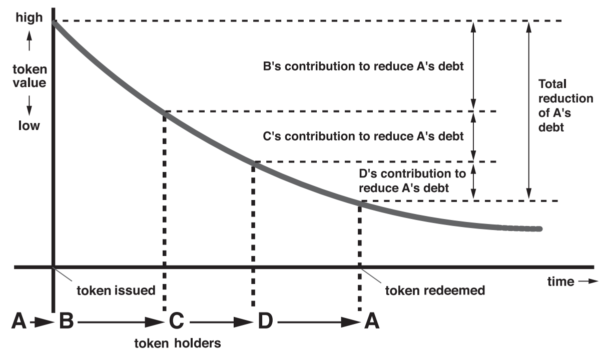

Fig. 1. Reduction over time and its effects.

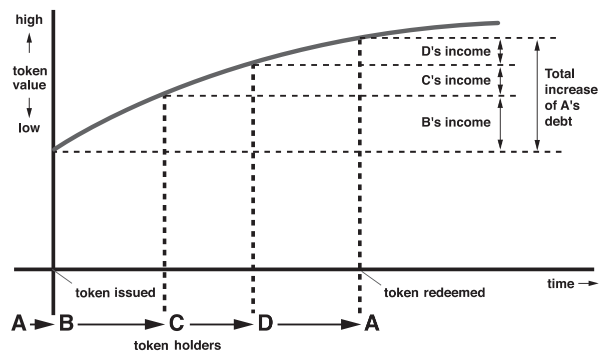

Fig. 2. Multiplication over time and its effects.

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Unfortunately, these ideas have not received wide acceptance. However, situations are changing.

Bitcoin [4] is now well-known and an accepted digital currency. Another example is Ethereum [5], under development and experimented widely, which make use of "blockchain," the record-keeping foundation first developed for Bitcoin, as a platform of executing "smart contracts" as distributed applications. A blockchain, or a distributed ledger, is like a "promise-fixation device in the air" that keeps records of promises, which can withstand partial failures and *churns*. It can be used for implementing an unstoppable monetary system because money is essentially a promise that its recipient can also use it as money.

This paper proposes to utilize a new digital currency with planned depreciation to build a sustainable economic model for ADR. Then, we will generalize this concept as proof of disposal (POD), which, we believe, provides a more accountable foundation for solving social problems with digital currency than many Initial Coin or Cryptoasset Offering (ICO) in practice today.

Remaining of this paper is organized as follows. Section II gives the background information on orbital debris (OD) and ADR. Section III shows the design of a digital currency that promotes ADR by imposing its cost to users of the monetary tokens. Section IV evaluates the feasibility of the proposed design of the currency by simulating issuance of tokens based on the real estimations of collisions among orbital objects. Section V discusses the potential societal influences and other applications of the same design. Finally, Section VI gives conclusive remarks.

II. Orbital Debris and ADR

The instability of the OD population in low Earth orbit (LEO, the region below 2000-km altitude), the "Kessler Syndrome," was predicted by Kessler and Cour-Palais more than 30 years ago [6]. Recent modeling studies of the OD population in LEO suggested that the current environment had already reached the level of instability. Mitigation measures commonly adopted by the international space community, including those of the Interagency Space Debris Coordination Committee (IADC) and the United Nations, may be insufficient to stop the future population growth. In response to this new finding, an official IADC modeling study was conducted in 2008 to assess the stability of the current environment. Study participants were Agenzia Spaziale Italiana (ASI), British National Space Center [now U.K. Space Agency (UKSA)], European Space Agency (ESA), Japan Aerospace Exploration Agency (JAXA), and National Aeronautics and Space Administration (NASA). The goal was to investigate the stability of the current environment using the 1 January 2006 population as the initial condition. The 200-year future projection adopted a "best case" scenario where no new launches and no explosion beyond January 1, 2006 were allowed. At the conclusion, a follow-up study based on an updated environment (including fragments from Fengyun-1C, Cosmos 2251, and Iridium 33), a more realistic future lunch traffic cycle, and postmission disposal implementation, was recommended. Finally, the IADC designated the follow-up study as an official action item (AI) 27.1 because of its potential significance. The objective of AI 27.1 was to investigate the stability of the future environment and reach a consensus on the need to use ADR to stabilize the future environment. Participants included ASI, ESA, Indian Space Research Organization (ISRO), JAXA, NASA, and UKSA. Details of AI 27.1, its outcomes, and recommendations are summarized in [7].

