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Paper:

Computational Study on Strategyproofness of Resource Matching in Crowdsourced Manufacturing

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The need for a sustainable society has grown rapidly. This trend requires new production system concepts following an era of mass customization. As one of these new concepts, "crowdsourced manufacturing" has attracted noticeable attention. In such systems, each participant shares their manufacturing resources for ecosystem co-prosperity, providing new value for the next society. To realize such a concept, it is important to (1) match resource requests and resource offers so as to achieve high efficiency, and (2) induce participants to act in a fair way. Previously, some studies showed production efficiency improvements. Nevertheless, relatively few studies have been conducted on induction mechanisms. The purpose of this study is to develop induction mechanisms for participants. Concerning induction mechanisms, we focus on two viewpoints: (a) matching stability, and (b) "strategyproofness." These viewpoints are well-known concepts in the market design research field. We previously proposed a resource matching stability analysis method and mechanism for inducing participants to accept matching plans. Formally, a matching method is "strategyproof" when it is a dominant strategy for all participants to submit their true information. However, it is hard to satisfy this condition. Practically, it would be useful to evaluate the strength of an induction, even if the matching method is not strategyproof. In this study, we propose indices for showing the strength of induction ("strength of strategyproofness"). Subsequently, we evaluate matching methods, and show that participants will state false information to maximize their profit in a system with resource matching methods for the profit maximization of the entire system. As the resource providers, they can obtain greater profit by submitting false information regarding resource usage fees. Then, the profits of the resource requesters are unfairly impaired. Furthermore, we propose a new resource matching method, inspired from the "nucleolus" concept in cooperative game theory. The proposed method reduces the maximum dissatisfaction (i.e., profit loss) of resource requesters and resource providers, based on profit sharing. The computational results show that the proposed method induces participants to submit true information, while maintaining high production efficiency.

Keywords: distributed production, resource matching, cooperative game theory

1. Introduction

In recent decades, the manufacturing industry has faced rapid and major changes in business circumstances [1]. Diversification in customer needs is driving changes in the market environment, e.g., increases in product types, and shortened product life cycles. Moreover, geopolitical risks, such as trade friction, are causing changes in the business environment, e.g., fluctuations in raw material prices, and changes in appropriate areas for production. Thus, there is a need for a flexible and low-asset production system in the industry.

In addition, the development of new information and communication technology (ICT), such as cloud computing and "Internet of Things" technology, is remarkable. The utilization of these technologies has accelerated the digitalization of society. The discussions in the manufacturing field remains very active. Many projects have been launched in collaborations among industry, academia, and governments, such as "Industrie 4.0" in Germany, "Industrial Internet" in the U.S.A., and "Industrial Value Chain Initiative" in Japan [2–4]. In these projects, one of the most promising concepts for future production systems is that of a "connecting factory," for decentralizing manufacturing and improving productivity at low asset levels.

In addition, the need for a sustainable society has grown rapidly. This trend requires new production system concepts following the era of mass production and mass customization. The International Electrotechnical Commission proposed "crowdsourced manufacturing" [5]. This concept is based on sharing-economy principles. Each participant shares manufacturing resources to improve as-

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set utilization, and participants cooperate in the prosperity of the ecosystem. Although this concept is not suited for continuously processed products (e.g., chemical products), it is assumed to be better suited for assembled products requiring expensive equipment for machining processes, inspection processes, etc.

Even before the rise of the digitalization era, numerous researchers had identified that decentralized, cooperative production structures can realize a quick response to market changes. Concepts including the "dynamic supply chain," "collaborative network enterprise," and "cloud-based manufacturing" [6–9] have been proposed. Crowdsourced manufacturing evolved from these concepts; its key feature is "symbiosis" for co-prosperity, which is a new value for the next society.

Monostori et al. [10, 11] and Váncza et al. [12] provided extensive literature overviews regarding many research aspects of distributed production networks.

Wu et al. [9] presented the main obstacles to realizing cloud-based manufacturing. The list includes not only ICT-related items, but also business models, such as those for data ownership and profit distribution.

Freitag et al. [13] clarified the dynamics of resource sharing among two factories, using a discrete event simulation model and control-theoretic model.

Kaihara et al. [14, 15] clarified the effect of the number of participants in crowdsourced manufacturing using an agent-based simulation model. They paid attention to the fact that each participant has independent key performance indicators (KPIs). They proposed a supervised agent-based simulation model that assigned the resource requests of participants to their own equipment prior to equipment owned by other participants.

