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A mutualistic framework for sustainable capacity sharing in manufacturing

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Abstract

In order to decrease the ecological impact and footprint of supply chain actors, a promising mechanism for sustainability in the industry is represented by sharing resources with each other in a mutualistic way. The paper aims at introducing a novel framework that facilitates the collaborative work of manufacturing facilities and helps participants dynamically and safely negotiate available capacities shared within the federation. The center of the framework is an open API cloud- and simulation-based platform which supports the strategic collaboration of federated companies while helping them optimize resource utilization, avoid shortages and minimize the environmental impact of their logistics.

Keywords: collaboration, supply chain, sustainability, resource sharing, mutualism, reciprocity

1. Introduction

Globalization has changed production systems: first large companies, and then following them, SMEs shifted from rigid and centralized manufacturing approaches towards decentralized production networks, due to increasing internationalization, development of new sales markets, skilled workforce, etc. [1]. Another indicator of this process is the increasing customization and fluctuation of production orders, which challenges manufacturing companies. They have to adapt to decreasing lead times and complete orders that they may not have the right equipment for. The paradigms introduced in the middle of this section are able to cope with these challenges by enabling decentralized work.

Nevertheless, in connection with decentralization, another important issue is *sustainability*. In decentralized production networks, optimizing logistics (e.g., order from the closest CNC manufacturer company), and taking area-specific energy prices into account could decrease the environmental footprint of the companies [2]. However, these aspects could be considered efficiently if a global view is obtained from the whole system, and optimization decisions are made based on information provided by the participants. Another problem is, they somehow have to be motivated to share information about their activities – without this, optimization is very challenging. In this paper we present a collaboration model where manufacturing companies are enabled to cooperate with each other in a decentralized way, on the basis of a mutualistic mechanism. This cooperation will be driven and empowered by a federating platform, whose main purpose is to attract participants through the provision of services for the avoidance of capacity-shortages (via resource sharing) and the minimization of the environmental impact deriving from the supply chain logistics. Capacity information sharing will be essential in order to optimize collaborations at a global level.

In literature, decentralized production approaches have been investigated by researchers for years. *Distributed manufacturing* aims at increasing the enterprises' flexibility and agility with a decentralized manufacturing system consisting of autonomous entities. However, as [4] states, none of them has a global view of the system, thus, optimization on a global level is not possible. *Sharing economy* is identified in [3] as "an economic model based on sharing underutilized assets between peers without the transfer of ownership […]".

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In this case, the word "sharing" is a little misleading because it usually assumes the lack of reciprocity and joint possession of the shared resources. Participants are asked to share capacities with each other in a *crowdsourced* way, which means cooperating within a brokering federation based on the members' actual and expected orders or available extra capacities [5]. Crowdsourcing works on a distributed way and increases the flexibility and the service level of the system: this cooperation, mediated by a broker whose goal is to minimize the environmental footprint, can enable resource utilization optimization on a global level.

2. State of the art

As stated in [6], sharing resources via crowdsourcing could be a solution for Build-to-Order (BTO) companies, who are facing difficulties in reaching a high machine utilization level – since, to meet the order deadlines, such companies usually have to keep excess production capacities. An example of this type of collaboration is Swiss Virtuellefabrik [7], where SMEs are focusing on manufacturing unique products needing special equipment. The orders are distributed between the members by brokers, and the group of companies could not efficiently utilize their resources without working together. Another similar, manufacturing-as-a-service (MaaS) platforms are Xometry [8], MFG [9], and Fictiv [10]. They provide CNC, 3D printing, injection molding services in general. In case of Xometry and Fictiv, the matching between customers and manufacturers is done by the platform, the customer is not able to influence the choice. Xometry even uses ML and AI algorithms to determine the price promptly, based on previous jobs with its manufacturers, and the manufacturer is not known for the customer. In contrast, in case of MFG, the customer has to compare the manufacturers, the prices, lead time, etc. and choose the best option. Because of this, customer ratings, reviews are also available to support decision making.