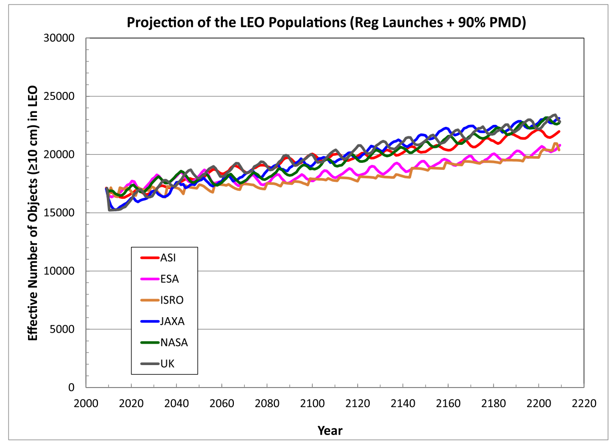


Fig. 3. Effective numbers of objects 10 cm and larger in LEO predicted by the six different models. All models assumed no future explosion and 90% compliance of the commonly adopted mitigation measures.

In order to constrain the many degrees of freedom within IA 27.1, some reasonable assumptions were made. First, it was assumed that future launch traffic could be represented by the repetition of the 2001–2009 traffic cycle. Second, the commonly adopted mitigation measures were assumed to be well-implemented. In particular, a compliance of 90% with the postmission disposal "25 year" rule for payloads (i.e., spacecraft, S/C) and upper stages (i.e., rocket bodies, R/Bs) and a complete passivation (i.e., no future explosions) were also assumed. However, collision avoidance maneuvers were not allowed, as in the previous study. In addition, an 8-year operational lifetime for payloads launched after May 1, 2009 was uniformly adopted.

Each participating member agency was asked to use its official, or best, models for solar flux prediction, orbit propagation, and collision probability calculation for AI 27.1. Collision probability calculations were limited to 10 cm and larger objects. The NASA Standard Breakup Model [8] was used by all participants for their future projections, as it was determined that participants did not employ any other fragmentation model. The participants were encouraged to conduct as many Monte Carlo (MC) simulations as time and resources allowed to achieve better statistical results. Finally, IA 27.1 conclusions were drawn primarily from the average results of each participating model, determined through MC simulations.

Fig. 3 summarizes the projections of the OD population in LEO through the year 2209, assuming no future explosion and a 90% compliance of the commonly adopted mitigation measures, from the six models. All models predict a future population growth. The average increase is 30% in 200 years.

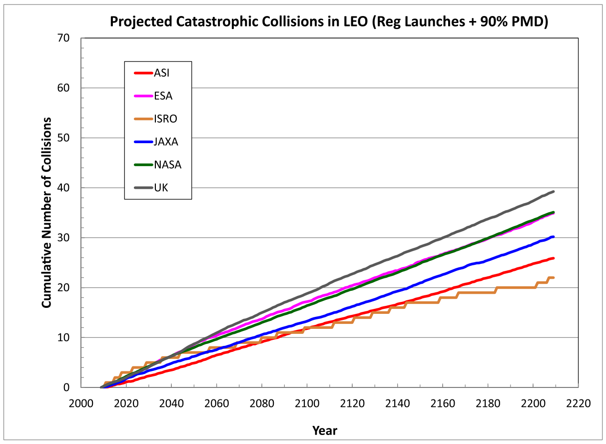
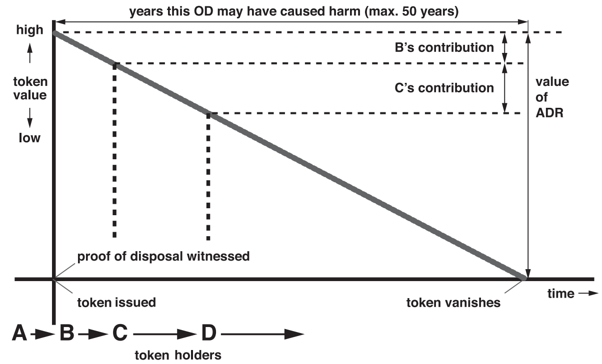


Fig. 4. Cumulative numbers of catastrophic collisions predicted by the six models.