Hibino et al. [16] proposed a synchronization mechanism for distributed manufacturing simulation systems. The proposed method utilized a shared storage model to communicate between parallelly executed simulators.

Kádár et al. [17] proposed a collaboration platform for supporting a mutual exchange of information concerning resource requests and offers and providing resource matching plans. The agent-based simulation results showed that this platform realized "plug & collaborate" efficiently.

In designing crowdsourced manufacturing systems, it is important to recognize the impact of the selection of the resource matching method(s). Nevertheless, most of the previous studies are aimed at verifying productivity. Considering the key feature of crowdsourced manufacturing, i.e., "symbiosis," it is also important to determine how to induce participants to act fairly.

Szaller et al. [18] presented a resource sharing model where participants were motivated to keep their promises by taking trust and reputation into consideration when resource matching.

Considering the above, we focus on two features of resource matchings: stability and strategyproofness. These features are well-known in market design theory [19].

In [20], we proposed an evaluation method for determining the stability of matching. The evaluation results

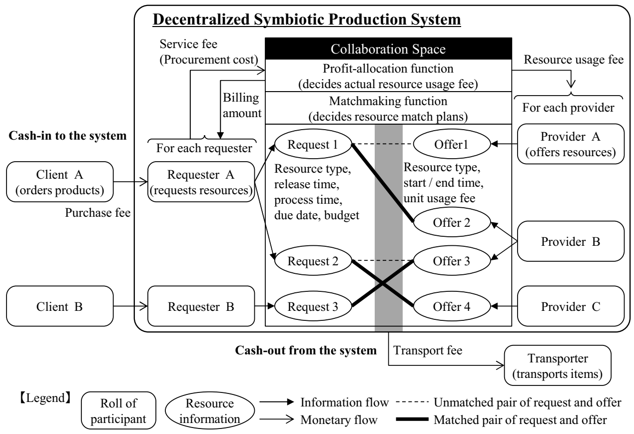

Fig. 1. Overview of crowdsourced manufacturing system.

showed that maximizing the whole system profit led to instable resource matching plans. This indicated that some participants might not follow the plans, so as to maximize their individual profit.

In [21], we proposed a stability improvement method; it balanced the whole system profit and matching stability using a cost sharing mechanism.

In this study, we propose some indices of "strength of strategyproofness," and a new resource matching method for inducing participants to act fairly.

2. Crowdsourced Manufacturing System

2.1. Overview of the System

Figure 1 shows the model of the crowdsourced manufacturing system. Each participating company (participant) shares its production equipment resource via the collaboration space. Unlike vertically integrated production systems, the participants can act as both resource requesters and providers, depending on the production situation.

The participants make their production plan for a predetermined "production planning term" in advance, to satisfy product orders from clients. As a result, if their equipment resources are expected to be insufficient to satisfy the product orders, the participants send a request the collaboration space, to obtain available equipment resources owned by other participants. Conversely, when resource surpluses are expected, participants register the available equipment resources to the collaboration space, to offer them to satisfy other participants' resource requests.

At the time of a resource request, a participant submits the resource type, release time, process time, due date, and procurement budget (resource usage fee + transportation fee) to the collaboration space as the resource request information. Here, the "resource type" is information for determining whether the providing resource is appropriate for the request. In addition, we assume that requests are not divisible. This assumption is reasonable from the perspective of quality assurance. When a participant can procure equipment resources from another participant, we assume that the participant obtains a requester profit (RP), in the amount of (procurement budget − procurement fee).

At the time of a resource offer, the participant submits the resource type, start/end times of the resource offer, and unit price of the resource usage to the collaboration space as resource offer information. When the offered resources are procured by other participants, we assume that the participant obtains a provider profit (PP), in the amount of (unit price × process time).

The participants tend to maximize their RP (as requesters) and PP (as providers).

The collaboration space has two functions: matchmaking and profit allocation. The matchmaking function decides resource matching plans based on resource request and offer information registered by the participants, and informs the participants about the plan. The profit-allocation function decides the billing amount for resource requesters and resource usage fees for resource providers, in view of the symbiosis. The main subject of this study concerns a resource matching method for the matchmaking function.

