B05

経済学からのデブリ問題分析

Overview of Space Debris from Economics

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宇宙ゴミ問題は長期的なグローバルアクションの大切さ及び不確実性の大きさから気候変動と同様の特徴がある. PMD90%実行+ADR5~10 機/Year が低軌道環境維持に必須であることが IADC の取り組みによって明らかにされている. しかし、PMD は実行率が十分に上昇せず、ADR についてはコストの捻出方法が見通せない. 技術力の問題もあるが、経済的側面が非常に大きい. 過去の経済的側面からの取り組みは、他の環境問題からのアナロジーが多く、体系的とは言い難い. 一方、環境経済学はミクロ経済学の一分野として急速に適用範囲が拡大している学問体系であり気候変動の IPCC 等において中心的な役割を担っている. そこで本発表では、この考え方を元に、国際的にデブリ問題並びに PMD と ADR のコストの位置づけを明らかにする. そして、各国が国際的に受け入れられる制度枠組みに要求される課題を検討する.

Space debris is an emerging global environmental problem. PMD of 90% and ADR of 5 to 10 every year is required for maintaining the status of LEO. Fulfillment rate of PMD is, however, still in unsatisfied level and its associated cost of ADR is unclear. This provides the challenge from both of technology and economics. Previous studies on economics of space debris are mostly analogy from environmental problems on the earth. Environmental economics, holding two Nobel Prize winners, can potentially provide key tool to understand this problem. In this study, we provide how environmental economics merits on understanding and solving debris problem including cost of PMD and ADR. Finally, we discuss requirements for economic scheme which are acceptable in international space scene.

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Background (1)

- Space debris is urgent problem.
- Typical problem of ‘externality’
  - Externality or ‘fault of market’: Cost for mitigating debris is not included in economic activity for space development.
  - Pre-consumption over utility or pushing cost to the future generation.
- Field of ‘environmental economics’
  - Emerging field of economics since 1990s’.
  - Pollution, greenhouse gases, ocean plastics, over development, etc.
- Domestically, it’s not applied for space debris yet.

Background (2)

- Ex. SSR (Space Sustainability Rating) is proposed abroad.
- Letizia et al. Acta Astronautica, 2019

$$I = p_c \cdot e_c + p_e \cdot e_e$$ Effect of collision and explosion

$$I = \int_{t_0}^{\Delta t_{oper}} I(a,i)dt + \alpha \left(\int_{\Delta t_{oper}}^{t_e} I(a,i)dt \right) + (1-\alpha) \left(\int_{\Delta t_{oper}}^{t_l} I(a,i)dt \right)$$

Under operation Under PMD Under Natural decay

- Discussions are conducted form practical aspects.
- There is no basement for systematic estimation of economical and social influence of SSR to Japan.

Index

- Problem of externality
- Review of past literature.

  [1] Nodir Adilov*, Peter J. Alexander**, Brendan M. Cunningham***, "An Economic Analysis of Earth Orbit Pollution," Environ Resource Econ. 19 Jan. 2014, Springer.

  * Purdue Univ., ** FCC., ***USNA

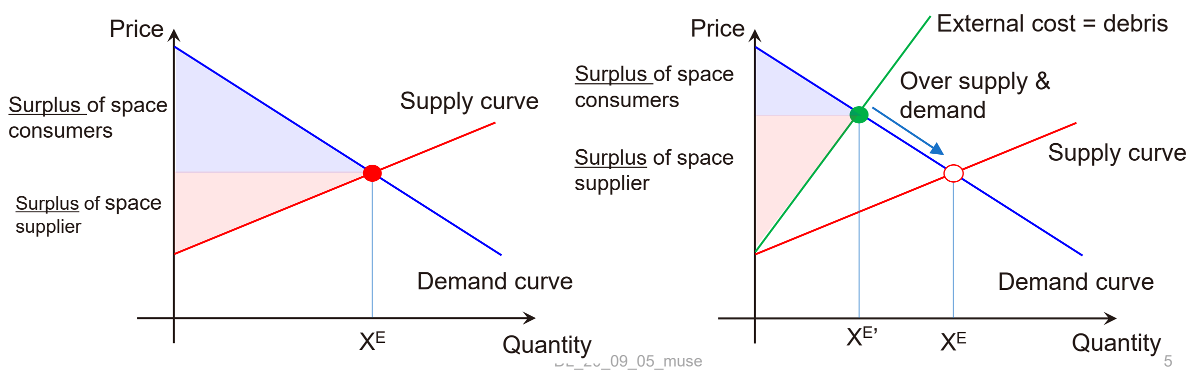
  [2] Molly K. Macauley****, "The economics of space debris: Estimating the costs and benefits of debris mitigation," Acta Astronautica, volume 115, October–November 2015, Pages 160-164