In collaborative scenarios in general, participants have to be encouraged to keep their promises and to have a commitment to their plans and goals [13]. Trusting in each other's promises is one of the main pillars of the system, which also helps to increase the service level of the participants. Considering trustfulness in resource sharing systems is a useful tool to incite the participants to keep their promises and reduce the risks.

In [14], a trust-based resource sharing mechanism is presented, but the resource-offer matching does not happen in the federation center. Agents are sending messages directly to each other – thus, there is no possibility to inject a global optimization mechanism. Resource sharing methods have been investigated widely by researchers in the past years: for example [15] present a model where the robustness of capacity allocation was studied in dynamic production networks, [16] introduces an architecture for secure information sharing across enterprises, and [17] investigates the possible cheatings in resource sharing with a game theory approach.

The main novelty of the proposed collaboration model is to consider capacity constraints at each facility level, and combine mutualism, sustainability, and trustworthiness with dynamic resource sharing. Here, matching requests with offers is done on the basis of information disclosure, by a brokering and optimizing platform called Open Manufacturing Federation (OMF). *The aim of the OMF is not to create a system which is operating merely on market rules (resource sharing does not happen for free and capacity offerors request a price for their services), but to generate the conditions of a mutualistic environment for sustainable collaboration, among actors that are exposed to sudden demand fluctuations in their supply chain. Nevertheless, the federation aims also at increasing the effectiveness and competitiveness of its members, by enabling a better utilization and optimization of their resources.*

Mutualism can be seen as a means of collaboration, in which actors with different objectives can benefit from the relationship. In manufacturing systems, a similar relationship could be noticed between companies and MaaS platforms [11]. Mutualism is two-directional, as also highlighted in this paper: a single facility necessitates the OMF for dynamically adapting to market demands and virtually augmenting its production configuration. On the contrary, the OMF needs as many facilities as possible, in order to increase the sustainability of collaborations and so, in turn, to attract more and more supply chain actors.

3. Definitions

Open Manufacturing Federation (OMF) is a broker that provides its services for a group of collaborating manufacturing facilities, who are members of the federation. Collaboration is only possible between federation members. Facilities are allowed to join or quit the federation at any time. To join, the interaction protocol has to be accepted, an NDA needs to be signed, and a certain quality level has to be achieved. (Note: in this paper, the authors do not deal with companies who wanted to join the federation, but they were refused.) All facilities - modelled with agents - are allowed to offer their temporarily unused capacities and also to send requests to the OMF when having capacity shortages. The OMF receives the offers and requests to match them (if possible) with considering environmental awareness. The federation members also have the opportunity to receive fragmented offers from different facilities through the OMF and cancel an offer, a request, or a contract for some reasons (finding a less expensive, faster, or more trustable partner). There is also an opportunity for the federation members to exit the OMF any time, and external facilities to join. The OMF provides services to its members: request-offer matching, reputation computation, etc. – described in detail in the later sections of the paper. The aim of OMF is not to provide the best option for a request, but to offer some good alternatives.

A *facility* is an autonomous decision-maker of the resource sharing model. It can communicate with the OMF: offer and request resources. Based on its decision mechanism, it can choose the appropriate one from the offers suggested by the OMF. In the presented model, *capacity* can be a human, a machine, a logistic buffer, or a storage. Four categories are distinguished here:

- free-internal: free capacity of a facility *not* announced to the OMF (known only locally),
- free-public: free capacity of a facility announced to the OMF (known by the OMF and the capacity-requesting facilities),
- assigned-internal: capacity (planned to be) used by the owner, and
- assigned-public: capacity (planned to be) used by another facility (contracted via the OMF)

Possible events influencing the available capacities of a facility are: (1) new production order, which requires additional capacity, (2) resource breakdown which requires substitution, (3) cancelled production order which frees capacity, and (4) new or repaired equipment that increases capacity.

A *job* is a work that has to be done to fulfil an incoming order, it is determined by its capacity requirements: type (or types – a job may require multiple different resources), amount, earliest start time, and due date. The processing time of a job is the time that is necessary for the facility to perform it (more free capacities of the required type may lead to an earlier completion of the job than the due date). The authors use the following simplifying assumption: the amount of required capacity multiplied with the difference between the earliest start time and the due date must remain the same.