The matchmaking function is intended to earn a cash flow (inflow of cash − outflow of cash) from the crowd-sourced manufacturing system. In this case, the cash inflow is the amount of the orders from the clients, and the cash outflow is the transportation costs. However, it is difficult for the matchmaking function to grasp the price of the orders, as the price is generally confidential and not disclosed by the resource requesters. Therefore, we assume that resource requests with a large procurement budget are worthwhile for resource requesters (and the whole system), to thereby obtain a large amount of cash inflow from the clients. Then, we define the system profit (SP) as the amount of (procurement budget − transportation fee) of the matched requests. The SP is equal to the sum of the RP and PP.

2.2. Resource Matching Methods

The matchmaking function makes an optimal resource matching plan in the view of the KPIs (e.g., the SP). This plan consists of the following items: (a) a combination of the matching edges (i.e., pairs of resource requests and offers) and (b) the start and end times of the resource usage of each selected matching edge. The resource matching planning is formulated as the following mixed integer programming problem (MIPP) [20].

[Objective Functions]

Two objective functions are considered. Each resource matching method optimizes one of these objectives.

$$\text{maximize: } RP, \quad (1)$$

$$\text{maximize: } SP. \quad (2)$$

Equations (1) and (2) indicate the maximization of the RP and SP, respectively. In the following sections, methods with different objective functions are denoted as "(M1) RP maximization" (i.e., Eq. (1)) and "(M2) SP maximization" (i.e., Eq. (2)). Although we focus on SP rather than RP for co-prosperity, we examine the method (M1) for comparison.

[Constraints]

$$\sum_{\forall e \in E_r} x_e \leq 1, \quad \text{for } \forall r \in REQ, \quad (3)$$

$$\sum_{\forall t \in \{EST_e, \ldots, LST_e\}} y_e^t = x_e, \quad \text{for } \forall e \in ME, \quad (4)$$

$$\sum_{\forall e \in E_f} \sum_{s=\max\{t-PT_{ER_e}+1, EST_e\}}^{\min\{t, LST_e\}} y_e^s \leq 1,$$
$$\text{for } \forall f \in OFF, \ \forall t \in \{ST_f, \ldots, ET_f\}, \quad (5)$$

$$cost_r = \sum_{\forall e \in E_r} (UPF_{EO_e} \cdot PT_r + TF_e) \cdot x_e,$$
$$\text{for } \forall r \in REQ, \quad (6)$$

$$cost_r \leq BGT_r, \quad \text{for } \forall r \in REQ, \quad (7)$$

$$RP = \sum_{\forall r \in REQ} \left(BGT_r \cdot \sum_{\forall e \in E_r} x_e - cost_r \right), \quad (8)$$

$$SP = \sum_{\forall r \in REQ} \left(BGT_r \cdot \sum_{\forall e \in E_r} x_e \right) - \sum_{\forall e \in ME} (TF_e \cdot x_e). \quad (9)$$

[Notations]

- REQ: Set of resource requests, defined by registered request information from participants.
- OFF: Set of resource offers, defined by registered offer information from participants.
- ME: Set of candidate matching edges, i.e., valid combinations of resource requests and offers in view of budget, due date, etc.
- x_e: Decision variable. This takes a value of "1" when a matching edge e constitutes the optimal plan, and "0" otherwise ($e \in ME$).
- y_e^t: Decision variable. This takes a value of "1" if the resource request begins to occupy the resource offer in matching edge e at time t, and "0" otherwise ($e \in ME$, $t \in \{ST_{EO_e}, \ldots, ET_{EO_e}\}$).
- $cost_r$: Variable indicating procurement cost for the request r ($r \in REQ$).
- RP: Variable indicating the requester profit.
- SP: Variable indicating the system profit.
- PT_r: Constant indicating the process time (length of request term) of request r ($r \in REQ$).
- BGT_r: Constant indicating the budget of request r ($r \in REQ$).

TF_e : Constant indicating the round-trip transportation fee on a matching e ($e \in ME$).

ST_f/ET_f: Constants indicating the start/end time of resource offer f ($f \in OFF$), respectively.

UPF_f: Constant indicating the unit price of the resource usage of offer f ($f \in OFF$).

EST_e/LST_e: Constants indicating the earliest/latest starting times of resource usage to satisfy the constraints of the release time and delivery dates of resource request on matching edge e ($e \in ME$), respectively.