  ****Resources for the Future (Thinktank)

- Our activity
- Evolution and target

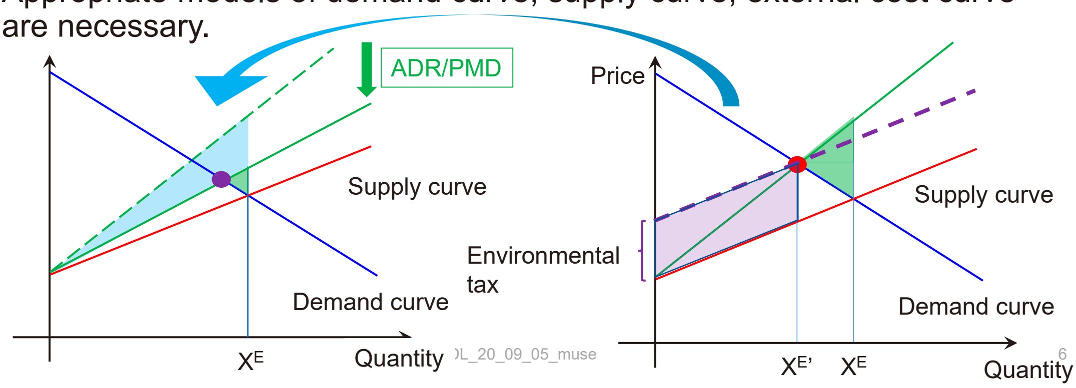
Problem of externality (1)

- External cost: If not, market price falls and goods are over supplied.
- Space consumers and suppliers over enjoy surplus from the development.



Problem of externality (2)

- PMD/ADR lowers inclination of the external cost curve.
  - ‘Environmental/Pigovian tax’ or sales of ‘emission right’ can be applied for the cost for lowering the inclination.
- Appropriate models of demand curve, supply curve, external cost curve are necessary.

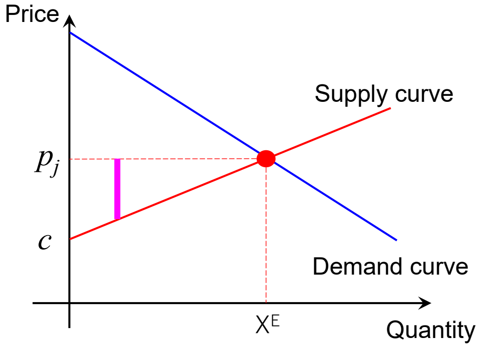


Review of Ref. [1] (1)

- Surplus (or profit) of a space supplier per one unit of space service by a satellite j.

$$\pi_j/q_j = p_j - c - r/q_j - F/q_j$$

π_j : Surplus (Profit)
p_j : Price of a unit of space service
c : Cost for a unit of space service
q_j : Quantity of service by one satellite of a supplier
r : Cost for launching a satellite
F : Fixed cost for operating a satellite



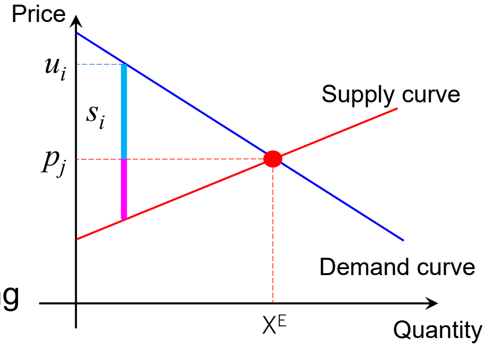
Review of Ref. [1] (2)

- Surplus of a space consumer i per one unit of space service.

$$s_i = u_i - p_j - t \cdot d(i,j)$$

s_i : Surplus which j serves to i
u_i : Utility
p_j : Price of a unit of space service
t : Accessing cost to a space service
$d(i,j)$: Distance for accessing a space service (abstracted inconvenience)

- Evaluation by introducing number of launching L which maximizes ▌ or ▌.



Review of Ref. [1] (3)

- Neglecting existing satellites and existing debris. L: number of new launching
- Assuming fully competitive market.
- Assuming total quantity of the demand as one: the demand per a satellite is $1/L$.

Maximizing the suppliers' surplus $L_{com} = \sqrt{\frac{(\beta+(1-k\phi))t}{(1-k\phi)(r+F+\beta(1-k\phi)F)}}$

Maximizing the sum of surpluses of the suppliers and the consumers

$$L_{soc} = \frac{1}{2}\sqrt{\frac{(\beta+(1-k\phi))t}{(1-k\phi)(r+F+\beta(1-k\phi)F)}}$$

β: discount factor, ϕ: probability of a satellite which becomes debris. k : probability of a debris which destroys satellites.