An *offer* is sent to the OMF to find a matching request and includes the machine type, time interval, and the amount of offered capacity. It is also important to define a minimum amount of capacity that can be used if a requester facility does not need all of it. Making an offer technically means changing free-internal capacity to free-public.

A *request* is sent to ask for free-public capacity: it consists of the technical information (anonymised CAD files, material, tolerances, and manufacturing method) of the product to be manufactured – which determines the machine type(s) that the manufacturer must have. A request also contains the capacity requirements of the job to be outsourced (mentioned earlier). It also contains information about whether the requested capacity can be divided, and if yes, the maximum number of fragments the job can be divided into. There is also a minimum reputation value for the facilities whose offer can be accepted to complete a specific request.

A *contract* is an agreement between two facilities via the OMF by accepting a matching offer-request pair. It describes the time interval when one facility uses the other facility's capacities, the payment and cancellation conditions.

4. Model structure

The authors consider only discrete resources, and in case of jobs, the setup times are not explicitly modelled, they are included in the processing times of the jobs that are performed on a First Come First Served (FCFS) basis by the facilities. Distance between facilities, their equipment (capacity types) are also considered, but the authors do not deal with the modelling of premises, buffers, calendars, shifts, maintenances, etc. Simulating production and logistic systems helps to make better decisions in connection with operations planning, scheduling, real-time control, operating policies, and performance analysis [18]. It is here assumed that each facility has a simulation model about its production and is able to make decisions based on it (or at least capable of creating forecasts good enough to make decisions based on them).

Preconditions for the presented resource sharing model are as follows. First, compatibility and quality check of facilities/equipment are important for quality assurance purposes: production plants have to ascertain in the quality of the resources shared by other facilities in order to use them with minimal risks. Safety margins for the resources are considered as well: facilities do not offer all of their free resources. They might have different KPIs and decision criteria – however, in this paper, the authors do not deal with the local decision-making mechanism of the facilities in detail.

The OMF and the facilities have pre-defined minimum response times, and also a maximum time allowed to react to a collaboration request. Minimum response time is necessary because each facility has to create forecasts to make the right decision, and the OMF also has to run its matching algorithm. If a facility does not react in the maximum response time, the OMF assumes that it did not want to accept any of the offers. The OMF also checks on the validity of offers (i.e., are they expired or not), and evaluates the performance of facilities in order to provide information for its match-making mechanism (note: an offer may be invalid due to the FCFS approach). If two facilities agree and contract on resource usage, the conditions of the contract cancellation (e.g., penalty) should also be defined. If a facility requests and uses the resources of another, this is compensated according to some payment scheme.

Optimization is done both on *facility* (local) and *inter-facility* (global) level. The first means that a facility tries to maximize its profit, the utilization of its resources and minimize the used energy (e.g., public utilities to operate the machines, fuel to transport products) by making decisions about using its capacities for internal or external jobs. In the model, the decisions are made locally: facilities can decide the amount of offered and requested capacity and requesting facilities can choose from the offers, which are suggested by the OMF. A requesting facility decides between offers by taking the price, transport cost, and the reliability of the offering facility into consideration. An offering facility might outsource a job even though it has the appropriate capacity to finish it, if it notices that an offer made through the OMF is less expensive than using its own capacities. The OMF is responsible for the inter-facility level of optimization, by taking into consideration environmental awareness in the matching algorithm between capacity requests and offers, favouring offering facilities that are closer to requesting ones with the aim to reduce energy and fuel consumption due to logistics and routing.

The authors assume that the facilities are honest with each other and with the OMF as well: they do not try to manipulate the system by sending false messages or providing false trust values.

A facility may terminate an already signed contract or cancel an offer or a request already announced to the OMF. A facility receives a penalty for "changing its mind" after the permitted temporal terms. Cancelling a signed contract can occur both from the requesting and from the offering side. In this case, the facility's reputation value is relevantly reduced by the OMF, the cancelling facility's trust value against the other facility decreases, and it may have to pay a pecuniary penalty to the contracted facility (for causing financial loss by not completing the job or reserving the contracted capacity needlessly). Cancelling an offered capacity or a request before matching only comes with a decrease in reputation, to incite facilities to send the OMF only serious information, this way avoiding the OMF to be overloaded.