ER_e: Constant indicating the resource request on matching edge e ($e \in ME$).

EO_e: Constant indicating the resource offer on matching edge e ($e \in ME$).

E_x: Set of the matching edges containing the resource request or offer x ($x \in REQ \cup OFF$).

Equation (3) indicates that there is at most one resource offer matched for each resource request. Eq. (4) indicates that, when a matching edge is selected, the resource usage starts between the earliest and latest starting times of the corresponding resource request. Eq. (5) indicates that each resource offer cannot be occupied by multiple resource requests simultaneously. Eq. (6) is a calculation of the resource procurement cost. Eq. (7) indicates that the resource procurement cost does not exceed the procurement budget. Eqs. (8) and (9) calculate the RP and SP, respectively.

3. Strategyproofness of Resource Matching

In crowdsourced manufacturing, it is important that all participants submit true information concerning their resource requests and offers. If some participants strategically submit false information to obtain greater individual profits, others will be forced to act strategically, so as to prevent a loss of profits. This viewpoint is called "strategyproofness" [19]. A matching method is strategyproof if it is a (weakly-)dominant strategy for all participants to submit their true information.

In this study, we attempt to evaluate resource matching methods from the perspective of strategyproofness. Although theoretical analyses are desirable, they are often too difficult, owing to the combinatorial optimization nature of resource matching. As the matching problem is NP-hard, it is time-consuming to evaluate the gain of all sets of participants' strategies. Thus, as a practical matter, we take a simulation-based approach. We consider that strategyproofness informs participants that they will be disadvantaged owing to the submission of false information. Therefore, we define the "strength of strategyproofness index" as the loss of profits caused by the submission of false information. It would be useful to evaluate the strength of induction, even if the matching method is not theoretically strategyproof.

First, we assume some greedy participants in the simulations. When they act as requesters, they exaggerate their resource procurement budget, so as to pretend their requests are important for the whole system. Then, when they act as providers, they will increase the unit price of resource usage, to obtain greater usage fees. Thus, we define two types of strength of strategyproofness indices (SSIs) as follows.

Type-1 indices are defined independently for each resource matching instance.

$$p_R = \frac{\overline{RP}^H - \overline{RP}^G}{\overline{RP}^H}, \quad \dots\dots\dots\dots \quad (10)$$

$$p_P = \frac{\overline{PP}^H - \overline{PP}^G}{\overline{PP}^H}. \quad \dots\dots\dots\dots \quad (11)$$

Equations (10) and (11) indicate the losses of profits caused by false information submission from greedy requesters and greedy providers, respectively. In these equations, $\overline{RP}^H$ and $\overline{RP}^G$ denote the average RPs of the honest (i.e., not greedy) requesters and greedy requesters, respectively. And, $\overline{PP}^H$ and $\overline{PP}^G$ denote the average PPs of the honest providers and greedy providers, respectively.

Type-2 indices are defined by comparison with an ideal situation (i.e., all participants are honest).

$$\hat{p}_R^G = \frac{\overline{RP} - \overline{RP}^G}{\overline{RP}}, \quad \dots\dots\dots\dots \quad (12)$$

$$\hat{p}_P^G = \frac{\overline{PP} - \overline{PP}^G}{\overline{PP}}. \quad \dots\dots\dots\dots \quad (13)$$

Equations (12) and (13) indicate the losses of profits of greedy requesters and greedy providers, as compared with profits in the ideal situation, respectively. Here, $\overline{RP}$ and $\overline{PP}$ are the average of the RP and PP in the ideal situation, respectively. These indices indicate the benefits of ecosystem collaboration.

If the indices defined above are positive, the matching method is considered to be virtually strategyproof.

We note that the indices cannot be computed in reality, but only in simulation. We assume that these indices are useful in designing crowdsourced manufacturing systems.

4. Evaluation Results

In this section, we evaluate the "strength of strategyproofness" of the resource matching methods discussed in Section 2.2.

4.1. Simulation Conditions

We generate participants, resource requests, and offers using a pseudo-random sequence, according to the conditions shown in **Table 1**. These conditions are based on use cases in industry (e.g., industrial equipment production with machining equipment sharing).

Table 1. Simulation conditions.