Review of Ref. [1] (4)

- L_{com}, L_{soc} increase as $k\phi$ approaches unity.
  - The decrease of competitors becomes dominant and increase p: the price of services.
- The optimum number of launching for the suppliers is double of that of the whole society.
  - The tendency is similar even if you assume r, launching cost, as a function of preventing debris.
- Assertion and discussion
  - Voluntary approach is not effective.
  - Command and control is ineffective. Its not reasonable to force heterogeneous supplier to obey same regulations or to use same technology.
  - ADR
    - it's not clear how to distribute the cost to consumers.
  - Environmental tax (Pigovian tax) is reasonable.
- ADR should be conducted by some environmental tax.

Review of Ref. [2] (1)

- One Period Model (2011-2030, 2031-2050)
- Analysis of contribution of the number of satellites to the external cost.

- Using ‘benefit ’ instead of ‘utility’. ‘Benefit’ is usually used for public works.
  - Emphasizing space development as infrastructure.

- Evaluating productivity loss of satellite by debris collision as externality.
  - In Ref. [1], the maximum value of sum of consumers’ surplus and suppliers’ surplus is used for evaluation of externality.

Review of Ref. [2] (2)

- Assumption
  C: Additional cost for debris including avoidance and defense
  P: Profit of decrease of collisional risks
  R: Rebate
  - Without rebate: Indifferent to the other suppliers’ satellites.
    $$C = P$$
  - With rebate: Conscious to the other suppliers’ satellites.
    $$C = P + R$$

- Combination of environmental tax & rebate is equivalent to a deposit system

Review of Ref. [2] (3)

- Result: Tax, Graveyard tax and rebate, Avoidance tax & rebate
- Environmental tax & rebate is more effective than straightforward tax

Loss of productivity: 10%, large collision probability

	Tax [M$]	Graveyard tax/rebate [M$]			Maneuver tax/rebate [M$]		
Low (0.003)	0.3	0.2	0.1	0.1	0.3	0.1	0.2
Medium (0.012)	1.2	0.9	0.3	0.6	1.0	0.2	0.8
High (0.020)	2.1	1.6	0.5	1.1	1.7	0.4	1.3

Loss of productivity: 50%, large collision probability

	Tax [M$]	Graveyard tax/rebate [M$]			Maneuver tax/rebate [M$]		
Low (0.0003)	1.2	0.9	0.3	0.6	1.0	0.2	0.8
Medium (0.001)	4.6	3.4	1.2	2.2	3.8	0.8	3.0
High (0.002)	8.0	6.0	2.0	4.0	6.5	1.4	5.1

Our activity (1)

- Previous studies require improvements from viewpoint of engineering.
  - By height of satellites → congestion degree, orbit decay
  - Division of intact objects from the others
- An example of modification;
  - Surplus (or profit) of a space supplier per one unit of space service by a satellite j.

$$\pi_j/q_j = p_j - c - r/q_j - F/q_j - C_m/q_j - C_p/q_j - C_a/q_j$$

C_m : Avoidance cost for a satellite
C_p : PMD cost for a satellite
C_a : ADR cos for a satellite

Our activity (2)

- Ex, we are considering about ‘Filed of utility density’, ‘filed of surplus density’ and ‘field of externality density’ in orbital space.

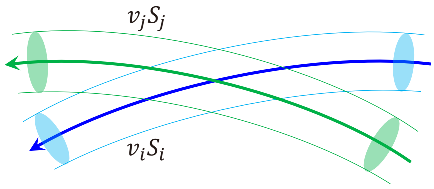
  v_j: velocity of a satellite

  Π_j : surplus produced by a satellite per unit time

  S: area of a circle which has avoidance distance

  π_j: density of the orbital space

  $\Pi_j \propto v_j S_j \pi_j$ then, $\pi_j \propto \Pi_j/(v_j S_j)$



- If another satellite pass the orbit with v_i with avoidance radius of S_i,

$$\Pi_i \propto \Pi_j \frac{v_i S_i}{v_j S_j}$$

Next evolution and the target

- Prediction of appropriate cost for the orbital space utilization
- How to raids the funds for ADR
  - Orbital space utilization tax
  - Trading of launching
  - Deposit system for PMD/ADR
- Considering economical impact on satellite enterprise, ADR enterprise, space industry and whole society

- Important is, the externality is not from debris but from the moment of launching.