Scalable hypernetwork-based manufacturing services supply-demand matching towards Industrial Internet platforms

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***Abstract*—With the deeper application of sensor & cloud-based environment into manufacturing, deploying the Industrial Internet platforms towards smart manufacturing has been more concerned. Based on the platforms, ubiquitous enterprises could participate in and support cross-enterprise collaboration, so that their distributed manufacturing facilities and capabilities could be shared and utilized in the form of manufacturing services (MSs). However, in order to achieve the successful application of the platforms, how to settle the supply-demand matching (SDM) of distributed manufacturing facilities and capabilities in the form of MSs, namely MSs-SDM, becomes one of the most urgent problems to be solved. In addition, the trend of manufacturing socialization makes this problem much more scalable. In this context, this paper aims to establish a set of hypernetwork-based models for the scalable MSs-SDM problem at first. An enterprises collaborative network is derived which is as the projection of the underlying MSs-SDM situation to the upper-layer enterprises. Secondly, a method according to the evaluation on cross-enterprise collaboration is proposed for this problem. In which, the created utilities, the rates of service invocation and task allocation from both the global view of overall network and the local view of each participated enterprise are evaluated. Finally, two steps of experiments introducing scalabilities illustrate the feasibility of the proposed models and the effectiveness of the derived method for MSs-SDM optimization, and further reveal five managerial implications to improve the operation and industrial practice of the platforms.**

***Index Terms*—Manufacturing service (MS), supply-demand matching (SDM), Industrial Internet platform, cross-enterprise collaboration, hypernetwork, scalability**

I. Introduction

To achieve information collection of distributed manufacturing with sensor-based environment as well as dynamic sharing of heterogeneous resources with cloud-based environment, a series of Industrial Internet platforms supporting collaboration among ubiquitous enterprises are put forward towards smart manufacturing [1-3]. There have existed some Industrial Internet platforms, for example, MindSphere platform of Siemens, Predix platform of GE, ABB Ability platform, IoT Foundation platform of IBM, etc. By introducing the concept of manufacturing service (MS), those platforms are being developed based on cyber-physical systems (CPSs) and service-oriented architecture (SOA) [4-6]. It makes possible that the distributed manufacturing resources and capabilities which are in the form of MSs, would be centralized and managed in logical and could be distributed and collaborated in use as well [4]. Thus, it is helpful to improve productivity and value creation by cross-enterprise collaboration and the corresponding socialized sharing of manufacturing resources and capabilities in the form of MSs [7, 8].

For the socialized and ubiquitous sharing of MSs with cloud-based environment in Industrial Internet platforms, many challenges are derived immediately especially the scalability [9]. As we know, one of the common issues need to be addressed in various advanced manufacturing systems (AMSs) is supply-demand matching (SDM) and optimal allocation of diverse manufacturing resources [10], so is it in Industrial Internet platforms. Therefore, as the platforms are becoming more and more concerned, how to make decisions for SDM problem of MSs, namely MSs-SDM, is an urgent problem to determine whether the platforms could be applied.

In the operation process of an Industrial Internet platform, large numbers of users participate in, including service providers and consumers. Thus, there are various manufacturing tasks and demands being submitted abruptly by multiple consumers to the platform at some point or during a certain time interval. Meanwhile, the real-time information of diverse idle MSs owned by different providers are also published on the platform. These MSs can meet diverse function requirements of different tasks. The MSs-SDM problem is to get the mapping between each submitted task or demand and one of its appropriate services. Therefore, the result of this problem reveals the matching relationships between the demands or tasks and the corresponding appropriate MSs, as well as the collaboration among the participated enterprises, as shown in Fig. 1.

For the mentioned MSs-SDM problem, a hypernetwork-based solution framework and the corresponding hypernetwork modelling method are explored in previous work [10, 11]. Because of the advantages of complex network-based approach, this paper would carry out some further improvement by introducing multi-layer hypernetwork models to address this scalable issue. *Firstly*, hypernetwork models with the scalable

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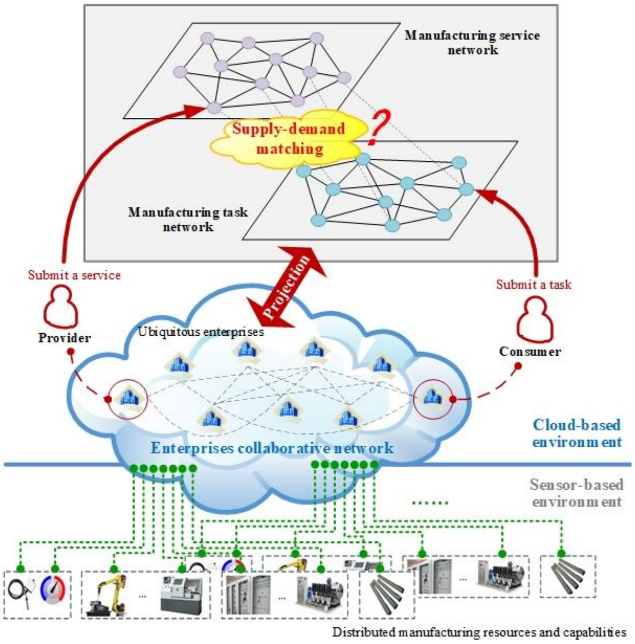


Fig. 1. Manufacturing services supply-demand matching under the environment of Industrial Internet platforms.

nodes and edges pave the way for scalability modelling and even characteristics statistics of the participated enterprises as well as their services and tasks under the environment of Industrial Internet platforms. *Secondly*, because of the multi-layer network topology, hypernetwork models are much easier to depict and reveal diverse kinds of correlations between each two heterogeneous nodes and to find and add new correlations, and further to compare the paths and mapping with services and tasks in topologies.

Based on but different from the previous proposed framework, the further contributions of this paper are highlighted as follows.

a) A set of hypernetwork-based models are defined and used to describe the scalable optimization problem of MSs-SDM. With the established models, an upper-layer enterprises collaborative network is derived and extracted from the underlying MSs-SDM situation.
b) A method considering the evaluation on cross-enterprise collaboration is proposed for MSs-SDM optimization based on both global and local indicators of the upper-layer enterprises collaborative network.
c) Two steps of experiments employing particle swarm optimization algorithm are conducted to analyze effectiveness of the proposed models and method introducing supply-demand dual scalabilities, and further demonstrate its potential application and reveal some managerial implications for industrial practice.

The remainder of this paper is organized as follows. The related work is reviewed in Section 2. In Section 3, the multi-layer and scalable hypernetwork-based models of the MSs-SDM problem are defined and established from four aspects. As the projection of underlying MSs-SDM situation, an enterprises collaborative network is extracted and the corresponding method considering its evaluation on cross-enterprise collaboration is proposed in Section 4. Groups of experiments considering different scales of supply and demand are conducted and deeply analyzed in Section 5. Finally, Section 6 provides a conclusion and points out the future work.

II. Related work

A. Discussions and methodologies of MSs-SDM

There exist many studies related to the MSs-SDM issues, such as, service discovery [7, 12], service recommendation [13], service selection [14], service composition [15, 16], etc. In general, most of the existing related studies just pay attention to the single object of supply (i.e., manufacturing resources or services), which could be classified into the following three stages [17]. (a) For the first stage of studies which are on *a single service*, there are the studies on service description, service evaluation, and service selection. (b) For the second stage of studies which are on *service chain*, it mainly covers the discussions on service composition and supply chain collaboration. (c) For the third stage of studies which are on *service network*, they are mainly carried out on service composition network, supply network, and so on. View from the abovementioned three stages, because of the derived correlations among the socialized and ubiquitous MSs and among the diverse requirements, the third stage of discussion based on network topology is becoming an inevitable trend. As to the scalable MSs-SDM issues, the demand-driven factors cannot be ignored, thus both supply and demand are indispensable. As it said before, the existing studies just considered the supply aspect of services. However, they are rare to take both supply and demand into account at the same time.

In order to achieve reasonable cost-efficiency of supply and high-efficient completion of demand, researchers are trying to take the matching problem as an integer programming model [18], or match services or tasks hierarchically based on their flow and path [19]. In addition, there are various indicators referred to the matching problem, for example, service allocation based on business indicators [20], matching based on interests of supply and demand in remanufacturing [21], business environment rules-based matching [22], etc. Even though the SDM by characteristics comparison and analysis with resource database have been carried out, these studies still did not concern the correlations among MSs as well as among different business operations. Furthermore, during the operation process of Industrial Internet platforms, when the quantities of service and demand expand rapidly, these methods would be inefficient and unable to meet the operational requirements of dynamics and scalabilities.

B. Applications of complex networks in SDM related problems

With the trend of network topology-based discussion mentioned before, most of the existing studies focus on optimization and coordination of supply chain or supply chain network, e.g., hypernetwork-based design and optimization of integrated e-supply chain [23], dynamic production networks of autonomous work systems [24], demand and capacity sharing in supply network collaboration [25], etc. As to the typical collaboration analysis based on the theory of complex networks, most of studies are mainly about the robustness and vulnerability analysis of collaborative production networked organizations [26, 27], the clustering and modularity analysis of enterprise relationship network [28], complex networked enterprises collaboration in production industry [29], and so on. However, these studies just considered the business relationships from the layer of enterprises, while ignored the underlying matchable relationships and the detailed matching results between different supplies and demands.

Actually, the logical models of enterprises collaborative networks which are driven by different demands and resulted from the specific manufacturing collaborative activities, are determined by the underlying mapping relationships between supply and demand (i.e., the results of MSs-SDM). In consequence, a worthwhile topic is carried out, that is how to use the SDM results to analyze collaboration of the upper-layer enterprises, and to evaluate and improve SDM strategies as well as their value creation at the same time. The key point of this topic is to achieve the mutual mapping and transformation between SDM relationships and cross-enterprise collaboration relationships. In response to this topic, a hypernetwork-based solution framework and the modelling method are proposed in the authors' previous work [10, 11].

After reviewing the related literatures, the following research gaps would be identified:

(a) Most of the related work just considered the supply aspect of services, but the studies taking supply and demand into account simultaneously are rare.

(b) The supply-demand dual scalabilities during the operation process of Industrial Internet platforms make a big difference to the MSs-SDM problem, the explored methods would be unable to meet the operational requirements of dynamical scalabilities.

(c) The cross-enterprise collaboration based on Industrial Internet platforms always depends on the underlying matchable relationships and matching results between different supplies and demands, which is almost ignored in the existing discussions.

Considering the above research gaps and grounded in the previous work, it is inspired that introducing the hypernetwork models is potential to describe, solve, and discuss both the MSs-SDM optimization problems and the derived cross-enterprise collaboration evaluation simultaneously.