The flowchart of the collaboration model is depicted in Fig.1, where the inputs are marked with blue arrows, the outputs are marked with orange ones.

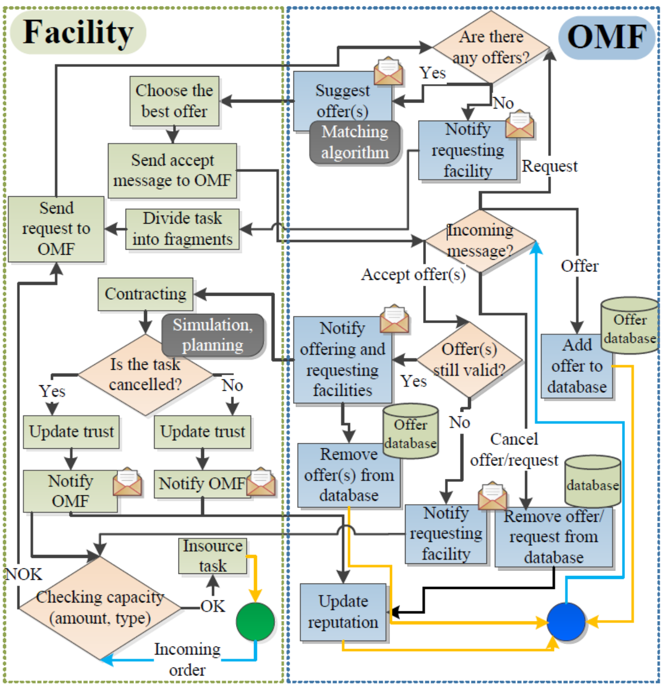

Fig.1. Flowchart of collaboration in the OMF

When the OMF receives a message, it processes it according to its nature (offer, request and cancellation - offer/request/contract). The OMF updates the collaboration repository and waits for new incoming messages (this process is on the right edge of the figure).

4.1. OMF main functionality

The most important goal of the OMF is to provide a request-offer match for outsourcing and capacity sharing facilities, supporting a better resource utilization to its members. It provides access to a continuously increasing capacity sharing community – the OMF operates like a dynamic augmentation of the facility, which can be extremely useful in case of fluctuating customer orders. The OMF recommends offers coming from new facilities, providing the requesting participants a higher chance to find the best (if any) offer. It minimizes the disclosure of capacity-related information to prevent facilities querying and planning on the basis of all of the other facilities' capacity. The OMF might take daily exchange rates and area-specific energy prices into account when making suggestions for matching offers. Another major attribute is proactivity: if the platform notices that a better (e.g., faster, less expensive) facility entered the federation, it can propose this choice for consideration to the interested parties, also in case an existing contract or a contract is in progress. Sustainability is addressed by recommending offers with lower environmental impact (closer partner, fewer logistics), and, as it has a global view about the members, by optimizing logistics as well. OMF will also have the ability to plan with capacities, leveraging long-term contracts (e.g., request capacity for the next year). It could happen that a single offering facility does not have the required amount of resources to satisfy a request: in this case the request could be fulfilled by fragmenting capacity offers from different facilities. The matching algorithm of the OMF can handle this situation, too.

Fig.2 depicts an example of a match between a request and two offers. The basis of the matching algorithm is that he sum of all offers time interval must be contained in the requesting facility scheduling plan for the requested resource.