Parameter	Description
Planning term	The matching planning term is set to 40.
Resource type	Two resource types. Each participant has one type randomly selected. Each resource type is held by half of the participants.
Company properties	150 participants located at geometric point $(u(0,1), u(0,1))$ in the Euclidean plane. The numbers of greedy participants are 30, 60, 90, and 120, and the false rates are 10%, 20%, and 50%.
Resource request properties	The occurrence probability at each time slot is 10%. The release time is set to the occurrence time. The process time is set to $u(1,3)$. The due time is set to (release time + process time + $u(6,8)$). The unit budget is set to $f(50,20)$.
Resource offer properties	The occurrence probability at each time slot is 10%. The release time is set to the occurrence time. The offer term length is set to $u(1,8)$. The unit usage fee is set to $f(20,10)$.
Transportation	The transport speed is set to 1 per unit distance, and the unit fee is set to 10 per unit distance.

In **Table 1**, $u(a,b)$ is a uniform random number in the range of $[a,b]$, and $f(\mu,\sigma)$ is a random number with a probability density function obtained by the truncation of the normal distribution with the mean value μ and standard deviation σ at the point of $\mu \pm \sigma$. The greedy participants exaggerate the budget, and increase the unit price, by the "false rate." We simulate two cases independently: (1) greedy requester and (2) greedy provider.

The computational environment is the following. PC: Xeon E-2690 2.9 GHz, Intel Corp., 256 GB memory; OS: Windows Server 2016 Standard, Microsoft Corp.; Solver: Gurobi Optimizer 7.5.2, Gurobi Optimization.

4.2. Evaluation Results

Tables 2 and **3** show the SSIs against the requesters (i.e., (1) greedy requester case) of the resource matching methods (M1) and (M2), respectively. The results are averaged over 20 random instances, based on different seeds of the pseudo-random sequence. The bold cell shows the negative indices, that is, where the matching method is not strategyproof. "Average" rows show the averaged value of the cases (i)–(iv). The notations are the same for all of the following tables.

As shown in **Tables 2(a)** and **3(a)**, the indices are positive in most scenarios; the greedy requesters lose their profits due to the exaggerations. This is because they are forced to procure high-cost resource offers, even if the cost is over their true budget. A higher false rate causes additional profit loss. In the case of (M2), the indices are larger than (M1). This is because (M2) tends to force the number of resource matchings to be as large as possible.

As shown in **Tables 2(b)** and **3(b)**, profits of the greedy requesters are less than that in the ideal case, in most scenarios. Therefore, it is better to submit the true budgets (as is the case for all requesters).

A participant cannot anticipate the number of the greedy participants in advance, so the expected profit loss is important to their decision. The all averaged values (in the "Average" row) in **Tables 2** and **3** are positive. Therefore, the matching methods (M1) and (M2) are expected to induce participants to submit true budgets in practice (i.e., "virtually strategyproof").

In the discussion above, the scenarios of "60 greedy requesters" seems singular, especially (M1) in **Table 2**. In these scenarios, the greedy requesters obtain greater

Table 2. Strength of strategyproofness indices (SSIs) of (M1) against the requesters.

(a) The results of the index p_R.

Num. of the greedy participants	False rate		
	(a) +10%	*(b) +20%*	*(c) +50%*
(i) 30 (20%)	2.2%	2.2%	2.7%
(ii) 60 (40%)	**−0.8%**	**−0.9%**	**−0.4%**
(iii) 90 (60%)	2.6%	2.6%	3.0%
(iv) 120 (80%)	3.2%	3.3%	3.6%
Average	1.8%	1.8%	2.2%

(b) The results of the index $\hat{p}_R^G$.

Num. of the greedy participants	False rate		
	(a) +10%	*(b) +20%*	*(c) +50%*
(i) 30 (20%)	1.8%	1.8%	2.4%
(ii) 60 (40%)	**−0.4%**	**−0.4%**	0.2%
(iii) 90 (60%)	1.1%	1.2%	1.9%
(iv) 120 (80%)	0.7%	0.9%	1.6%
Average	0.8%	0.9%	1.5%

Table 3. SSIs of (M2) against the requesters.

(a) The results of the index p_R.

Num. of the greedy participants	False rate		
	(a) +10%	*(b) +20%*	*(c) +50%*
(i) 30 (20%)	2.9%	3.4%	4.5%
(ii) 60 (40%)	**−0.3%**	0.2%	1.4%
(iii) 90 (60%)	3.6%	4.1%	5.1%
(iv) 120 (80%)	4.0%	4.5%	5.7%
Average	2.5%	3.0%	4.2%

(b) The results of the index $\hat{p}_R^G$.