III. Hypernetwork-based models of the MSs-SDM problem

With different demands and objectives, a variety of MSs-SDM optimization problems under the environment of Industrial Internet platforms could be configured. On one hand, for *different demands*, a primitive task stays in the hypernetwork model as an isolated node, and a compound task would be divided into many subtasks with the certain workflow and exists in the hypernetwork model as a directed subgraph. On the other hand, for *different objectives*, there are some contradictions when different service providers and consumers make their own decentralized decisions and take different kinds of evaluation indicators into consideration. However, towards Industrial Internet platforms, both of primitive tasks and compound tasks always co-exist in their practical operation process, and the system-centered decision-making is considered in priority. Therefore, multiple primitive and compound tasks, and the system-centered objectives are selected to configure the MSs-SDM optimization problem which is discussed firstly in this paper. The proposed hypernetwork-based optimization models are illustrated from the following four aspects. Notations are defined in Table 1.

TABLE I
NOMENCLATURE

Notations	
E	set of the participated enterprises
$k = 1,2,\dots,NoE$	number of the participated enterprises, $NoE = \|E\|$
e_k	the enterprise k
S^k	set of services submitted by e_k
$i_k = 1,2,\dots,n_k$	number of services submitted by e_k, $n_k = \|S^k\|$
$s_{i_k}^k$	the i_kth service submitted by e_k
T^k	set of tasks submitted by e_k
$j_k, p, q = 1,2,\dots,m_k$	number of tasks submitted by e_k, $m_k = \|T^k\|$
$t_{j_k}^k$	the j_kth task submitted by e_k
$Link_{T^k}$	the incidence matrix of the set of tasks T^k, where its element $l_{pq}^k = \begin{cases} 1, \text{the tasks are executed from } t_p^k \text{ to } t_q^k \\ 0, \text{there is no execution process between } t_q^k \text{ and } t_p^k \\ -1, \text{the tasks are executed from } t_q^k \text{ to } t_p^k \end{cases}$
S_Net	manufacturing service network
S	set of services submitted by all participated enterprises
$i, i' = 1,2,\dots,NoS$	number of services submitted by all enterprises, $NoS = \sum_{k=1}^{NoE} n_k$
s_i	the service i
E^S	the incidence matrix of the set of services S, where its element $e_{ii'}^S = \begin{cases} 1, \text{exists a function complementary edge between } s_i \text{ and } s_{i'} \\ 0, \text{no edge between } s_i \text{ and } s_{i'} \\ -1, \text{exists a function similar edge between } s_i \text{ and } s_{i'} \end{cases}$
W^S	the weight matrix of the set of services S, where its element $w_{ii'}^S$ is to describe the function-similar degree between each two similar services, $w_{ii'}^S \in (0,1]$
T_Net	manufacturing task network
T	set of tasks submitted by all participated enterprises
$j, j' = 1,2,\dots,NoT$	number of tasks submitted by all enterprises, $NoT = \sum_{k=1}^{NoE} m_k$
t_j	the task j
E^T	the incidence matrix of the set of tasks T, where its element $e_{jj'}^T = \begin{cases} 1, \text{exists a function complementary edge between } t_j \text{ and } t_{j'} \\ 0, \text{no edge between } t_j \text{ and } t_{j'} \\ -1, \text{exists a function similar edge between } t_j \text{ and } t_{j'} \end{cases}$
W^T	the weight matrix of the set of tasks T, where its element $w_{jj'}^T$ is to determine the execution process direction between each two tasks, $w_{jj'}^T = \begin{cases} 1, t_j \text{ is the input of } t_{j'} \\ 0, \text{no execution workflow between } t_j \text{ and } t_{j'} \\ -1, t_j \text{ is the output of } t_{j'} \end{cases}$
E^{S_T}	Set of hyper-edges between S_Net and T_Net, where its element $e_{ij}^{S\_T} = \begin{cases} 1, s_i \text{ is matchable/can be used to execute } t_j \\ 0, s_i \text{ is unmatchable/cannot be used to execute } t_j \end{cases}$
U	the multi-attribute utility
$l = 1,2,\dots,L$	number of evaluation indicators considered in U
$Value_l$	the lth evaluation indicator considered in U, where the element $value_{l_{ij}}$ reveals the value of the lth evaluation indicator resulted when s_i is invoked by t_j
U_l	the utility of the lth evaluation indicator
w_l	the weight of U_l, $\sum_{l=1}^{L} w_l = 1$
$u_{l_{ij}}$	the utility of the lth evaluation indicator resulted when s_i is invoked by t_j
u_{ij}	the multi-attribute utility created when s_i is invoked by t_j
$P_{ij}^{S\_T}$	set of utility evaluation parameters corresponding to each $e_{ij}^{S\_T}$
u_{e_k}	the created utility of e_k
SAU	the system average utility
TR_{e_k}	rate of task allocation of e_k
SAT	the system average rate of task allocation
STT	the system total rate of task allocation
SR_{e_k}	the rate of service invocation of e_k
SAS	the system average rate of service invocation
STS	the system total rate of service invocation
Decision variables	
$A = \{a_{ij}\}_{NoS \times NoT}$	a matrix for recording the MSs-SDM situation between services and tasks, where $a_{ij} = \begin{cases} 1, & s_i \text{ is selected for } t_j \\ 0, & s_i \text{ is not selected for } t_j \end{cases}$

A. Problem description

The description of the participated enterprises are supplemented in this paper to address the scalable MSs-SDM optimization problem based on the previous proposed hypernetwork framework, which is composited of manufacturing service network (S_Net), manufacturing task network (T_Net), and hyper-edges (E^{S_T}) between these two networks [11]. The supplemented parts are mainly to reveal relationships that each manufacturing service and task belong to which enterprise. As the result, the scalable MSs-SDM problem to be addressed in this paper is described as follows.

1) Models of the participated enterprises

Formulas (1) and (2) show the set of the participated enterprises and the description model of each participated enterprise. For each participated enterprise e_k, no matter it is a service provider or a consumer, there is the information of both the submitted services and tasks in its description model. The numbers of its services and tasks submitted to the platform are marked as n_k and m_k respectively.

$$E = \{e_k | k = 1,2,\dots,NoE\} \tag{1}$$

$$\begin{aligned} & e_k = < S^k, T^k > \\ & S^k = \{s_{i_k}^k | i_k = 1,2,\dots,n_k\} \\ & T^k = \{t_{j_k}^k | j_k = 1,2,\dots,m_k\} \end{aligned} \tag{2}$$

As mentioned before, each task node indicates a primitive task which is indecomposable, and a compound task is presented as a subgraph which consists of a set of primitive task nodes with a certain workflow in the hypernetwork-based models. In order to illustrate the workflow of the subtasks submitted by e_k, the incidence matrix of tasks is supplemented in formula (3).

$$\mathrm{Link}_{T^k} = \{l_{pq}^k | p,q = 1,2,\dots,m_k\} \tag{3}$$

Obviously, the role of an enterprise can be judged by the information of its services and tasks in the above models according to the following rules.

- If $S^k = \emptyset \,\&\, T^k = \emptyset$, or $n_k = 0 \,\&\, m_k = 0$, e_k has registered but submits neither service nor task to the platform.
- If $S^k \neq \emptyset \,\&\, T^k = \emptyset$, or $n_k \neq 0 \,\&\, m_k = 0$, e_k is a service provider.
- If $S^k = \emptyset \,\&\, T^k \neq \emptyset$, or $n_k = 0 \,\&\, m_k \neq 0$, e_k is a service consumer.
- If $S^k \neq \emptyset \,\&\, T^k \neq \emptyset$, or $n_k \neq 0 \,\&\, m_k \neq 0$, e_k is both a service provider and a consumer.

2) Models of manufacturing service network S_Net

From the systematic perspective of an Industrial Internet platform, considering all of services submitted by each enterprise, manufacturing service network is supplemented, as shown in formula (4).

$$\begin{aligned} & S\_Net = < S, E^S, W^S > \\ & S = \{s_i | s_i = 0,1; i = 1,2,\dots,NoS\} \\ & E^S = \{e_{ii'}^S | e_{ii'}^S = -1,0,1; i,i' = 1,2,\dots,NoS\} \\ & W^S = \{w_{ii'}^S | w_{ii'}^S \in (0,1] \text{ when } e_{ii'}^S = -1; i,i' = 1,2,\dots,NoS\} \end{aligned} \tag{4}$$

In the above models, $e_{ii'}^S = -1$ illustrates the function-similar edge and $w_{ii'}^S$ describes the corresponding function-similar degree between each two similar services. As a result, $w_{ii'}^S$ is meaningful only when $e_{ii'}^S = -1$. Moreover, under the environment of an Industrial Internet platform, almost all of the services could be divided into two categories which are either repeatedly invoked by different tasks at the same time or exclusively invoked by only one task, namely repeatable services and non-repeatable services. In order to illustrate these two categories of services, a repeatable service is marked as $s_i = 1$ and a non-repeatable service is marked as $s_i = 0$, respectively. The numbers of repeatable services and non-repeatable services are recorded as NoS_r and NoS_nr.

For all services in the platform, $S = \bigcup_{k=1}^{NoE} S^k$. It is necessary to make the correspondence and transformation between the service ID in $S_N$et model and the service ID in the corresponding enterprise description model. Similar to the chained data storage, in the model of $S_N$et, the i_kth service $s_{i_k}^k$ of the enterprise e_k is represented as $s_{i_k+\sum_{r=1}^{k-1} n_r}$. Thus, the enterprise that s_i in $S_N$et belongs to can be judged by formula (5). Known from formula (5), the service s_i in $S_N$et is the $(i - \sum_{r=1}^{k-1} n_r)$th service of the kth enterprise.

$$\begin{cases} 0 < i \le n_k, \text{when } k = 1 \\ \sum_{r=1}^{k-1} n_r < i \le \sum_{r=1}^{k} n_r, \text{when } k \ge 2 \end{cases} \tag{5}$$

3) Models of manufacturing task network T_Net

Similar to the models of $S_N$et, manufacturing task network $T_N$et is supplemented as formula (6).

$$\begin{aligned} & T\_Net = < T, E^T, W^T > \\ & T = \{t_j | j = 1,2,\dots,NoT\} \\ & E^T = \{e_{jj'}^T | e_{jj'}^T = -1,0,1; j,j' = 1,2,\dots,NoT\} \\ & W^T = \{w_{jj'}^T | w_{jj'}^T = -1,0,1; j,j' = 1,2,\dots,NoT\} \end{aligned} \tag{6}$$

Different from the $w_{ii'}^S$ in $S_N$et, $w_{jj'}^T$ in $T_N$et is to determine the execution process direction between each two different task nodes. In addition, same as the model of $S_N$et, all of tasks in the platform are listed in the set $T = \bigcup_{k=1}^{NoE} T^k$. The j_kth task $t_{j_k}^k$ of the enterprise e_k is the $(j_k + \sum_{r=1}^{k-1} m_r)$th task in $T_N$et, which is marked as the task $t_{j_k+\sum_{r=1}^{k-1} m_r}$. Thus, the task node t_j in $T_N$et can be deduced by formula (7).