- The issuer A is the consortium. The first token holder B is a remover.
- Depreciation in reality can be stepwise, such as yearly or monthly.

Fig. 5. ADR currency.

The short-term fluctuation, occurring on a timescale of approximately 11 years, is due to the solar flux cycle.

Fig. 4 summarizes the cumulative number of catastrophic collisions happened within the 200-year projection period. Catastrophic collisions, such as the one between Iridium 33 and Cosmos 2251 in 2009, result in the complete fragmentation of the objects involved and generate a significant amount of debris. They are the main driver for future population growth. The steepest curve (UKSA) represents a catastrophic collision frequency of one event every 5 years, whereas the shallowest curve (ISRO) represents a frequency of one event every 9 years. Catastrophic collisions happened primarily at altitudes of 700–800 km, 900–1000 km.

The outcomes of AI 27.1 confirm the instability of the current OD population in LEO. They also highlight two key elements for the long-term sustainability of outer space activities. First, compliance of the mitigation measures, such as the 25-year rule, is the first defense against the future population growth. The need for a full compliance must be emphasized. The 90% compliance assumption made in the simulations is certainly higher than the current reality. If the international space community cannot reach this level soon, future population growth will be far worse than the outcomes of AI 27.1, and it will certainly make future environment stabilization much more difficult. Second, to stabilize the future environment, more aggressive measures, such as ADR, must be considered. Remediation of the environment after more than 50 years of space activities is complex, difficult, and will likely require a tremendous amount of resources and international cooperation. The international community should initiate an effort to investigate the benefits of environmental remediation, explore various options, and support the development of the most cost-effective technologies in preparation for actions to better preserve outer space for future generations.

III. Design of Digital Currency for ADR

A. Overview of the Design

We propose that the cost of ADR can be paid by circulating digital currency tokens that depreciate over time, issued by global cooperation (a consortium) of parties interested in space development, in exchange with proofs of ADR. We call the body of cooperation *the consortium* hereafter. We call a party that conducts ADR *a remover*. We call the monetary system we propose *the ADR currency*.

Fig. 5 shows the overview of the design of the ADR currency.

B. Initial Token Value

Since the catalog of all observed OD is available, we can calculate the risk of collisions. The consortium defines how the risk is calculated, representing the international space community. Probability of accidental collisions is calculated according to the defined function, and then the collision flux is translated into a monetary value. All calculations are conducted and published on the same blockchain platform on which the ADR currency circulates, in order for all stakeholders to be able to verify that these are correctly done.

In the translation, for example, the total cost of space development for the past 60 years can be used. The monetary value can be divided proportionally to the probabilities of collisions, which is iteratively reevaluated as ADR proceeds.

The initial token value is decided by the consortium according to the following steps.

1) For each OD, the consortium periodically publishes the probability of collisions and the estimated token value with its depreciation schedule (the estimation expires after a certain duration of time).
2) A remover conducts an ADR (for the time being, a complete removal is assumed for the sake of discussion), to which the consortium issues a token.
3) For each OD, the consortium recalculates the probability of collisions.

C. Depreciation

An ADR currency token depreciates as Fig. 5 shows.

We would like to accelerate removal and decelerate the space development while the number of debris is growing. Originally upon conceiving the idea of the ADR currency, we thought that the value of the tokens may be set to increase at first, to the extent allowed by the consortium, and when the number of debris stops growing, the token starts depreciating, thereby accelerating the industry.

However, the span for achieving the nongrowth appears to be too long, such as 100∼200 years. Therefore, we have abandoned the idea of accelerating removal and decelerating spending by increasing the token values for the ADR currency (this idea is illustrated in Section V-D for another application).

Instead, the tokens shall depreciate down to zero[1] value over the duration of time the OD is estimated to cause harm, limited by, for example, 50 years.

D. Incentive Compatibility

For a given OD, the higher its probability of collisions is, the higher is the initial token value would be when the ADR is performed. The longer the duration of time the OD would cause harm, the more slowly the corresponding token would depreciate. As a result, a remover would want to aim for removing an OD with higher probability of collusions that would stay for a longer time. The incentive provided by the currency design is compatible with our intention to make future space development safer and easier.

The tokens pay their cost by themselves through contributions by the token holders, who are likely to be benefited by the removal of the OD. This scheme imposes virtually no cost to the consortium.