Num. of the greedy participants	False rate		
	(a) +10%	*(b) +20%*	*(c) +50%*
(i) 30 (20%)	2.4%	2.9%	4.1%
(ii) 60 (40%)	0.0%	0.5%	1.6%
(iii) 90 (60%)	1.9%	2.2%	3.3%
(iv) 120 (80%)	1.3%	1.6%	2.8%
Average	1.4%	1.8%	3.0%

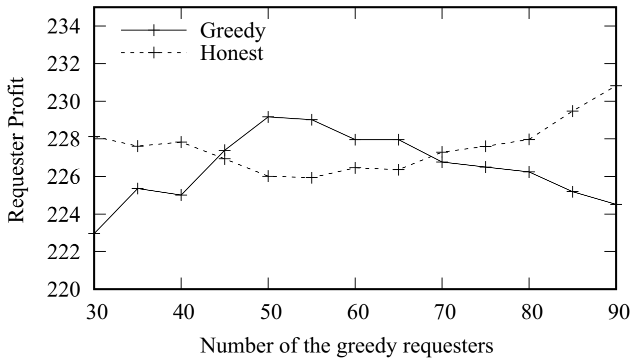

Fig. 2. Requester Profit distribution around 60 greedy requesters (false rate = 10%) based on (M1).

Table 4. SSIs of (M1) against the providers.

(a) The results of the index p_P.

Num. of the greedy participants	False rate		
	(a) +10%	*(b) +20%*	*(c) +50%*
(i) 30 (20%)	15.5%	28.9%	60.1%
(ii) 60 (40%)	12.2%	26.7%	56.4%
(iii) 90 (60%)	12.3%	26.5%	53.4%
(iv) 120 (80%)	14.3%	26.8%	49.0%
Average	13.6%	27.2%	54.7%

(b) The results of the index $\hat{p}_P^G$.

Num. of the greedy participants	False rate		
	(a) +10%	*(b) +20%*	*(c) +50%*
(i) 30 (20%)	11.7%	23.0%	53.2%
(ii) 60 (40%)	5.2%	14.3%	39.2%
(iii) 90 (60%)	1.5%	6.3%	22.8%
(iv) 120 (80%)	**−1.9%**	**−2.4%**	0.3%
Average	4.1%	10.3%	28.9%

profit than the honest ones, although not by a significant amount.

Figure 2 shows the RPs of the honest and greedy requesters (false rate = 10%) based on matching method (M1). As shown in this figure, the RP of the greedy requesters has a peak at approximately 50 greedy requesters. This is because greedy requesters can steal resources from honest requesters when the number of greedy requesters is low. However, as number of greedy requesters increases, the probability of their requests being assigned to high-cost resource offers increases.

Tables 4 and **5** show the SSIs against the providers (i.e., (2) greedy provider case) in the resource matching methods (M1) and (M2), respectively.

As shown in **Table 4(a)**, in the case of (M1), the greedy providers obtain less profit than the honest providers based on the increment of the usage fee, as the requesters procure offers with lower costs. A higher false rate causes additional profit loss. It does not depend on the occupancy rate of the greedy providers. However, as shown

Table 5. SSIs of (M2) against the providers.

(a) The results of the index p_P.

Num. of the greedy participants	False rate		
	(a) +10%	*(b) +20%*	*(c) +50%*
(i) 30 (20%)	**−11.8%**	**−18.1%**	**−28.4%**
(ii) 60 (40%)	**−14.1%**	**−18.4%**	**−30.2%**
(iii) 90 (60%)	**−13.8%**	**−17.7%**	**−28.1%**
(iv) 120 (80%)	**−7.9%**	**−11.8%**	**−19.9%**
Average	**−11.9%**	**−16.5%**	**−26.6%**

(b) The results of the index $\hat{p}_P^G$.