$$\begin{cases} 0 < j \le m_k, \text{when } k = 1 \\ \sum_{r=1}^{k-1} m_r < j \le \sum_{r=1}^{k} m_r, \text{when } k \ge 2 \end{cases} \tag{7}$$

It shows that t_j of $T_N$et is the $(j - \sum_{r=1}^{k-1} m_r)$th task submitted by the enterprise e_k. In addition, if $l_{pq}^k \neq 0$ between tasks t_p^k and t_q^k in the enterprise e_k, there also exists an edge between the corresponding task nodes $t_{p+\sum_{r=1}^{k-1} m_r}$ and $t_{q+\sum_{r=1}^{k-1} m_r}$ in $T_N$et, as shown in formulas (8) and (9).

$$e_{(p+\sum_{r=1}^{k-1} m_r)(q+\sum_{r=1}^{k-1} m_r)}^T = 1 \tag{8}$$

$$w_{(p+\sum_{r=1}^{k-1} m_r)(q+\sum_{r=1}^{k-1} m_r)}^T = l_{pq}^k \tag{9}$$

4) Models of hyper-edges E^{S_T}

The hyper-edges between service nodes and task nodes indicate the matchable correlations. The set of hyper-edges is defined as formula (10).

$$E^{S\_T} = \{e_{ij}^{S\_T} | e_{ij}^{S\_T} = 0,1; i = 1,2,\dots,NoS; j = 1,2,\dots,NoT\} \tag{10}$$

Based on the models of $S_N$et, $T_N$et and E^{S_T}, there is no doubt that the matchable relationships are determined by the function-related correlations between services as well as between tasks. Consequently, each hyper-edge $e_{ij}^{S\_T}$ associates with the edges e_{i*}^S in $S_N$et and e_{*j}^T in $T_N$et. If s_i is matchable with t_j namely $e_{ij}^{S\_T} = 1$, all of the function-similar services of s_i, which are marked as s_*, are also matchable with t_j. That is to say, if $e_{ij}^{S\_T}=1$ and $e_{i*}^{S}=-1$, then $e_{*j}^{S\_T}=1$. Similarly, if $e_{ij}^{S\_T}=1$ and $e_{*j}^{T}=-1$, then $e_{i*}^{S\_T}=1$. It means that all the function-similar tasks of t_j, which are marked as t_*, also can be executed by s_i.

B. Indicators modelling

In this paper, the evaluation indicators are defined with the multi-attribute utility theory [30], as shown in formula (11). Four indicators, such as cost, energy consumption, risk and time, are considered firstly in this paper. It means that L is set as 4 in formula (11).

$$U=\sum_{l=1}^{L} w_l U_l \tag{11}$$

Based on the multi-attribute utility model, the constituent utility $u_{l_{ij}}$ corresponding to those four evaluation indicators when s_i is selected for t_j is evaluated as formula (12), in which, $Value_l$ is treated as the set of any kind of evaluation indicators. In this paper, define the notations $value_{1_{ij}}$ – $value_{4_{ij}}$ are the respective values of cost, energy consumption, risk and time, namely $cost_{ij}$, $energy_{ij}$, $risk_{ij}$ and $time_{ij}$. As a result, the multi-attribute utility u_{ij} which is created if s_i performs t_j is calculated by formula (13).

$$\begin{aligned}&Value_l=\left\{value_{l_{ij}} \mid l=1,2,\dots,L; i=1,2,\dots,NoS; j=1,2,\dots,NoT\right\}\\ &u_{l_{ij}}=\begin{cases}\min(value_{l_{*j}})/value_{l_{ij}}, \text{ if } value_l \text{ is negatively correlated with } u_l\\ value_{l_{ij}}/\max(value_{l_{*j}}), \text{ if } value_l \text{ is positively correlated with } u_l\end{cases}\end{aligned} \tag{12}$$

$$u_{ij}=\sum_{l=1}^{L} w_l u_{l_{ij}} \tag{13}$$

Obviously, where the hyper-edge exists namely $e_{ij}^{S\_T}=1$, the utility and the value of evaluation indicators exist. Therefore, the set of utility evaluation parameters $P_{ij}^{S\_T}$ corresponding to each hyper-edge is defined as formula (14). However, $P_{ij}^{S\_T}=\emptyset$ if $e_{ij}^{S\_T}=0$.

$$\begin{aligned}&e_{ij}^{S\_T}=1\rightarrow P_{ij}^{S\_T}=\{u_{ij}, cost_{ij}, energy_{ij}, risk_{ij}, time_{ij}\}\\ &i=1,2,\dots,NoS; j=1,2,\dots,NoT\end{aligned} \tag{14}$$

C. Objective functions modelling

It is assumed that the utility u_{ij} created by s_i performing t_j is evenly shared by both of the enterprise who is the provider of s_i and the enterprise who is the consumer submitting t_j. Therefore, as to the enterprise e_k submitting n_k services and m_k tasks to the platform, its utility u_{e_k} can be calculated by formula (15).

$$u_{e_k}=\frac{1}{2}\sum_{j=1}^{NoT}\sum_{i=1+\sum_{r=1}^{k-1}n_r}^{\sum_{r=1}^{k}n_r} u_{ij}\times a_{ij}+\frac{1}{2}\sum_{j=1+\sum_{r=1}^{k-1}m_r}^{\sum_{r=1}^{k}m_r}\sum_{i=1}^{NoS} u_{ij}\times a_{ij} \tag{15}$$

As a result, there are the following three categories of objective functions by the centralized or system-centered decision making, all of which are considered from the perspective of the whole system. As shown in formulas (16)-(18), three further definitions namely $\overline{NoE}$, $\overline{NoE1}$ and $\overline{NoE2}$ are supplemented here before illustrating different objective functions. $\overline{NoE1}$ is the set of enterprises providing no service and $\overline{NoE2}$ is the set of enterprises submitting no task in current MSs-SDM solution, and $\overline{NoE}$ is the set of enterprises who both provide no service and submit no task.

$$\text{If } \sum_{j=1}^{NoT}\sum_{i=1+\sum_{r=1}^{k-1}n_r}^{\sum_{r=1}^{k}n_r} a_{ij}=0, \text{ then } e_k\in\overline{NoE1} \tag{16}$$

$$\text{If } \sum_{j=1+\sum_{r=1}^{k-1}m_r}^{\sum_{r=1}^{k}m_r}\sum_{i=1}^{NoS} a_{ij}=0, \text{ then } e_k\in\overline{NoE2} \tag{17}$$

$$\text{If } \sum_{j=1}^{NoT}\sum_{i=1+\sum_{r=1}^{k-1}n_r}^{\sum_{r=1}^{k}n_r} a_{ij}=0 \text{ and } \sum_{j=1+\sum_{r=1}^{k-1}m_r}^{\sum_{r=1}^{k}m_r}\sum_{i=1}^{NoS} a_{ij}=0, \text{ then } e_k\in\overline{NoE} \tag{18}$$

1) Maximization of average utility

Based on u_{e_k}, formula (19) is for calculating the average utility of the whole system (*SAU*). Formula (20) is the objective function when maximizing *SAU*.

$$\begin{aligned}&SAU=\sum_{k=1}^{NoE} u_{e_k}\Big/\left(NoE-|\overline{NoE}|\right)\\ &\text{i.e., } SAU=\sum_{j=1}^{NoT}\sum_{i=1}^{NoS} u_{ij}\times a_{ij}\Big/\left(NoE-|\overline{NoE}|\right)\end{aligned} \tag{19}$$

$$\max SAU \tag{20}$$

2) Maximization of average rate of task allocation

According to the elements of decision coefficient a_{ij}, the quantity of the allocated tasks of enterprise e_k is $\sum_{j=1+\sum_{r=1}^{k-1}m_r}^{\sum_{r=1}^{k}m_r}\sum_{i=1}^{NoS} a_{ij}$. For each enterprise e_k, its rate of task allocation TR_{e_k} is calculated by formula (21). And the average rate of task allocation for the whole system (*SAT*) is shown in formula (22). Then formula (23) is the objective function for maximizing *SAT*.

$$TR_{e_k}=\sum_{j=1+\sum_{r=1}^{k-1}m_r}^{\sum_{r=1}^{k}m_r}\sum_{i=1}^{NoS} a_{ij}\Big/m_k \tag{21}$$

$$SAT=\sum_{k=1}^{NoE}\frac{\sum_{j=1+\sum_{r=1}^{k-1}m_r}^{\sum_{r=1}^{k}m_r}\sum_{i=1}^{NoS} a_{ij}}{m_k}\Big/\left(NoE-|\overline{NoE2}|\right) \tag{22}$$

$$\max SAT \tag{23}$$

In addition, the total rate of task allocation for the whole system (*STT*) can be concluded by formula (24).

$$STT=\sum_{j=1}^{NoT}\sum_{i=1}^{NoS} a_{ij}\Big/NoT \tag{24}$$

3) Maximization of average rate of service invocation

Similarly, the quantity of the invoked services of e_k is $\sum_{j=1}^{NoT}\sum_{i=1+\sum_{r=1}^{k-1}n_r}^{\sum_{r=1}^{k}n_r} a_{ij}$. Then the rate of service invocation of each enterprise SR_{e_k} and the average rate of service invocation for the whole system (*SAS*) are carried out as formulas (25) and (26). Formula (27) is the objective function for maximizing *SAS*.

$$SR_{e_k}=\sum_{j=1}^{NoT}\sum_{i=1+\sum_{r=1}^{k-1}n_r}^{\sum_{r=1}^{k}n_r} a_{ij}\Big/n_k \tag{25}$$

$$SAS=\sum_{k=1}^{NoE}\frac{\sum_{j=1}^{NoT}\sum_{i=1+\sum_{r=1}^{k-1}n_r}^{\sum_{r=1}^{k}n_r} a_{ij}}{n_k}\Big/\left(NoE-|\overline{NoE1}|\right) \tag{26}$$

$$\max SAS \tag{27}$$

Moreover, the total rate of service invocation for the whole system (*STS*) is concluded by formula (28).

$$STS=\sum_{j=1}^{NoT}\sum_{i=1}^{NoS} a_{ij}\Big/NoS \tag{28}$$

D. Constraints modelling

Each primitive task or subtask decomposed from any compound task just needs one service to perform itself. It is worth mentioning that the result of MSs-SDM is obtained from hyper-edges, and each task node would be allocated at most only one service node, as defined in formulas (29) and (30). For the non-repeatable services, there exists the specific constraint as shown in formula (31).

$$A = \{a_{ij}\}_{NoS\times NoT} \subseteq E^{S\_T} \quad (29)$$

$$\sum_{i=1}^{NoS} a_{ij} \leq 1 \quad (30)$$

$$\sum_{j=1}^{NoT} a_{ij} \leq 1, \text{if } s_i = 0 \quad (31)$$

IV. MSs-SDM METHOD BASED ON CROSS-ENTERPRISE COLLABORATION EVALUATION

As we know, the result of underlying MSs-SDM situation also could be presented as the upper-layer model of enterprises collaborative network, which is described as $E_N$et. The model of $E_N$et is much more suitable for the evaluation, statistics and analysis on cross-enterprise collaboration in view of the overall system of an Industrial Internet platform and therein participated enterprises, so as to more easily address and visualize the decision making of MSs-SDM optimization.

