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Technical Paper

Resource allocation in cloud-based design and manufacturing: A mechanism design approach

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ABSTRACT

The focus of this paper is on matching service seekers and service providers, such as designers and machine owners, in cloud-based design and manufacturing (CBDM). In such decentralized scenarios the objectives and preferences of service seekers are different from those of service providers. Current resource configuration methods are unsuitable because they optimize the objectives of only one type of participants – either service seekers or service providers. Existing marketplaces based on first-come-first-serve (FCFS) approach are inefficient because they may not result in optimal matches. To address these limitations there is a need for mechanisms that result in optimal matching considering the private preferences of all the agents. In this paper, we formulate the resource allocation problem as a bipartite matching problem. Four bipartite matching mechanisms, namely, Deferred Acceptance (DA), Top Trading Cycle (TTC), Munkres, and FCFS are analyzed with respect to desired properties of the mechanisms such as individual rationality, stability, strategy proofness, consistency, monotonicity and Pareto efficiency. Further, the performance of these mechanisms is evaluated under different levels of resource availability through simulation studies. The appropriateness of matching mechanisms for different scenarios in CBDM such as fully decentralized, partially decentralized and totally monopolistic are assessed. Based on the analysis, we conclude that DA is the best mechanism for totally decentralized scenario, TTC is most appropriate when cloud-based resources are used in an organizational scenario, and Munkres is the best mechanism when all resources are owned by a single agent.

1. Introduction: matching decentralized service seekers and providers

Cloud-based design and manufacturing (CBDM) is a decentralized, service-oriented design and manufacturing model where participants utilize product development resources, such as CAE tools and manufacturing equipment, using cloud computing, and other related technologies [30]. It is an extension of cloud-based manufacturing (CBM), which is a model for "ubiquitous, convenient, on-demand network access to a shared pool of configurable design and manufacturing resources" [31]. One of the primary advantages of the decentralized model of design and manufacturing over the traditional manufacturing model of owning all resources is that it addresses the contradiction between *scarcity* and *redundancy* of manufacturing resources [25]. It allows small and medium-sized enterprises (SMEs) who lack manufacturing equipment to benefit from enterprises who own the equipment, but do not use them at the full capacity. Such a decentralized model is particularly attractive with the availability of Internet-connected digital manufacturing equipment such as 3D printers. In such an environment, designers can print their designs at any 3D printer connected to the cloud rather than at one particular site.

CBDM involves interactions among two groups of participants: service seekers and service providers. *Service seekers* need to manufacture or use computational resources, but do not possess the capabilities to do so. *Service providers* own and operate equipment or other resources and are ready to offer users instantaneous access to these capabilities. An effective CBDM platform must be able to effectively support the important tasks of resource discovery, service scheduling, service matching. Several research efforts have been focused on issues such as resource virtualization technologies, resource and service publication and discovery [24], service composition, efficiency [26], reliability and security management [27]. A review of challenges and research gaps in these emerging manufacturing models is provided by Tao and co-authors [23].

The focus in this paper is on service matching, which involves determining which service providers will serve different service seekers. The service seekers and the service providers have

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Nomenclature

$\|P\|$	number of service providers
$\|S\|$	number of service seekers
μ	matching mechanism
$\mu(d_i)$	agent to which d_i is assigned through μ
μ_R	matching mechanism μ for the preference ordering R
f	single attribute utility
$j \succ_i k$	i strictly prefers j over k
$j \succeq_i k$	i prefers j over k
P	set of service providers
p	probability distribution of the attribute values
p_{-i}	set of all service providers excluding p_i
q_{p_j}	vacancies offered by service provider p_j
R_{p_j}	preference ordering of provider p_j over its alternatives
R_{s_i}	preference ordering of seeker s_i over its alternatives
S	set of service seekers
s_{-i}	set of all service seekers excluding s_i
u_{ij}	utility of agent i being matched to alternative j
w_{ki}	weight for attribute X_k for agent i
X	set of all attributes

different, often conflicting, objectives. Service seekers are interested in desired part quality at a minimum price, while service providers are generally interested in maximizing revenue from their available capacity. Additionally, the specific quality desired by each service seeker, and the price they are willing to pay are different; and the capabilities of each service provider may be different. Therefore, there are as many different objectives as there are participants in the system. One of the primary requirements of a CBDM platform is to determine an *optimal allocation of resources considering the objectives of all the participants*.