Num. of the greedy participants	False rate		
	(a) +10%	*(b) +20%*	*(c) +50%*
(i) 30 (20%)	**−11.1%**	**−17.9%**	**−30.6%**
(ii) 60 (40%)	**−11.5%**	**−17.1%**	**−33.8%**
(iii) 90 (60%)	**−10.4%**	**−16.3%**	**−34.3%**
(iv) 120 (80%)	**−7.8%**	**−14.8%**	**−33.2%**
Average	**−10.2%**	**−16.5%**	**−33.0%**

in **Table 4(b)**, in case (iv), most providers are greedy, the greedy providers obtain more profit than that in the ideal case. This means that the total profit of the providers will increase because of the false information. Although this is the motivation to submit false information, the providers will hesitate to do so, as the profits of the greedy providers are less than those of the honest providers. As a result, (M1) is virtually strategyproof against the providers.

In contrast, as shown in **Tables 5(a)** and **(b)**, in the case of (M2), all values are negative, that is, the greedy providers obtain greater profits. This is because the matchmaking function does not consider profit distribution, and sometimes utilizes high-cost resource offers to maximize the SP. This means that the profits of requesters unfairly move to providers. As mentioned above, we focus on "SP maximization" rather than "RP maximization" for co-prosperity. Thus, a new matching method is required to reduce the motivation of greedy providers to submit false information. In this study, we propose a new method with characteristics of both (M1) and (M2), to improve the strength of the strategyproofness.

5. Strategyproofness Improvement Method

In this section, we propose a matching method for balancing SP maximization with high strength of the strategyproofness. The key idea of our method is the combination of (M1) and (M2). (M1) has a high strategyproof property as shown in the previous section, and will improve the strength of the strategyproofness of (M2). The simplest way to combine the two methods is to maximize a weighted linear sum of the two objective functions (Eqs. (1) and (2)). However, it is difficult to decide the appropriate weight value. Accordingly, we adopt a profit-sharing method inspired by the "nucleolus" concept in cooperative game theory. The nucleolus distributes the profit of an entire coalition, to minimize the maximum value of dissatisfaction among players. There are some other related concepts (e.g., Shapley values). Among such concepts, nucleolus is considered to have a co-prosperity [22] and highly convincing nature [23]. This nature matches the aim of the crowdsourced manufacturing concept.

5.1. Resource Matching with Profit-Sharing

First, we define game structure for profit-sharing. We consider that there are two players: 1) the group of requesters which represents all requesters and aims to maximize the sum of the RP, and 2) the service provider of the collaboration space, who aims to maximize the SP. The matchmaking function decides the profit distribution between these players, to minimize the maximum value of dissatisfaction. It decides the sum of the PP implicitly, as the SP is equal to the sum of the RP and PP. This mechanism does not require arbitrary weight value tuning, and is of a convincing nature.

Next, we propose a resource matching method with profit-sharing, as shown in the following steps.

< The Matching Steps of the Proposed Method >

Step 1: Calculate the maximum value of the RP (RP^*) and SP (SP^*) with the resource matching methods (M1) and (M2), respectively.

Step 2: Define the maximum dissatisfaction, as shown below.

$$maxD = \max(RP^* - RP, SP^* - SP) \quad (14)$$

Equation (14) indicates the maximum gap of the RP and SP from their maximum values. Here, *maxD* is a variable indicating the maximum dissatisfaction.

Step 3: Calculate the nucleolus by solving the MIPP as below, and obtain the minimum value of *maxD* ($maxD^*$).

[Objective Function]

$$\text{minimize: } maxD \quad (15)$$

[Constraints]
In addition to Eqs. (3)–(9), the following constraints are considered to calculate *maxD*.

$$maxD \geq RP^* - RP \quad (16)$$

$$maxD \geq SP^* - SP \quad (17)$$

Step 4: Maximize the SP while maintaining the minimum value of *maxD*. In addition to Eqs. (3)–(9), (16), and (17), the following constraint is considered in (M2).

$$maxD = maxD^* \quad (18)$$

In the following sections, we denote the proposed method as "(M3) RP-SP balancing."

Table 6. SSIs of (M3) against the requesters.

(a) The results of the index p_R.

Num. of the greedy participants	False rate		
	(a) +10%	*(b) +20%*	*(c) +50%*
(i) 30 (20%)	2.5%	2.8%	3.6%
(ii) 60 (40%)	**−0.6%**	**−0.4%**	0.6%
(iii) 90 (60%)	3.0%	3.3%	4.2%
(iv) 120 (80%)	3.7%	3.8%	4.8%
Average	2.1%	2.4%	3.3%

(b) The results of the index $\hat{p}_R^G$.