A. *Projection modelling: enterprises collaborative network*

As a directed and weighted network, $E_N$et is modeled as formula (32) based on the projection of the underlying MSs-SDM situation. The topology and attributes of $E_N$et are determined by $A = \{a_{ij}\}_{NoS\times NoT}$.

$$\begin{aligned} &E\_Net = <E, E^E, W^E> \\ &E^E = \left\{ e^E_{kk'} \middle| e^E_{kk'} = \sum_{j=1+\sum_{r=1}^{k'-1} m_r}^{\sum_{r=1}^{k'} m_r} \sum_{i=1+\sum_{r=1}^{k-1} n_r}^{\sum_{r=1}^{k} n_r} a_{ij} \right\} \\ &W^E = \left\{ w^E_{kk'} \middle| w^E_{kk'} = \sum_{j=1+\sum_{r=1}^{k'-1} m_r}^{\sum_{r=1}^{k'} m_r} \sum_{i=1+\sum_{r=1}^{k-1} n_r}^{\sum_{r=1}^{k} n_r} u_{ij} \times a_{ij} \right\} \\ &k, k' = 1,2,\dots,NoE \end{aligned} \quad (32)$$

When the edge $e^E_{kk'} = 0$, there is no edge directed from the enterprise e_k to $e_{k'}$, that is to say, all of the n_k services of e_k are not selected to execute any task of $e_{k'}$. When $e^E_{kk'} > 0$, there exists a directed edge from e_k to $e_{k'}$ revealing that some services of e_k are invoked for the tasks of $e_{k'}$. Therefore, if $e^E_{kk'} = 0$ and $e^E_{k'k} = 0$, there is no collaborative relationship between these two enterprises. Refer to the weight $w^E_{kk'}$, it is defined as the created utilities by the services of e_k performing the tasks of $e_{k'}$ when e_k collaborates with $e_{k'}$.

B. *Cross-enterprise collaboration evaluation based on enterprises collaborative network*

After $E_N$et is extracted and modeled, the specific collaboration evaluation of each participated enterprise (i.e., u_{e_k}, TR_{e_k} and SR_{e_k}) can be analyzed by the local characteristics of the node e_k in $E_N$et. In addition, the collaboration evaluation of the overall system (i.e., SAU, SAT, STT, SAS and STS) also can be assessed by the global characteristics of the whole network.

Corresponding to the edge $e^E_{kk'}$ and the weight $w^E_{kk'}$ in the model of $E_N$et, the evaluated utilities u_{e_k} and SAU can be also calculated as shown as formulas (33) and (34).

$$u_{e_k} = \frac{1}{2}\sum_{k'=1}^{NoE} w^E_{kk'} \quad (33)$$

$$SAU = \left(\frac{1}{2}\sum_{k=1}^{NoE}\sum_{k'=1}^{NoE} w^E_{kk'}\right) \Big/ (NoE - |\overline{NoE}|) \quad (34)$$

For each enterprise e_k, the quantity of its allocated tasks is $\sum_{k'=1}^{NoE} e^E_{k'k}$, so that the evaluated rates of task allocation TR_{e_k}, SAT and STT could be calculated by formulas (35)-(37), respectively.

$$TR_{e_k} = \sum_{k'=1}^{NoE} e^E_{k'k} / m_k \quad (35)$$

$$SAT = \sum_{k=1}^{NoE} \frac{\sum_{k'=1}^{NoE} e^E_{k'k}}{m_k} / (NoE - |\overline{NoE2}|) \quad (36)$$

$$STT = \sum_{k=1}^{NoE}\sum_{k'=1}^{NoE} e^E_{k'k} / NoT \quad (37)$$

Similarly, the quantity of the invoked services of e_k is $\sum_{k'=1}^{NoE} e^E_{kk'}$, then the evaluated rates of service invocation SR_{e_k}, SAS and STS also could be assessed by formulas (38)-(40), respectively.

$$SR_{e_k} = \sum_{k'=1}^{NoE} e^E_{kk'} / n_k \quad (38)$$

$$SAS = \sum_{k=1}^{NoE} \frac{\sum_{k'=1}^{NoE} e^E_{kk'}}{n_k} / (NoE - |\overline{NoE1}|) \quad (39)$$

$$STS = \sum_{k=1}^{NoE}\sum_{k'=1}^{NoE} e^E_{kk'} / NoS \quad (40)$$

V. EXPERIMENTS AND ANALYSIS

In this work, a simulation system is developed for the operation of Industrial Internet platforms under the scalable environment. The developed simulation system is coded in Matlab and implemented on a PC with a 3.10-GHz i7-5558U CPU, 4.00GB of RAM and Windows 10 of 64 bits.

A. *Experiments setting and algorithm*

Regarding to the proposed models of hypernetwork-based MSs-SDM optimization and the method based on cross-enterprise collaboration evaluation, the particle swarm optimization (PSO) algorithm is selected in the subsequent experiments.

As we know, the flow of PSO algorithm is simple and easy to implement with the real number coding, and there are not too many parameters that need to be adjusted, compared to other standard algorithms [31]. Except the above basic features, this algorithm is selected especially because of the following two kinds of specific applicability for the hypernetwork-based models. *On one hand*, PSO algorithm is much suitable to address the high-dimensional optimization problems. One of the most obvious characteristics of the hypernetwork model is scalability, thus the dimensions of the MSs-SDM optimization problem grow dynamically as the total number of the submitted tasks in an Industrial Internet platform. Advantageously, each particle in PSO algorithm is composed with multiple dimensions, and the dimension of particles could be determined and defined by the number of tasks in the demand-driven MSs-SDM optimization problem. *On the other hand*, PSO algorithm is usually better to deal with multi-complex constrains in optimization problems. In this hypernetwork-based MSs-SDM optimization problem, the set of hyper-edges of each task is different, so is the feasible solution (i.e., the set of matchable services) corresponding to each task. It is one of the most complex constrains in this problem. Exactly, both initialization and iteration of each dimension of a particle could be set up with different ranges specifically. Therefore, PSO algorithm is considered in this paper in priority rather than others.

As shown in Fig. 2, the detailed flow of the subsequent experiments is elaborated as follows.

Step 1: Initialization of the MSs-SDM problem and indicators. Build the models with the supplemented enterprises information according to formulas (1)-(4), (6), and (8)-(10). And calculate the utilities of hyper-edges after the indicators assignment of cost, energy consumption, risk and time referring to formulas (12)-(13).
Step 2: Output of the initial hypernetwork models.
Step 3: Selection of objective functions from formulas (20), (23) and (27).
Step 4: Solution of the hypernetwork-based optimization by employing PSO algorithm.
Step 4.1: Initialize the particle swarm N, and the corresponding initial velocity and location of particles.
Step 4.2: Calculate the fitness value of each particle according to the selected objective function (20), (23) or (27).
Step 4.3: Calculate the individual optimal value of each particle P_r. If the current value is more optimal than P_r, then update P_r to the current value.
Step 4.4: Calculate the global optimal value of particles P_g. If the current value is more optimal than P_g, then update P_g to the current value.
Step 4.5: Evolve the velocity and location of particles referring to formulas (41) and (42).
Step 4.6: If it meets the ending condition, then output the optimal solution, otherwise turn to Step 4.3.
Step 5: Modelling of E_Net. Build and output the model of $E_N$et which is the projection of the obtained optimal solution of MSs-SDM by formula (32).
Step 6: Evaluation of the enterprise-related (*local*) indicators for cross-enterprise collaboration in $E_N$et. Calculate the utility u_{e_k}, the rate of task allocation TR_{e_k}, and the rate of service invocation SR_{e_k} of each enterprise node by formulas (33), (35) and (38).
Step 7: Evaluation of the system-related (*global*) indicators for cross-enterprise collaboration in $E_N$et. Similarly, calculate the *SAU*, *SAT*, *STT*, *SAS*, and *STS* according to formulas (34), (36), (37), (39) and (40), respectively.

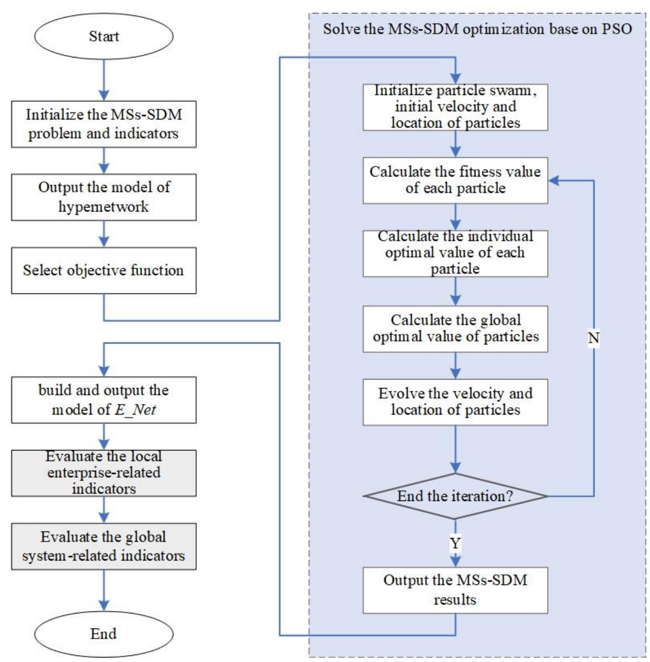


Fig. 2. Flow chart of the experiments.

In Step 4, the velocity and location of particles evolve by formulas (41) and (42). As to the parameters setting of PSO, the inertia weight ω is set to 0.7, the learning factors are set as $c_1 = c_2 = 2$, α and β are the random numbers from 0 to 1, and constraint factor $\gamma = 1$.

$$v_{rj}^{k+1} = \omega \times v_{rj}^{k} + c_1 \times \alpha \times (p_{rj}^{k} - x_{rj}^{k}) + c_2 \times \alpha \times (p_{gj}^{k} - x_{rj}^{k}) \quad (41)$$

$$x_{rj}^{k+1} = x_{rj}^{k} + \gamma \times v_{rj}^{k+1} \quad (42)$$

According to the constraint shown in formula (29), $A = \{a_{ij}\}_{NoS \times NoT} \subseteq E^{S\_T} = \{e_{ij}^{S\_T}\}_{NoS \times NoT}$. For the demand-driven MSs-SDM optimization, the quantity of the optional services for task node t_j is $\sum_{i=1}^{NoS} e_{ij}^{S\_T}$, it results in that the total solution space reaches $\prod_{j=1}^{NoT}\left(\sum_{i=1}^{NoS} e_{ij}^{S\_T}\right)$. Therefore, based on the information of hyper-edges E^{S_T}, some other related parameters of PSO are adjusted for the hypernetwork-based MSs-SDM optimization models as follows.