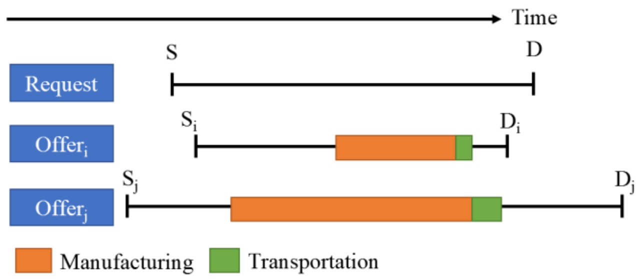

Fig.2. Example for a match between two offers and a request

4.2. Trust and reputation definition and calculation

Trust and reputation are terms that are difficult to define – they are based on a complex belief of dependability, competence, and integrity. There is no widely accepted definition for these words, but in most practical systems, trust means a subjective value that is based on direct experiences, and reputation is a public value, which includes indirect information about a partner [12]. In this work, trust is computed and updated by each facility after each contract; it is based on previous direct interactions with another OMF member – it can be interpreted as *the facility's subjective opinion* about another one's performance. In contrast, each facility has a reputation value, which is more like a rating that qualifies the specific facility for the others (can be interpreted similarly as Google reviews). It is computed and updated continuously by the OMF after each interaction, and basically determined based on the trust value given by the requesting facilities. As mentioned before reputation is also influenced by cancelling signed contracts or taking back announced offers and requests, and *contains all the other facility's opinions*. Both trust and reputation values are numeric, and between 0 (lowest) and 100 (highest) but reputation values are accessible only to OMF members. This way, they can contract with an unknown partner with lower risk, as they will see its reputation through the offer provided by the OMF (as a facility can't have a trust value about an unknown partner, it will rely on the reputation value only).

When a facility signs a contract then it is expected to: (1) complete (do not cancel) the job, (2) complete it on time, and (3) complete it in with the expected quality. The subjective trust value is computed based on these three things, as can be seen in Eq. (1) – the base of the computation method is described and validated in [14].

$$trust_i^{m,n} = \left(100 - \frac{L_i \cdot 100}{t_d - t_e}\right) \cdot \alpha \cdot \mu \quad (1)$$

Here, $trust_i^{m,n}$ means the trust rating given by $facility_m$ to $facility_n$ in connection with job_i. L_i is the lateness with finishing the job, t_e is the earliest start time and the t_d is the due date (we suppose that $L_i < t_d - t_e$). μ is a subjective rating about the quality of the completed work, and the role of penalty factor α is to sanction lateness to a greater extent: if $L_i \leq 0$, then α will be equal to 1, if $L_i \geq 0$, then α will be a constant model parameter between 0 and 1. Lower α means higher penalty for exceeding the due date. Based on Eq. (1), if a job is finished on time and in the expected quality, the trust value will be equal to 100. If the job is finished with some delay, the result of the subtraction in the brackets means some kind of percentage lateness with the job.

Eq. (1) showed the computation of trust in connection with one job – these values are cumulated and form the trust about a specific company, as reported in Eq. (2) and Eq. (3). For giving older feedbacks smaller weights than more recent ratings, modified exponential smoothing is applied, as used in different trust and reputation systems [19]. Eq (2) shows the computation of the time weight in time t_j, where t_j-t_r is the elapsed time from the rating time t_r, and Φ denotes the decay factor used to influence the shape of the function. Eq. (3) shows the computation of trust value $trust^{m,n}(t_r)$ that $facility_m$ computes about $facility_n$ when evaluating its offer in time t_r. Here, $trust_i^{m,n}$ (t) means the trust value given in time t for $task_i$, according to Eq. (1).

$$w(t_j) = \frac{\Phi}{\Phi + (t_r - t_j)} \quad (2)$$

$$trust^{m,n}(t_j) = \frac{\sum_{t=1}^{T} w_{m,n}(t) \cdot trust_i^{m,n}(t)}{\sum_{t=1}^{T} w_{m,n}(t)} \quad (3)$$

Reputation values are computed by the OMF, and they are updated using the same time decay function as introduced in Eq. (2) and Eq. (3). The difference between trust and reputation is that trust values are updated by the requesting facility after each interaction with any other facility, while in case of reputation, the OMF updates the reputation value of a specific facility after interacting with another OMF member.