IV. Feasibility

Evaluation of the effects of the proposed currency design will involve how the industry and market react to this design, which is not objectively estimated.[2] Instead, we evaluate the feasibility of the currency system by simulating issuance of tokens using the actual catalog data and orbital projections.

For the matter of discussion, we chose 3866 intact objects in LEO, i.e., uncrushed objects such as rocket upper fuselage or satellite platforms, from the catalog data as of April 1, 2017. The objects include operational satellites, as we cannot distinguish between unused objects and ones in use, unless the intentions are confirmed.

We divide space into (10/3)-km cubes and locate each object in a cube at a given time. Then, we examine whether each object has any neighbors in the cube they are located or in any of the adjacent cubes (this means that we consider a 10-km cube for each object). If such a neighbor is found, the collision flux is calculated according to the relative velocity of the objects. We iterate this procedure with a 1-day interval for 50 years in our simulated time to estimate the accumulated collision flux, or risk of collisions, for each object.

Fig. 6 shows the initial distribution of accumulated collision flux.

We consider series of ADRs where an object with the highest accumulated collision flux is removed from the orbit at a time. We approximate the effects of an ADR by removing the corresponding item from the same catalog data and recalculating the fluxes.

[1]If we decide that the token value does not go down to zero, it will have to be redeemed by the consortium when the minimum value is reached. When this happens, the consortium will have to pay the value to the final holder of the token.

[2]Effects of depreciating/amplifying currencies have been evaluated in depth by simulations with some assumed human behaviors in [9], for example.

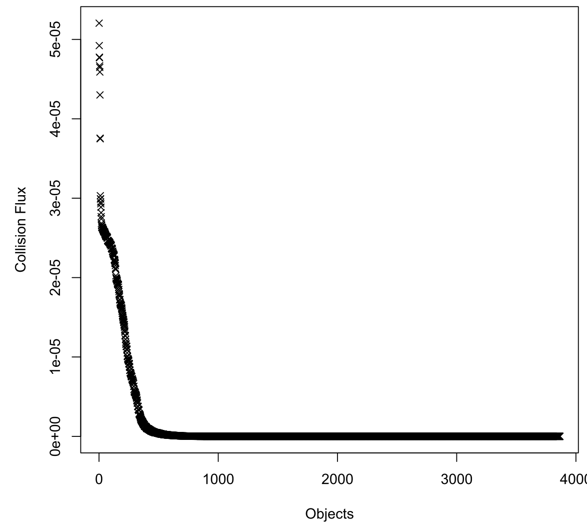


Fig. 6. Initial distribution of accumulated collision flux.

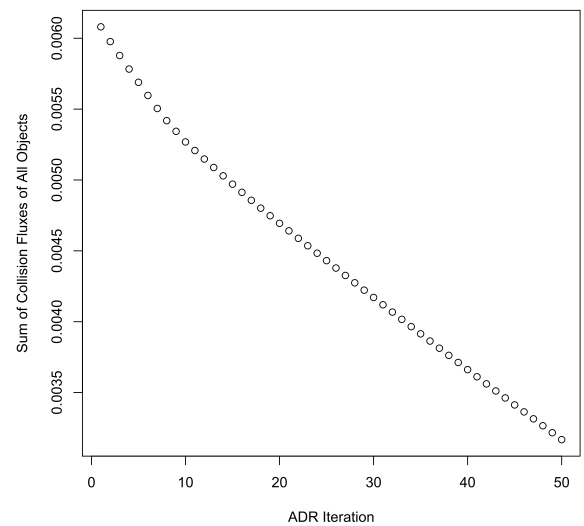


Fig. 7. Total collision fluxes.

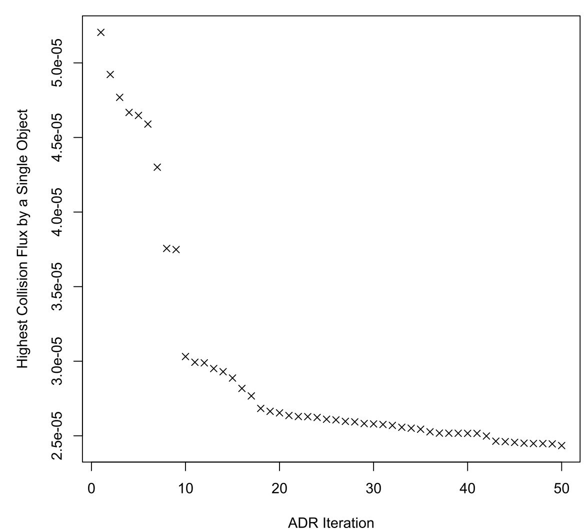


Fig. 8. Single object collision fluxes.