- Number of particles in the swarm: It assumes that the particles in the particle swarm are $P_1, P_2, \dots, P_N$, then the number of particles meets $N < \prod_{j=1}^{NoT}\left(\sum_{i=1}^{NoS} e_{ij}^{S\_T}\right)$. The number of particles is set to be 40 in the subsequent experiments.
- Dimension of particles: The dimension of each particle is the total quantity of tasks in the platform, i.e., $P_r = (x_{r1}, x_{r2}, \dots, x_{rNoT})$.
- Scope of particles: The element of the jth dimension of the rth particle x_{rj}, is the ID of a service which could be allocated for the task t_j, then the optional scope is $x_{rj} \in [0, \mathrm{NoS}]$. If $\sum_{i=1}^{NoS} e_{ij}^{S\_T} = 0$, i.e., there is no matchable service can be selected for the task t_j, thus $x_{rj} = 0$. Besides, if $x_{rj} = 1 \sim \mathrm{NoS}$, it means there has to be a hyper-edge between the corresponding service $s_{x_{rj}}$ and the task t_j when $e_{x_{rj}j}^{S\_T} = 1$.
- The max velocity of particles: It is set to be NoS in the subsequent experiments.
- Fitness function: It is one of the selected system-centered objective functions, e.g., the formula (20) for maximizing SAU, the formula (23) for maximizing SAT, or the formula (27) for maximizing SAS.

Based on the algorithm mentioned above, to solve and analyze this MSs-SDM optimization problem, the experiment conditions are set as below. We consider 20 enterprises, namely $NoE = 20$. The numbers of services and tasks of each enterprise submitted to the platform are generated randomly at the beginning of experiments. Besides, the hyper-edges between services and tasks as well as the number of repeatable services are also generated randomly. Four evaluation indicators of each hyper-edge are set from 1 to 10. Then the utility of each hyper-edge could be calculated by formulas (12) and (13).

The subsequent experiments are designed and classified into the following two steps:

(a) Firstly, an experiment is conducted when the services in the platform are enough but all of them cannot be invoked repeatedly. In total, 120 services and 30 tasks are considered, i.e., $NoS = 120$, $NoT = 30$ and $NoE = 20$.

(b) Secondly, the supply-demand dual scalabilities of the MSs-SDM problem is introduced in the remaining experiments. There are totally 5*7 groups of experiments designed. On one hand, considering different proportions of services to tasks, five groups of experiments are conducted, including NoS: NoT =4:1(120:30), 2:1(60:30), 1:1(30:30), 1:2(30:60) and 1:4(30:120). On the other hand, further considering different proportions of repeatable services to non-repeatable services, seven pairs of experiments are carried out for each of the above five groups of experiments, including NoS_r: NoS_nr =1:0, 4:1, 2:1, 1:1, 1:2, 1:4, 0:1.

In addition, each experiment runs three times for different fitness functions including max SAU, max SAT and max SAS.

B. Results and analysis when considering enough non-repeatable services

As mentioned above, for the first-step experiment, the services in the platform are all assumed as non-repeatable. Table 2 displays the corresponding quantities of services and tasks submitted by each enterprise to the platform. As shown in Table 2, the enterprises e_{20} is a service consumer, and the rest enterprises are both service providers and consumers.

TABLE II
THE QUANTITIES OF SERVICES AND TASKS OF EACH ENTERPRISE

e_k	e_1	e_2	e_3	e_4	e_5	e_6	e_7	e_8	e_9	e_{10}
n_k	4	7	7	4	4	5	4	5	4	11
$\sum_{k=1}^{k} n_k$	4	11	18	22	26	31	35	40	44	55
m_k	1	1	2	3	1	2	2	2	1	2
$\sum_{k=1}^{k} m_k$	1	2	4	7	8	10	12	14	15	17
e_k	e_{11}	e_{12}	e_{13}	e_{14}	e_{15}	e_{16}	e_{17}	e_{18}	e_{19}	e_{20}
n_k	10	5	6	6	6	7	11	4	10	0
$\sum_{k=1}^{k} n_k$	65	70	76	82	88	95	106	110	120	120
m_k	1	1	2	1	1	2	1	1	2	1
$\sum_{k=1}^{k} m_k$	18	19	21	22	23	25	26	27	29	30

1) *For maximizing system average utility*

Treating formula (20) as the fitness function, the related parameters are set as follows. The number of particles is 40, the dimension of particles is the same as the total number of tasks, the iterations of algorithm is set as 200, and other evaluation indicators are generated randomly.

$E_N$et is modelled based on the running result, as shown in Fig. 3. The sparse matrixes in Fig. 3(a1) are about the decision cooefficient A and the set of collaborative edges E^E, and Fig. 3(a2) displays the topology of $E_N$et both in random and circular layouts. The directed edges in the network demonstrate the optimal correlations from the supply to the demand, for instance, the directed edge from e_6 to e_{14}. Besides, the detailed mapping that which service is selected for which task is illustrated in the sparse matrix of A. Therefore, the task t_{22} submitted by e_{14} (i.e., t_1^{14}) is allocated with the service s_{29} submitted by e_6 (i.e., s_3^6). To analyze the obtained $E_N$et more intuitively, Fig. 3(a3) shows the statistics on enterprises collaboration of $E_N$et. The out-degree and in-degree of each node in $E_N$et respectively present the service invocation and task allocation situations of the corresponding enterprise. As to the self-loop of an enterprise node, it just exists when the enterprise is both a service provider and a consumer, and it indicates that the tasks of this enterprise are executed by its own services. Specifically, in this experiment, the enterprise e_{20} is a pure service consumer with no service submitted to the platform, which results in that this enterprise node has no out-degree in the model of $E_N$et. Obviously, the enterprise node of e_{20} cannot generate self-loop in the model of $E_N$et. In addition, in this MSs-SDM optimization problem for maximizing *SAU*, the out-degree of enterprise e_8 is 4, which is as the maximal out-degree of nodes in $E_N$et. It points out that the services of e_8 are invoked most frequently to serve for 4 tasks submitted by other enterprises, so that it is the most important enterprise with more collaborative relationships and collaboration capabilities than others. Conversely, the in-degree of e_4 is 3 which is the maximal in-degree of nodes in $E_N$et, there are 3 services submitted by other enterprises invoked for its tasks. It declares that the enterprise e_4 is with a strong dependence on collaboration with other enterprises.

In Table 3, it shows different indicators of cross-enterprise collaboration evaluation for maximizing *SAU*. The collaboration evaluation involves both the local enterprise-related indicators (e.g., u_{e_k}, TR_{e_k}, and SR_{e_k}) and the global system-related indicators (e.g., *SAU*, *SAS*, *STS*, *SAT and STT*).

TABLE III
CROSS-ENTERPRISE COLLABORATION EVALUATION FOR MAXIMIZING *SAU*

	e_k	u_{e_k}	TR_{e_k}	SR_{e_k}	e_k	u_{e_k}	TR_{e_k}	SR_{e_k}
Enterprise-related indicators	e_1	0.0365	1	0	e_{11}	0.2271	1	0.200
	e_2	0.2495	1	0.4286	e_{12}	0.1132	1	0.200
	e_3	0.2719	1	0.1429	e_{13}	0.2121	1	0.1667
	e_4	0.3056	1	0.5000	e_{14}	0.1728	1	0.1667
	e_5	0.1082	1	0.2500	e_{15}	0.2598	1	0.1667
	e_6	0.3028	1	0.4000	e_{16}	0.1962	1	0.1429
	e_7	0.2174	1	0	e_{17}	0.2226	1	0.2727
	e_8	0.4396	1	0.8000	e_{18}	0.0424	1	0
	e_9	0.1096	1	0	e_{19}	0.5222	1	0.3000
	e_{10}	0.3845	1	0.2727	e_{20}	0.0616	1	/
System-related indicators	*SAU*		*SAS*		*STS*		*SAT*	*STT*
	0.2228		0.2409		0.25		1	1

TABLE IV
CROSS-ENTERPRISE COLLABORATION EVALUATION FOR MAXIMIZING *SAT*

	e_k	u_{e_k}	TR_{e_k}	SR_{e_k}	e_k	u_{e_k}	TR_{e_k}	SR_{e_k}
Enterprise-related indicators	e_1	0.0531	1	0	e_{11}	0.0871	1	0
	e_2	0.1049	1	0.1429	e_{12}	0.1030	1	0.2000
	e_3	0.1732	1	0.1429	e_{13}	0.1617	1	0.1667
	e_4	0.2873	1	0.2500	e_{14}	0.4877	1	0.8333
	e_5	0.1208	1	0	e_{15}	0.2405	1	0.3333
	e_6	0.3554	1	0.4000	e_{16}	0.2818	1	0.4286
	e_7	0.1714	1	0	e_{17}	0.5757	1	0.5455
	e_8	0.3925	1	0.4000	e_{18}	0.0579	1	0
	e_9	0.1756	1	0.2500	e_{19}	0.2788	1	0.2000
	e_{10}	0.2776	1	0.1818	e_{20}	0.0349	1	/
System-related indicators	*SAU*		*SAS*		*STS*		*SAT*	*STT*
	0.2210		0.2355		0.2500		1	1

TABLE V
CROSS-ENTERPRISE COLLABORATION EVALUATION FOR MAXIMIZING *SAS*

	e_k	u_{e_k}	TR_{e_k}	SR_{e_k}	e_k	u_{e_k}	TR_{e_k}	SR_{e_k}
Enterprise-related indicators	e_1	0.1347	1	0.5000	e_{11}	0.1260	1	0.1000
	e_2	0.1094	1	0.1429	e_{12}	0.2396	1	0.4000
	e_3	0.3315	1	0.2857	e_{13}	0.2097	1	0.3333
	e_4	0.4711	1	0.5000	e_{14}	0.0982	1	0.1667
	e_5	0.0804	1	0	e_{15}	0.1431	1	0.1667
	e_6	0.2291	1	0.4000	e_{16}	0.1705	1	0
	e_7	0.3413	1	0.5000	e_{17}	0.1731	1	0.0909
	e_8	0.3422	1	0.4000	e_{18}	0.1610	1	0.5000
	e_9	0.3066	1	1	e_{19}	0.1988	1	0.1000
	e_{10}	0.3444	1	0.1818	e_{20}	0.0531	1	/
System-related indicators	*SAU*		*SAS*		*STS*		*SAT*	*STT*
	0.2132		0.3036		0.2500		1	1