Cancelling a signed contract (which is possible before the earliest start time of the specific job) causes trust and reputation loss computed by the OMF according to Eq. (4), where t_s means the time point of signing the contract, t_e is the earliest start time of the job, and t is the time point of cancelling. In this case, the reputation value of the cancelling party will be multiplied with p, as a penalty. Up to five contracts (this number is arbitrary) cancelled will cause the exclusion of the facility for an (exponentially) increasing length of time from the OMF, meaning its offers and requests will not be considered until this time is over. From the fifth cancelled contract, the facility is banned forever from the OMF. Cancelling an offer or request announced to the OMF before matching causes "only" 5% reputation loss.

$$p = 1 - \frac{t - t_s}{t_e - t_s} \quad (4)$$

4.3. Communication interface between Facility and OMF

OMF is intended to act as a Resource Broker in a FIPA-like brokering protocol (Foundation for Intelligent Physical Agent [20]), designed to support interactions in mediated systems and in multi-agent systems (MAS). OMF interface with facilities' MAS is based on the standardized application-level Hypertext Transfer Protocol (HTTP) [21]. Communication structure and the layers of the model can be seen in Fig. 3.

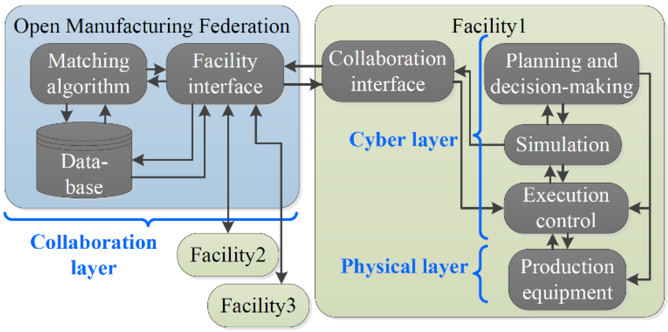

Fig. 3. Layers and components of the model

5. Experimental results

The performance of the federation members is currently investigated through agent-based simulation experiments performed with AnyLogic [23], the first results of the model are presented here. In the model, each agent represents a separate node and the OMF runs on a cloud-based platform. For the simulation model of a facility the SISO-STD-008-201, Standard for Core Manufacturing Simulation Data was applied [24]. A simulation with 19 facilities (each modeled as agent) was performed to investigate how the OMF affects the environmental impact of the collaborating facilities. The following cases were compared: (1) all the facilities always choose the least expensive offer regardless its environmental effect due to logistics, (2) all the facilities choose the most environmentally friendly offer regardless its price (3) ten facilities are environmentally conscious and always choose the most environmentally friendly offer, and the other nine are cost-centric and always choose the least expensive offer.

Environmental impact is measured in 100 kilometers run by trucks during logistics. The simulation was run for one month, and the facilities were located in the county seats in Hungary.

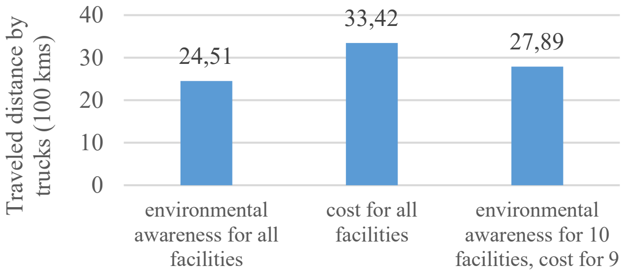

Fig.4. Environmental impact in case of different facility priorities

As one can see, if the OMF can provide offers with less environmental impact, more environmentally friendly cooperation is achievable.

6. Conclusion, future work

In this paper, a mutualistic collaboration framework for environment-aware capacity sharing was introduced, called Open Manufacturing Federation (OMF). The main goal of the OMF is to match capacity requests and offers of the facilities by taking sustainability aspects and the trustworthiness of the facilities into account. It operates like a dynamic augmentation of the facility, which helps to utilize resources on a higher level in case of a highly fluctuating demand. Contracting through the OMF comes with several advantages, e.g., receiving several capacity offers for a job, taking area-specific energy prices into account, and contracting with lower risk by considering the reputation of partners. In future works, the model will be extended with more complex jobs containing interdependent tasks, and simulation experiments investigating the effect of different model parameters. Allowing facilities to manipulate the system by lying about capacities or sending fake requests to the OMF with the aim of obtaining information about other member's free resources could also be an interesting research direction. Entry conditions could be extended for facilities as well, in order to ensure that only members who can add value to the OMF can participate.

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