Fig. 7 shows the changes of the sum of collision fluxes of all objects, and Fig. 8 shows the highest collision flux by a single object (i.e., the flux of the removed object), over 50 iterations

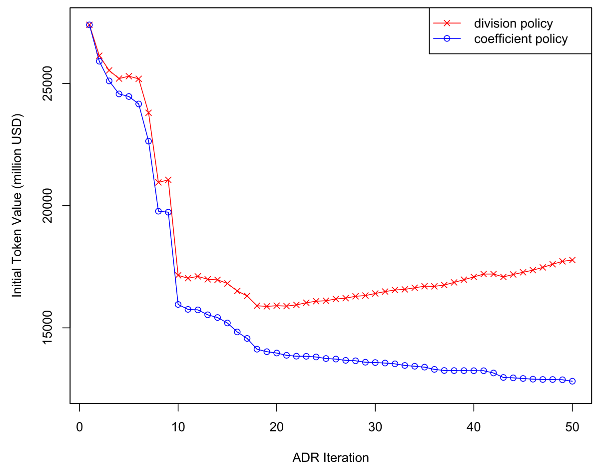


Fig. 9. Highest initial token values.

of ADRs as described earlier. We see monotonous decreases in both values.

For each orbital object, we assign an initial token value proportionally to its accumulated collision flux. To do so, we set the initial virtual budget of 3.2 trillion U.S. dollar, referring to our estimation of the total cost of space development for the past 60 years, which is the debt the space industry and the surrounding communities should be willing to repay over many years by taking the depreciating tokens as payments. For the first iteration of ADRs, we divide the budget proportionally to the accumulated collision flux of each object, and assign the value as the initial value of the token representing the object.

We consider two different policies for pricing for later iterations.

1) *Division Policy:* We subtract the initial token value of the removed object from the budget and recalculate in the same way. Over time, the sum of initial token values of removed objects will never exceed the initial virtual budget.
2) *Coefficient Policy:* We obtain the coefficient of translating the collision flux into a token value from the first iteration, and use the coefficient for later iterations. Over time, the sum of initial token values of removed objects may exceed the initial virtual budget.

Fig. 9 shows the highest initial token values (i.e., the token values of removed objects) for the first 50 iterations of ADRs, calculated in these two different policies. Note that in this paper, these tokens are valued for demonstration and prototyping purposes only, and the resulted token values do not necessarily suggest how much each ADR should be valued in reality.

With *division policy*, we see that the highest initial token value may increase as contribution rate of the collision flux of the removed object against the whole may increase overtime. With *coefficient policy*, on the other hand, the price monotonously decreases, as long as the highest collision flux keeps decreasing. For incentive reasons, monotonous decrease of highest initial token values is preferred, because it would not motivate removers to wait.

However, we should note that this simulation assumes no collisions happening (thus assuming no increase of objects), and in reality, the highest collision flux would not keep decreasing even with some ADRs. We may need more sophisticated policy to realize the monotonous decrease in prices.

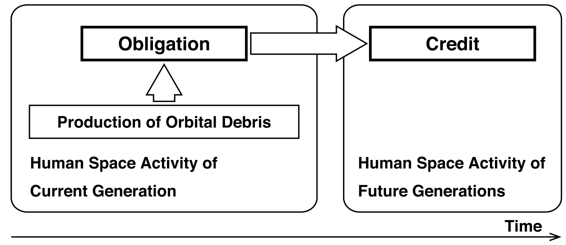


Fig. 10. Obligation and credit.

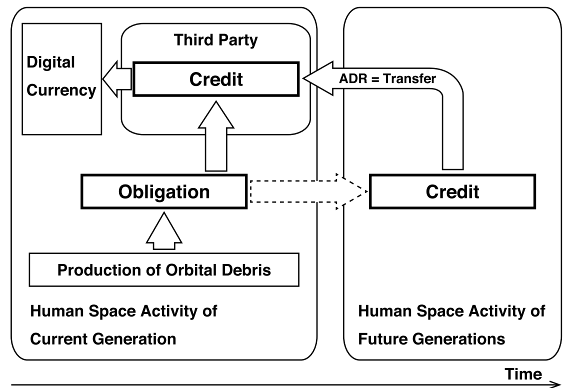


Fig. 11. Transfer of credit from future to today.