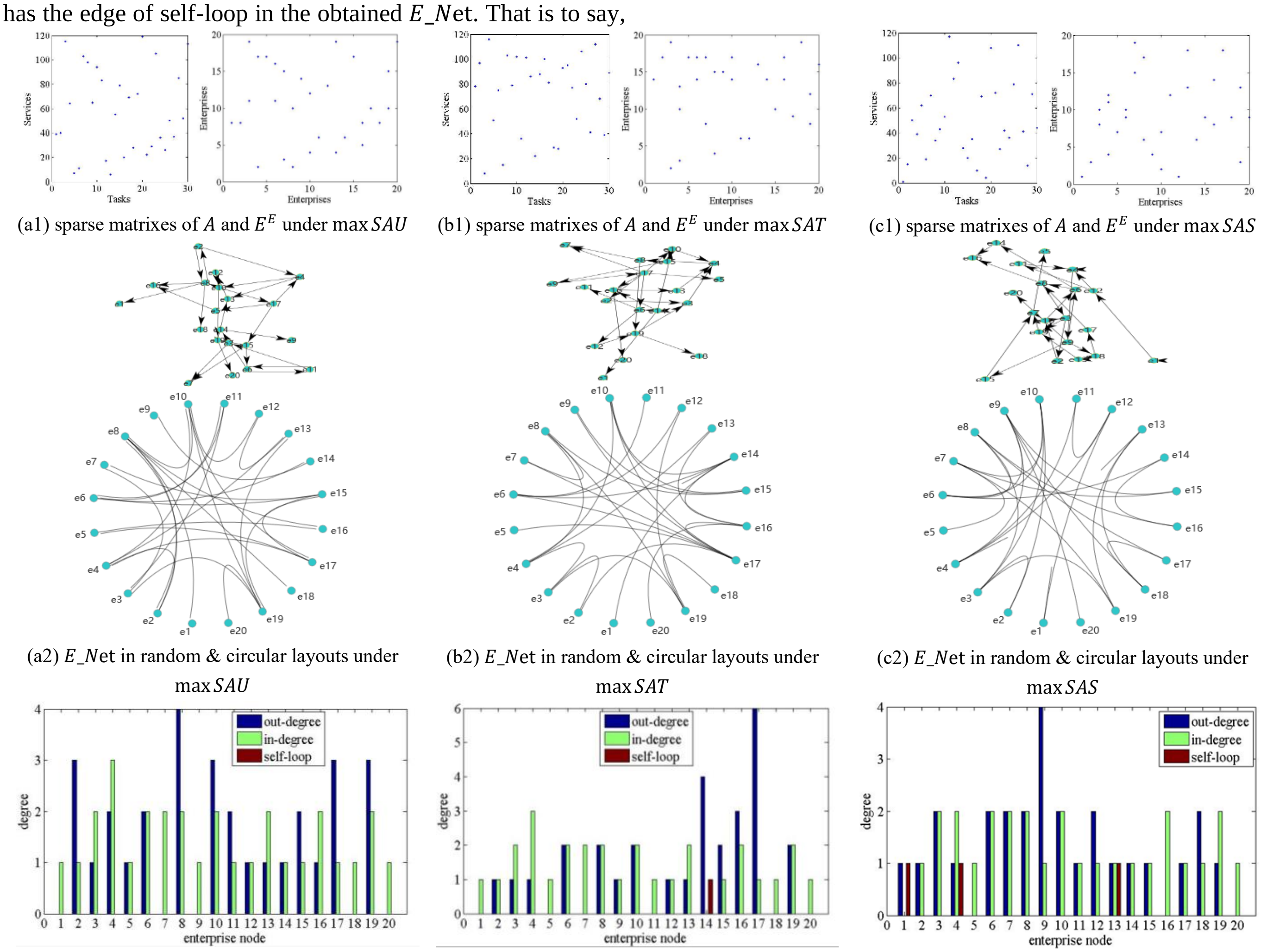
Known from Table 3, the enterprise-related indicator TR_{e_k} of each enterprise and the system-related indicators SAT and STT all reach the value of 1, which means that the result meets the actual requirement of MSs-SDM problem and all of tasks have been allocated appropriately. Accordingly, as the enterprise who is with more collaborative relationships and collaboration capabilities among those 20 enterprises in E_Net, e_{19} creates the maximal value of utility (i.e., 0.5222) which is such far higher than the value of SAU (i.e., 0.2228). Under this solution of MSs-SDM and its cross-enterprise collaboration evaluation, the system-related indicators SAS and STS are 0.2409 and 0.2500, which are very close values.

2) For maximizing system average rate of task allocation

Keeping the same methodology as well as the parameters setting, an experiment for maximizing SAT is carried out with formula (23) as the fitness function. Fig. 3(b1), (b2) and (b3) are the results of this experiment, and Table 4 shows the detailed cross-enterprise collaboration evaluation for maximizing SAT. Similar to the previous experiment for maximizing SAU, the results for maximizing SAT are also reasonable with the actual situations, owing to that the values of the enterprise-related indicator TR_{e_k} of each enterprise and the system-related indicators SAT and STT in Table 4 all stay at 1. However, there is a difference that the enterprise node e_{14} has the edge of self-loop in the obtained E_Net. That is to say, in this enterprise, some tasks are allocated by its own services. At this time, the system-related indicators SAU and SAS are 0.2210 and 0.2355, while the maximal STS is 0.2500. Besides, among those 20 enterprises in E_Net, no service of the enterprises e_1, e_5, e_7, e_{11} and e_{18} are selected for any task.

3) For maximizing system average rate of service invocation

Another experiment for maximizing SAS is carried out with formula (27) as the fitness function. Fig. 3(c1), (c2) and (c3) are the results of this experiment. From Fig.3(c3) we can see that the enterprises e_1 , e_4 and e_{13} have the edges of self-loop in the obtained E_Net. The maximal out-degree is of the enterprise e_9. What is more, the enterprises e_3, e_4, e_6, e_7, e_8, e_{10}, e_{16} and e_{19} are with strong dependence on collaboration with other enterprises because of their relatively higher in-degree. Table 5 shows the result of cross-enterprise collaboration evaluation for maximizing SAS. The values of the enterprise-related indicator TR_{e_k} of each enterprise and the system-related indicators SAT and STT in Table 5 also stay at 1. It means that this result also meets the actual requirement of MSs-SDM and all of tasks have been allocated appropriately as well. At this time, the system-related indicators SAU and STS are 0.2132 and 0.2500, while the maximal SAS is 0.3036. Moreover, the enterprise e_9 has full service allocation rate, but no service of the enterprises e_5 and e_{16} are selected for any task.



(a1) sparse matrixes of A and E^E under max SAU (b1) sparse matrixes of A and E^E under max SAT (c1) sparse matrixes of A and E^E under max SAS

(a2) E_Net in random & circular layouts under max SAU (b2) E_Net in random & circular layouts under max SAT (c2) E_Net in random & circular layouts under max SAS

(a3) enterprises collaboration under max SAU (b3) enterprises collaboration under max SAT (c3) enterprises collaboration under max SAS

Fig. 3. Experimental results with different objectives.

TABLE VI
NUMERICAL RESULTS ON CROSS-ENTERPRISE COLLABORATION EVALUATION AND COMPUTATIONAL PERFORMANCE FOR MAXIMIZING *SAU*, *SAT* AND *SAS* WHEN CHANING SCALABILITY