Conventional resource allocation methods based on multi-objective optimization are inappropriate for matching resources to service seekers in decentralized scenarios because they optimize the objective of one party only. The commonly used approach for matching in decentralized scenarios is a *marketplace* where service providers display capabilities and prices at a central location (e.g., on a website), and the service seekers self-select the providers based on their needs. This is a first-come first-serve approach (FCFS) because if a service provider's resource is available, it can be used by the service seeker who requests it first, and is willing to pay the asking price. Such a model is adopted in 3Dhubs [1], an online 3D printing service platform with around 25,000 service providers.

Several inefficiencies arise when service seekers are matched to service providers using FCFS. First, when resources are scarce, service seekers may have to wait indefinitely in the queue for the most sought after service providers. Second, only the service seeker's preferences are considered here, the preferences of the service provider are not explicitly considered. For example, a service provider with a high resolution 3D printer, which is more suitable to print jobs that demand higher detail capability, may be chosen first by a seeker who does not need such capability. Third, even in cases where two service seekers have first preference for the same service provider, the utility that each service seeker gains may be significantly different. Therefore, the match obtained from FCFS may not be optimal from the standpoint of the entire set of participants. Fourth, it is possible for participants to try and "game" the system by exhibiting strategic behavior, i.e., considering other participants' objectives and stating preferences that are different from their true preferences. For example, a service seeker may consider how much delay would result if he/she seeks the resource that best matches his/her requirement as there may be several other seekers in the queue prolonging the response time. When this happens it is not optimal for a service seeker to state his/her true preferences, but rather based on expectations about other service seekers' preferences. Finally, FCFS does not account for the specific requirements of different organizational scenarios. For example, for a central service provider organization, such as Shapeways [21], where all the resources are owned by the same company and the service seekers are independent designers who are interested in printing their parts, the objective is to allocate the jobs to the resources to maximize the total utility gained by the organization. On the other hand, in a totally decentralized scenario, such as 3Dhubs [1], the utilities of all service providers and seekers need to be accounted for in the matching algorithm.

To address the limitations of the FCFS matching mechanism, the central question addressed in this paper is: *How can service seekers be optimally matched to service providers in different decentralized design and manufacturing scenarios, considering the true preferences of all agents?* We propose the use of matching theory, which has been used for different matching problems such as matching students to schools, kidney donors to patients for transplant, and residents to hospitals. To the best of our knowledge, this is the first application of matching theory within the CBDM context. We analyze the applicability of different matching algorithms in different decentralized design and manufacturing scenarios. The effects of strategic behavior of participants on the efficiency of the matching are analyzed. We also study the influence of dynamic entry and exit of agents on the optimality of matches, which is crucial in a CBDM framework. Finally, we draw insights on the effects of market thickness and resource availability on these matching algorithms through simulation studies.

The paper is structured as follows. In Section 2, we discuss a specific problem of matching designers with 3D printing service providers, along with different organizational scenarios. The steps in matching seekers and providers, and three specific algorithms used in the paper are discussed in Section 3. The three algorithms are evaluated for different scenarios in Section 4. Simulation results are presented in Section 5, and closing comments in Section 6.

2. Matching designers and manufacturers – a specific problem in CBDM

2.1. Illustrative example: 3D printing services

Additive manufacturing is bridging the gap between designers and manufacturers by enabling rapid transition of concepts into physical prototypes and final products. The increasing popularity of additive manufacturing is partly due to the availability of mid-level consumer grade 3D printers, and access to robust 3D modeling software for the creation of geometric models.

To serve designers for whom it is economically not viable to own different printers for their needs, there has been an emergence of service organizations, such as Shapeways [21], who own a variety of 3D printing machines. The machines range from desktop printers for plastic parts to industrial scale metal printers, giving designers a myriad of options to choose from based on their needs. Designers can submit geometric models to these organizations and get them printed at the quoted price. These organizations typically also offer quality checks and assistance to designers to help them market and sell their products in return for a commission.

In addition to 3D printing service organizations, an alternate, decentralized scenario exists where designers who do not possess the necessary prototyping resources are able to connect with independent individuals who own those resources. These interactions are facilitated by service matching organizations, such as 3D Hubs