V. Discussion

A. "Proof of Disposal" Concept

In addition to physical or engineering aspect of OD including intact object described in Section II, the social aspect of OD and the proposed scheme is considered in this section, for generalization of the scheme for other applications.

We try to understand the proposed currency system in terms of obligation and credit. Once an OD is produced, the risk diffuses thinly and broadly to all orbits that share the same space with the object. The responsible body for the object does not suffer any disadvantage except for the thinly diffused risk. To make matters worse, the risk diffuses not only spatially but also temporally. The temporal spread of the risk is, in other words, a negative legacy from human space activity of the current generation to that of the future generations. Every time an OD is produced, human space activity of the current generation increases corresponding obligation to that of the future generations, and in consequence, human space activity of the future generations increases credit to that of the current generation (Fig. 10).

It seems impossible for a creditor in the future to recover the credit from the current obligor. It is possible, however, for some third party to transfer the credit from the future creditor through a present day activity, namely, ADR. The third party to conduct ADR reduces the negative legacy through the environment remediation, and therefore, ADR is considered equivalent to transferring the credit from the future to today. The scheme is shown in Fig. 11.

The transferred credit is a warranty for issuing a claim deed to be circulated as a digital currency token. The authors have named this scheme for issuing digital currency *POD*.

The scheme may be applicable for any kind of disposal of industrial or war wastes. For establishment of POD, however, the corresponding disposal has to be performed under the witness of the whole community, in order to prevent an untrue statement of disposal, and the knowledge of the disposal is presumably to be shared among the community members through the same blockchain platform that runs the currency system. From this point of view, ADR is one of the most suitable cases for POD.

B. Practical Values of POD Tokens

But would POD (in particular, ADR currency) tokens have any practical values, if they are issued by consortia of parties instead of banks, and with scheduled depreciation?

Because ADRs remediate space environment for a wide range of applications including weather forecasting, maritime, broadcasting, telecommunication, airline, and navigation, the consortium would actually involve many companies not directly associated with space development. In return, the currency system would attract lots of customers of such companies, who would want to use the tokens to pay for the services (the currency accelerates people's spending by design), such as mobile communication fees, for example. There may be a large body of the users who find practical values in the tokens.

There is also a reason why POD tokens need to be linked with existing monetary values. If such tokens are independent of other currencies, depreciation would not be effective for decreasing the token values as expected, because then tokens become scarcer, and more highly valued because of less supplies against demands in relative to other currencies. Therefore, POD tokens need to be pegged to an existing currency, such as U.S. dollar. A regulatory way to ensure such pegging may be to regard depreciation as donation to the consortium (because depreciation does reduce the debt of the consortium), which may be made tax-deductible in countries where the consortium is considered a charitable organization.

C. Related Work

1) Economics of Orbital Debris: Both [10] and [11] provide economic analyses of the problem of OD. The former proposes that classic Pigovian taxes on new launches would reduce the creation of new debris, and could also possibly fund ADR. However, it would require cooperation among competing nations that have created the majority of extant debris, and spontaneous deceleration of new launches would not incentivize these nations. The latter argues that the most reliable solution to the kind of problem is the establishment and enforcement of private property rights, which they find infeasible in this case. It also suggests that an institution to work on this problem would be classified along a spectrum that transcends the private–public dichotomy.

Indeed, our proposal of POD is based on our understanding that the solution would not come from the dichotomy but from the civil society.

2) Funding and Internet Technology: In recent years, a way of funding from general public through the Internet has become a popular practice. It is called *crowdfunding* [12]. However, crowdfunding is not necessarily a solution for implementing public works where sufficient money is unavailable, as it requires money to be gathered first. In the proposed scheme of POD, on the other hand, monetary medium is created on demand on a blockchain platform.