SAU SAS STS SAT STT			NoS: NoT														
			NoS > NoT						**NoS = NoT**			**NoS < NoT**					
			4:1 (120:30)			2:1 (60:30)			1:1 (30:30)			1:2 (30:60)			1:4 (30:120)		
(Iterations) (time /s)			*max SAU*	*max SAT*	*max SAS*	*max SAU*	*max SAT*	*max SAS*	*max SAU*	*max SAT*	*max SAS*	*max SAU*	*max SAT*	*max SAS*	*max SAU*	*max SAT*	*max SAS*
NoS_r : NoS_nr	**NoS_r ≫ NoS_nr**	1 : 0	*0.2744* 0.2499 0.25 1 1	0.1956 0.2274 0.25 *1* 1	0.1745 *0.3100* 0.25 1 1	*0.2194* 0.5050 0.5 1 1	0.1962 0.4483 0.5 *1* 1	0.1934 *0.7408* 0.5 1 1	*0.2488* 0.9371 1 1 1	0.2260 0.9615 1 *1* 1	0.1935 *1.4266* 1 1 1	*0.4774* 2.2403 2 1 1	0.3912 1.5130 2 *1* 1	0.3681 *2.8247* 2 1 1	*0.8308* 4.0200 4 1 1	0.7708 4.2400 4 *1* 1	0.7953 *5.1067* 4 1 1
			(166) (67.28)	(1) (1.5)	(68) (26.67)	(88) (34.20)	(1) (1.23)	(23) (9.69)	(23) (10.48)	(1) (1.2)	(38) (16.13)	(152) (100.53)	(1) (1.73)	(96) (63.58)	(53) (80.23)	(1) (3.97)	(86) (166.16)
	NoS_r > NoS_nr	4 : 1	*0.2600* 0.2499 0.25 1 1	0.1911 0.2386 0.25 *1* 1	0.1702 *0.3063* 0.25 1 1	*0.2253* 0.4040 0.5 1 1	0.2036 0.4875 0.5 *1* 1	0.2077 *0.7936* 0.5 1 1	*0.2421* 1.0210 1 1 1	0.2046 1.0455 1 *1* 1	0.1759 *1.2622* 1 1 1	*0.4414* 2.3988 2 1 1	0.3754 1.5893 2 *1* 1	0.4304 *2.7202* 2 1 1	*0.8376* 4.0089 4 1 1	0.7957 3.3491 4 *1* 1	0.7449 *5.1213* 4 1 1
			(64) (24.77)	(1) (1.45)	(31) (14.16)	(43) (19.69)	(1) (1.25)	(68) (36.47)	(68) (45.95)	(1) (1.33)	(152) (77.73)	(86) (81.5)	(1) (2.47)	(32) (22.39)	(44) (69.44)	(1) (3.38)	(64) (100.59)
		2 : 1	*0.2544* 0.2767 0.25 1 1	0.2021 0.2452 0.25 *1* 1	0.2039 *0.2912* 0.25 1 1	*0.2482* 0.4808 0.5 1 1	0.2126 0.4283 0.5 *1* 1	0.2072 *0.6442* 0.5 1 1	*0.2418* 1.1389 1 1 1	0.2136 0.9722 1 *1* 1	0.1988 *1.3111* 1 1 1	*0.4967* 1.8988 2 1 1	0.3860 1.9643 2 *1* 1	0.3935 *2.2500* 2 1 1	*0.8731* 4.5000 4 1 1	0.7779 4.3455 4 *1* 1	0.8075 *5.1273* 4 1 1
			(109) (46.72)	(1) (1.56)	(36) (17.47)	(141) (54.06)	(1) (1.61)	(71) (28.36)	(90) (31.03)	(1) (1.64)	(63) (41.48)	(76) (63.67)	(1) (1.98)	(149) (119.55)	(70) (132.81)	(1) (4.64)	(68) (121.03)
	NoS_r = NoS_nr	1 : 1	*0.2554* 0.2524 0.25 1 1	0.1823 0.2378 0.25 *1* 1	0.1988 *0.3798* 0.25 1 1	*0.2658* 0.5200 0.5 1 1	0.1903 0.4708 0.5 *1* 1	0.1751 *0.7350* 0.5 1 1	*0.2519* 1.1094 1 1 1	0.2127 1.0156 1 *1* 1	0.2002 *1.3438* 1 1 1	*0.4718* 1.6016 2 1 1	0.4321 1.3556 2 *1* 1	0.3975 *2.6337* 2 1 1	*0.8981* 3.9295 4 1 1	0.7732 3.5192 4 *1* 1	0.7920 *4.1026* 4 1 1
			(75) (28.59)	(1) (1.34)	(80) (29.39)	(172) (68.83)	(1) (1.31)	(82) (32.39)	(68) (33.59)	(1) (1.33)	(47) (28.5)	(33) (55.88)	(1) (2.22)	(55) (89)	(58) (165.22)	(1) (4.27)	(61) (293.64)
	NoS_r < NoS_nr	1 : 2	*0.2458* 0.2186 0.25 1 1	0.2129 0.2676 0.25 *1* 1	0.1840 *0.3256* 0.25 1 1	*0.2391* 0.5217 0.5 1 1	0.1970 0.4550 0.5 *1* 1	0.1811 *0.6208* 0.5 1 1	*0.2572* 0.9464 1 1 1	0.2223 0.9167 1 *1* 1	0.2035 *1.1786* 1 1 1	*0.4416* 1.9533 2 1 1	0.3811 1.9022 2 *1* 1	0.3699 *2.1911* 2 1 1	*0.8404* 4.5119 4 1 1	0.8199 4.6310 4 *1* 1	0.7645 *4.9881* 4 1 1
			(68) (29.91)	(1) (1.53)	(51) (23.98)	(194) (75.94)	(1) (1.61)	(64) (31.28)	(122) (60.56)	(1) (1.69)	(69) (43.91)	(101) (105.25)	(1) (2.56)	(121) (115.95)	(163) (391.41)	(1) (5.48)	(1) (5.45)
		1 : 4	*0.2484* 0.2468 0.25 1 1	0.2371 0.2387 0.25 *1* 1	0.2016 *0.3086* 0.25 1 1	*0.2347* 0.4008 0.5 1 1	0.1655 0.4300 0.5 *1* 1	0.2098 *0.6067* 0.5 1 1	*0.2273* 1.0088 1 1 1	0.2007 0.9298 1 *1* 1	0.1976 *1.2281* 1 1 1	*0.4383* 2.4649 2 1 1	0.3901 1.8421 2 *1* 1	0.4120 *2.3772* 2 1 1	*0.8341* 3.5333 4 1 1	0.7567 3.8167 4 *1* 1	0.7423 *4.2667* 4 1 1
			(90) (38.88)	(1) (1.52)	(119) (52.84)	(93) (76.97)	(1) (1.47)	(89) (64.72)	(94) (58.61)	(1) (1.56)	(92) (55.11)	(85) (126.55)	(1) (3.95)	(64) (94.92)	(118) (744.95)	(1) (8.16)	(1) (10.09)
	NoS_r ≪ NoS_nr	0 : 1	*0.2228* 0.2409 0.25 1 1	0.2210 0.2355 0.25 *1* 1	0.2132 *0.3036* 0.25 1 1	*0.2389* 0.5033 0.5 1 1	0.2183 0.4800 0.5 *1* 1	0.1914 *0.5700* 0.5 1 1	*0.2551* 1 1 1 1	0.2032 1 1 *1* 1	0.1957 *1* 1 1 1	*0.2539* 0.9474 0.9667 0.4211 0.4833	0.2148 1 1 *0.4702* 0.5	0.1996 *1* 1 0.4386 0.5	*0.2506* 1 1 0.2818 0.25	0.2185 1 1 *0.2927* 0.25	0.2034 *1* 1 0.2818 0.25
			(81) (63.50)	(1) (2.39)	(60) (42.33)	(141) (135.67)	(1) (1.83)	(140) (102.27)	(95) (235.69)	(1) (3.72)	(1) (3.3)	(148) (1651.81)	(1) (16.41)	(1) (13.78)	(98) (2355.52)	(1) (35.66)	(1) (47.5)

C. Results and analysis when introducing the scalability

In last step of experiments, the supplied services are enough and all of them are assumed as non-repeatable. But for the real-world environment, sometimes the number of tasks submitted to the platform are equal or even larger than the number of services. Moreover, although some services cannot be invoked repeatedly due to the limits of machines and other facilities, there also exists a category of services in the platform which are repeatable. To simulate the real-world conditions, another group of experiments introducing scalability are conducted by both changing the proportion of services to tasks and the proportion of repeatable services to non-repeatable services, namely $NoS:NoT$ and $NoS\_r:NoS\_nr$. Keeping the same methodology as well as parameters setting, the second-step of experiments, i.e., 5*7 groups of experiments in total, also run for maximizing SAU, SAT and SAS with the formulas (17), (20) and (24) as the fitness functions.

Table 6 shows the results on cross-enterprise collaboration evaluation and the algorithm's computational performance in such 5*7 groups of experiments by changing scalability. In which, the results on cross-enterprise collaboration evaluation involve the global system-related indicators, such as SAU, SAS, STS, SAT and STT; and the results on the algorithm's performance include iterations and time of convergence. From each row, 5 groups of experiments are provided and classified into three situations according to different $NoS\colon NoT$, including:

(a) for the situation when $NoS > NoT$, set $NoS\colon NoT$ =4:1(120:30) and 2:1(60:30);

(b) for the situation when $NoS = NoT$, set $NoS\colon NoT$ =1:1(30:30); and

(c) for the situation when $NoS < NoT$, set $NoS\colon NoT$ =1:2(30:60) and 1:4(30:120).

From each column in Table 6, 7 pairs of experiments are further carried out and classified into five situations according to different $NoS\_r\colon NoS\_nr$, including:

(a) for the situation when $NoS\_r \gg NoS\_nr$, set $NoS\_r\colon NoS\_nr$ =1:0, all services are assumed as repeatable;

(b) for the situation when $NoS\_r > NoS\_nr$, set $NoS\_r\colon NoS\_nr$ = 4:1 and 2:1;

(c) for the situation when $NoS\_r = NoS\_nr$, set $NoS\_r\colon NoS\_nr$ = 1:1;

(d) for the situation when $NoS\_r < NoS\_nr$, set $NoS\_r\colon NoS\_nr$ = 1:2 and 1:4; and

(e) for the situation when $NoS\_r \ll NoS\_nr$, set $NoS\_r\colon NoS\_nr$ = 0:1, all services are assumed as non-repeatable.

In order to explore the impact of scalability on the result of MSs-SDM problem, the following two subsections are carried out based on the numerical values in Table 6 to clarify the further analysis by changing the proportions $NoS\colon NoT$ and $NoS\_r\colon NoS\_nr$, respectively.

1) *Analysis by changing the proportion of services to tasks*

When changing the proportion of services to tasks $NoS\colon NoT$ and especially increasing the number of tasks, the supply of services is gradually insufficient so that the platform is difficult to operate successfully. Fig. 4 shows the comparisons on the evaluated global system-related indicators by changing $NoS\colon NoT$, in which, each figure reveals the comparison results under different $NoS\_r\colon NoS\_nr$. In addition, the indicators SAS and STS with any fitness function are demonstrated following the bottom horizontal axis, and others which are marked as dotted lines are demonstrated following the top horizontal axis. The mentioned indicators in Fig. 4 are fitted by smoothing splines. When calling the fit function in Matlab, we fit a smoothing spline model by specifying “smoothing spline”. The smoothing spline s is constructed for the specified smoothing parameter p and the specified weights w_i. The smoothing spline minimizes $p\sum_i w_i(y_i - s(x_i))^2 + (1-p)\int(\frac{d^2s}{dx^2})^2 dx$. And p is automatically selected in the “interesting range”. The interesting range of p is often near $1/\left(1+{h^3}/{6}\right)$ where h is the average spacing of the data points.

Observed from Fig. 4(a), all of services are non-repeatable when $NoS\_r\colon NoS\_nr$ =0:1, the values of SAU with different fitness functions are almost in a stable range (e.g., [0.2228, 0.2551] for max SAU, [0.2032, 0.2210] for max SAT, and [0.1914, 0.2132] for maxSAS). However, the supply, which is enough or not, has a greater impact on SAT and STT as well as SAS and STS. When $NoS > NoT$ namely $NoT\colon NoS < 1$ in this figure, the supply is sufficient. As to $NoS = NoT$ namely $NoT\colon NoS = 1$, the supply may be sufficient or insufficient. It depends on the diversity of hyper-edges, but it is enough in this experiment. Therefore, when the supply is sufficient, both SAT and STT reach 1, STS always equals to NoT/NoS, and SAS equals to or slightly floats up and down around NoT/NoS. It reveals that all demands are allocated properly, and the number of invoked services depends on the demands. As to the context when the supply is insufficient namely $NoT\colon NoS > 1$, STS and SAS almost stay at 1, STT and SAT may equal or approximately equal to NoS/NoT. It reveals that all non-repeatable services are invoked, but it still cannot meet excessive demands.