Num. of the greedy participants	False rate		
	(a) +10%	*(b) +20%*	*(c) +50%*
(i) 30 (20%)	2.0%	2.4%	3.2%
(ii) 60 (40%)	**−0.2%**	0.0%	1.0%
(iii) 90 (60%)	1.4%	1.8%	2.7%
(iv) 120 (80%)	1.0%	1.3%	2.3%
Average	1.1%	1.4%	2.3%

Table 7. SSIs of (M3) against the providers.

(a) The results of the index p_P.

Num. of the greedy participants	False rate		
	(a) +10%	*(b) +20%*	*(c) +50%*
(i) 30 (20%)	11.0%	22.6%	50.2%
(ii) 60 (40%)	7.0%	20.7%	48.1%
(iii) 90 (60%)	7.9%	20.2%	43.7%
(iv) 120 (80%)	11.9%	21.0%	40.6%
Average	9.4%	21.1%	45.7%

(b) The results of the index $\hat{p}_P^G$.

Num. of the greedy participants	False rate		
	(a) +10%	*(b) +20%*	*(c) +50%*
(i) 30 (20%)	7.8%	17.1%	42.6%
(ii) 60 (40%)	1.7%	9.4%	30.1%
(iii) 90 (60%)	**−0.6%**	2.3%	12.3%
(iv) 120 (80%)	**−2.8%**	**−4.9%**	**−7.3%**
Average	1.5%	6.0%	19.4%

5.2. Evaluation of the Proposed Method

In this section, we evaluate the proposed method. The simulation conditions are shown in **Table 1**.

Table 6 shows the strategyproofness of the proposed method against the requesters. As with the methods (M1) and (M2), the proposed method is virtually strategyproof in most cases, and will reduce the motivation for requesters to exaggerate their budgets.

Table 7 shows the strategyproofness of the proposed method against the providers.

Table 7(a) shows that greedy providers' profits are less than those of the honest one in all cases. This means

Table 8. Loss of system profit (SP) against (M2) SP maximization.

(a) Greedy requester existence cases.

Method	False rate		
	(a) +10%	*(b) +20%*	*(c) +50%*
(M1) RP maximization	3.2%	3.1%	2.5%
(M3) Proposed	1.2%	1.1%	1.0%

(b) Greedy provider existence cases.

Method	False rate		
	(a) +10%	*(b) +20%*	*(c) +50%*
(M1) RP maximization	3.6%	3.8%	4.5%
(M3) Proposed	1.3%	1.4%	1.7%

that the proposed method will reduce the motivation for providers to increase their unit price. However, **Table 7(b)** shows that when greedy providers occupy the majority, they obtain greater profits than that in the ideal case. Although this is the motivation to submit false information, the providers will hesitate to do so. This is because the participants cannot anticipate the number of greedy participants in advance, and the expected profit losses (in the "Average" row) are all positive.

As a result, the proposed method is expected to induce participants to submit their true information when they request or offer resources.

Table 8 shows the loss of SP against (M2). The results are averaged over four scenarios (i)–(iv) with different numbers of greedy participants and 20 random instances, as shown in **Table 1**. The simulation results show that the loss of SP in the proposed method (M3) is less than that in (M1). This means that the proposed method can improve strategyproofness, with a limited loss of SP.

6. Conclusions

New production system concepts are required for a sustainable society. Crowdsourced manufacturing is a promising concept. This paper presented a new resource matching method for crowdsourced manufacturing. We focused on strategyproofness to thereby realize a co-prosperity ecosystem in which all participants act fairly. The proposed method is based on profit-sharing, as inspired by the nucleolus concept. The computational study showed that the proposed method forces greedy participants to lose their profit, and motivates them to submit true information related to resource matching with a limited loss of profit for the whole system.

The proposed method is not a strict method, and does not guarantee strategyproofness. Thus, additional approaches (e.g., audit of resource usage fee) will be helpful. Moreover, it is also important to carefully discuss broad perspectives with the participants, such as productivity, matching stability, and strategyproofness before deciding on the design of a crowdsourced manufacturing system.

In future work, we will examine the behavior of the proposed method under a wide range of simulation scenarios. We will also execute empirical research to demonstrate the validity of the proposed SSI. Moreover, research on emergent behavior (e.g., cartel) will be required.

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