Another way of funding that is becoming a popular practice is *ICO* [13], or a *crowdsale* of newly issued digital coins on a blockchain platform. Although both ICO and POD issue digital currency tokens, ICO is rather similar to crowdfunding, as it requires upfront money to purchase the coins. ICOs tend to attract more people more rapidly than crowdfunding, as people expect capital gains with an anticipation that the price of the coins will go up in the future. Because of this expectation, circulation as monetary medium is limited for the issued coins in ICO (spending is generally decelerated). Thus, the issued digital coins are not expected to help the community as a whole as means for payment among community members. Another point about ICO is that issued digital coins do not usually represent debt, so that ICO requires an external scheme for monitoring whether the proposed project is soundly ongoing or not.

3) Incentives and Attractions for Environmental Remediation: Plastic Bank [14] is another example of turning waste into a monetary medium, where recycling plastic is rewarded with digital tokens issued on some blockchain platform, in order to stop ocean plastic and help people ascend from poverty. Plastic Bank incentivizes collectors of ocean plastics by paying them a premium on top of the market rate, using funds raised by crowdfunding.

This idea is similar to POD. But with POD, we can unnecessitate crowdfunding and distribute the cost of the premium among receivers of the issued tokens, while spreading and promoting the idea along with circulation of the tokens at the same time.

However, whether we use crowdfunding or POD, an important question would be how helping environmental remediation can attract people and change their behaviors. Tushar *et al.* [15], for example, proposes a design inspired by motivational psychology, toward more environment-friendly use of air conditioning. Hu and Zhang [16] studies the robustness of incentive mechanisms with bounded rational behaviors. Sajadi *et al.* [17] studies the spread of social norms. We can learn from those studies how to attract people and organize people's participation in our proposed solution to the problem of OD.

D. Other Applications

POD is expected to work where disposal is observed publicly. Another possibly useful case is land mine clearing (Fig. 12). This example uses both amplifying and depreciating features of digital currency tokens issued in return for disposal. First, the issued tokens amplify their values for both incentivizing early removal of land mines and decelerating spending. Depreciation is delayed until zero land mine is achieved in the defined area, after which the area can be reconstructed with accelerated spending.

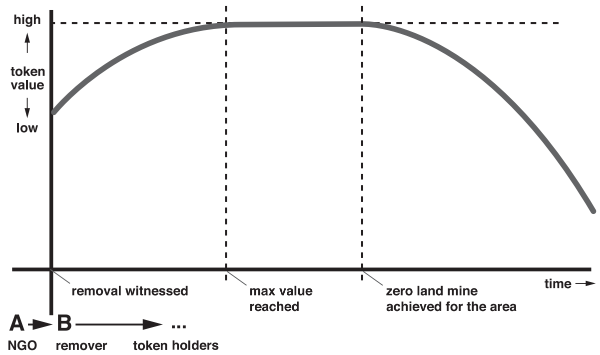


Fig. 12. Zero land mine currency.

E. Implementation and Prototyping

We believe that either Bitcoin or Ethereum can be used for implementing POD. However, both blockchain platforms are under a risk of being discontinued. If the price of the native token (bitcoin or Ether, respectively) goes down, the maintainers of the blockchain (often called *miners*) may have to leave the system, because the cost of maintaining the blockchain, which is usually covered by rewards they receive in the form of native tokens, would be valued more than the rewards.

To ensure sustainability of the ADR currency, which would have to continue for many tens of years, we take part in developing Beyond Blockchain One,[3] [18] a new open-source platform for record keeping that can use either Bitcoin or Ethereum (and even dynamically switch between them) for proof of existence of transactions in its early stage (and later, it will become independent). We are prototyping the ADR currency on top of this new platform.

VI. Conclusion

We proposed that the cost of removal of OD can be paid by circulating digital currency tokens whose values decrease over time, issued in exchange with proofs of ADR. We have shown that managing such a currency system, the ADR currency, is indeed feasible.

We consider that OD is a kind of debt owed by the human race of existing generation to the future generations. The ADR currency has an effect of transferring the corresponding credit to the present day. This concept can be generalized for many social debts publicly shared for starting and managing projects for social goods using blockchain platforms.

This is also an implementation of a belief that for a currency to be accountable, creation of monetary amount should be warranted by some kind of value in the real world, as opposed by many cases of ICO. The authors hope that the scheme we proposed in this paper will be considered as an alternative to crowdfunding or ICO for implementing public work as blockchain applications under low budget conditions.

[3]https://github.com/beyond-blockchain/bbc1

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