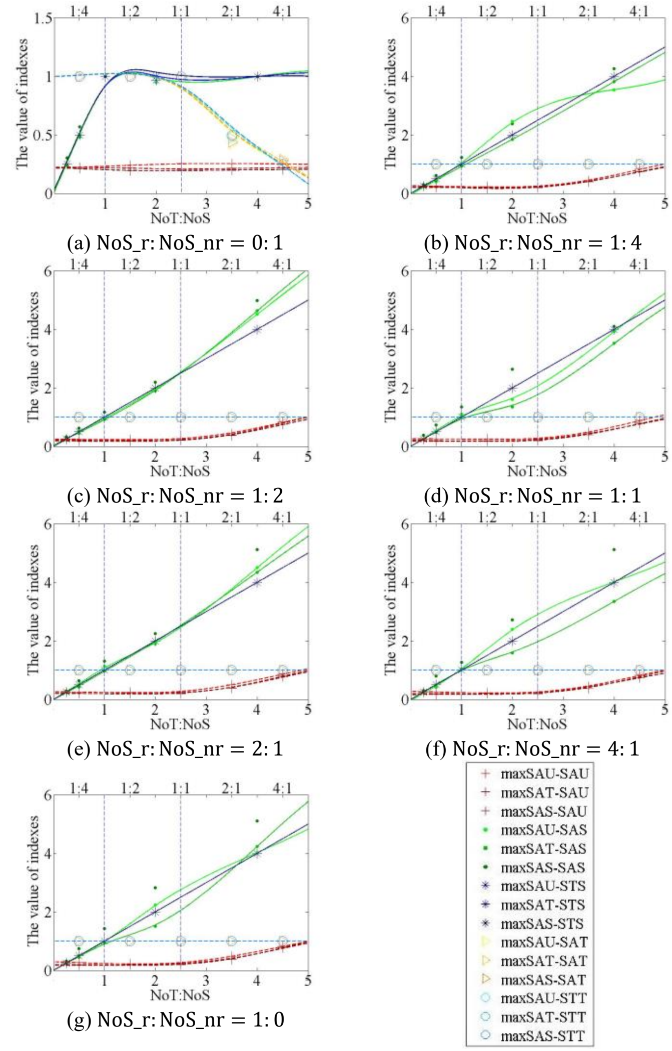


Fig. 4. Comparisons on global system-related indicators by changing the proportion of services to tasks (i.e., $NoS\colon NoT$).

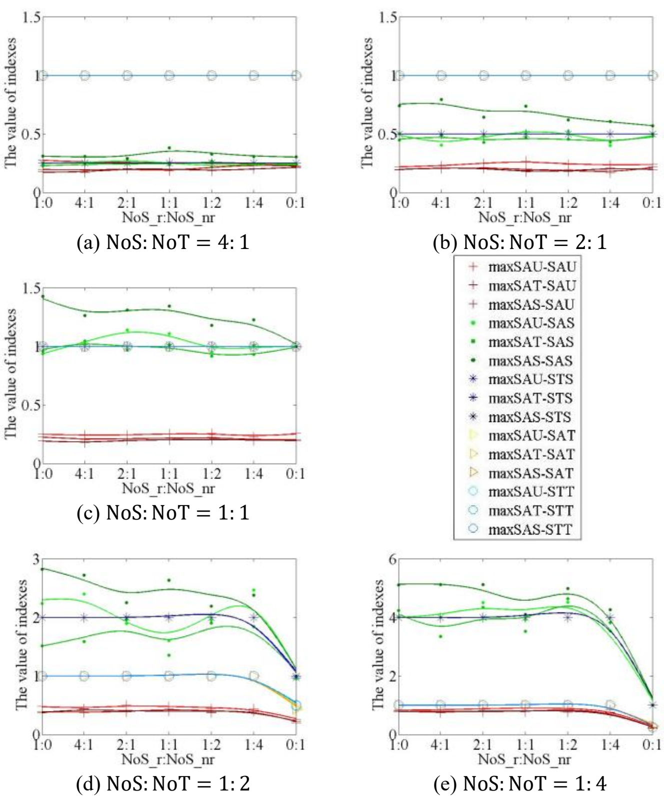
As to Fig. 4(b)-(g), no matter how much the proportion $NoS\colon NoT$ is, both SAT and STT always reach 1 because of the existence and increase of repeatable services. All of demands are matched and allocated. Moreover, similar to the left part of Fig. 4(a) when the supply is sufficient, STS always depends on NoT/NoS, and SAS floats up and down around NoT/NoS slightly. As to SAU, its value also stays at a stable range when $NoT\colon NoS \leq 1$ and will be greatly improved when $NoT\colon NoS > 1$ because of the growth of repeatable services invocation caused by excessive demands.

2) Analysis by changing the proportion of repeatable services to non-repeatable services

When changing the proportion of repeatable services to non-repeatable services NoS_r: NoS_nr and especially increasing the number of non-repeatable services, the supply of services is gradually insufficient when $NoS < NoT$ so that the platform may be also difficult to operate successfully. Fig. 5 illustrates the comparisons on the evaluated global system-related indicators by changing NoS_r: NoS_nr, in which, each figure reveals the comparison result under different NoS: NoT.

Known from Fig. 5(a)-(c), no matter how much the proportion NoS_r: NoS_nr is, the supply of services is enough when $NoS \geq NoT$. At this situation, the values of SAU almost keep stable, the values of both SAT and STT always reach 1, the values of STS stay at NoT/NoS, and the values of SAS float up and down around NoT/NoS.

Observed from Fig. 5(d) and (e) when $NoS < NoT$, the supply of services is enough and gradually becomes insufficient for excessive demands by increasing the number of non-repeatable services. When the supply is enough, as shown in the left parts of these two figures, the evaluated global system-related indicators except SAU reveal the same rules as mentioned above. As to the right parts of these tow figures, the supply becomes insufficient. At this situation, the values of SAS and STS almost finally converge to 1 from NoT/NoS, and the values of SAT and STT almost finally converge to NoS/NoT from 1. It is worth mentioning that, the value of SAU is improved to a higher stable range (e.g., [0.4383, 0.4967] and [0.8308, 0.8981] for max SAU) when although $NoS < NoT$ but the supply is sufficient. However, if the supply becomes insufficient, the value of SAU falls gradually and finally approaches to its value when so many services are excess (i.e., $NoS > NoT$).



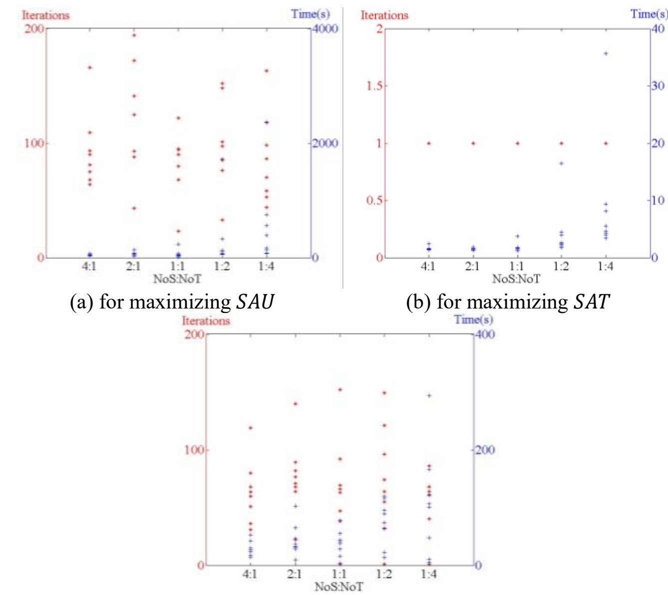
(a) NoS: NoT = 4: 1 (b) NoS: NoT = 2: 1 (c) NoS: NoT = 1: 1 (d) NoS: NoT = 1: 2 (e) NoS: NoT = 1: 4

Fig. 5. Comparisons on global system-related indicators by changing the proportion of repeatable services to non-repeatable services (i.e., NoS_r: NoS_nr).

***3)** Managerial implications*

TABLE VII
ANALYSIS CONCLUSION

Supply capacity	Enterprises collaboration evaluation	Indicators	Conclusions
Sufficient	Utility created by enterprises collaboration	SAU	Keeping a stable range, and improved as demand increases
	Services utilization for MSs-SDM	SAS STS	About NoT/NoS
	Tasks allocation by MSs-SDM	SAT STT	Remains at 1
In-sufficient	Utility created by enterprises collaboration	SAU	Falls to the lower stable range
	Services utilization for MSs-SDM	SAS STS	Approaches to 1 from NoT/NoS
	Tasks allocation by MSs-SDM	SAT STT	Falls to NoS/NoT from 1



(a) for maximizing SAU (b) for maximizing SAT (c) for maximizing SAS

Fig. 6. Statistics on the computational efficiency of PSO algorithm for maximizing *SAU, SAT* and *SAS* when changing scalability.

Table 7 concludes the above analysis by changing both NoS: NoT and NoS_r: NoS_nr. In addition, based on the numerical results on the algorithm's convergence interactions and time shown in Table 6, the statistics on the computational efficiency of PSO algorithm for the scalable MSs-SDM optimization problem are summarized in Fig. 6. From the observations and analysis, there are the following managerial implications.

(a) Both NoS: NoT and NoS_r: NoS_nr have a great impact on the operation of an Industrial Internet platform and its MSs-SDM optimization.

(b) During the operation process of an Industrial Internet platform, more services are not necessarily beneficial. When the supply of services is more than the demand, although SAU remains in a stable range, it is always at a lower value.

(c) The increase in the demand is conducive to the operation of the platform. When the demand is more than the supply but its supply capacity is sufficient (i.e., repeatable services exist), SAU is greatly improved.

(d) The existence and increase of repeatable services have no effect on STS, but will cause and aggravate the fluctuation between SAS and STS.

(e) The algorithm performs with better computational efficiency for maximizing SAT and SAS. As to maximizing SAU and especially when all services are non-repeatable, its computational efficiency decreases as the demand rather than the supply increases.

Based on the implications, in order to improve the operation of an Industrial Internet platform and motivate more users to participate in, there are some work need to be further explored, including supple-demand equilibrium and marginal utility analysis for MSs-SDM optimization with stochastic demand.

VI. Conclusions

Based on the sensor & cloud-based environment of Industrial Internet platforms, all production activities and business collaborations among different enterprises depend on the underlying MSs-SDM situation. Responding to this scalable MSs-SDM problem under the environment of Industrial Internet platforms, the hypernetwork-based models of MSs-SDM optimization are established, and an enterprises collaborative network model is derived from the underlying MSs-SDM situation and applied into cross-enterprise collaboration evaluation in this paper. In addition, a method for MSs-SDM optimization based on cross-enterprise collaboration evaluation is proposed and explored, which mainly refers to some local and global indicators such as the created utility, the rate of task allocation, and the rate of service invocation of both the participated enterprises and the overall system. Two steps of experiments are finally carried out to validate the effectiveness of the proposed models and method, to further analyze the supply-demand dual scalabilities of this optimization problem, and to summarize some managerial implications for the operation of an Industrial Internet platform.

As a result, by the proposed models and the derived method, it is applicable to conduct the upper-layer cross-enterprise collaboration evaluation from both of local and global views so as to achieve the underlying MSs-SDM optimization, no matter whether scalability exists. As well, it is helpful for the platform and its users to improve the created utility and the rate of service invocation while keeping full rate of task allocation when the supply of services is enough. However, oversupply is not good. When the demand is stochastic and excessive so that the supply of services become insufficient, how to find the appropriate proportions of services to tasks and especially repeatable services to non-repeatable services in order to improve the MSs-SDM optimization and reveal its supply-demand equilibrium, is one of the core issues to be addressed in future.

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