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Financial aspects of a trust-based resource sharing platform

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A R T I C L E I N F O

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A B S T R A C T

Since cooperation has been identified to be a key factor of future manufacturing firms' success, manufacturing concepts incorporating cooperation gained increasing interest within research and industry. However, the benefits from a financial standpoint have not yet been investigated thoroughly. Therefore, this paper investigates financial aspects of a resource-sharing platform where manufacturing companies can request resources (in case of shortage) or offer them (in case of surplus) through a central platform. In the first step, the additional costs and revenues are worked out in the context of a resource-sharing network. In the second step, a model is developed in order to evaluate and compare the additional costs (manufacturing, management, administrative, penalty, inventory and distribution costs) as well as the additional revenues (incomes) of a resource-sharing platform. Then, platform-based and direct exchange-based resource sharing algorithms are compared from the financial perspective. Finally, the model is validated and tested with experiments conducted using an agent-based simulation model. The findings (1) can be applied in the design and operation of such a platform, and (2) are helpful for companies who are considering this type of collaboration as a way to increase their competitiveness.

Introduction and motivation

The traditional model of the manufacturing industry is getting transformed. Driven by an on-demand, fit-for-purpose service philosophy, the manufacturing industry has to deal with increasingly complex supply networks, too [1–3]. Additionally, megatrends such as mobility, urbanization, ecology and digitization cause increased environmental (external) complexity to manufacturing companies [4,5]. As part of these megatrends, logistics and supply chain management are affected by major changes [2,6], which, as mentioned in [7], can be handled by new digital technologies developed under the Industry 4.0 era. Managing the resulting complexity is therefore one of the biggest challenges of supply chain management [3,8-10]. Only those companies that will accept and use these challenges to their advantage will remain competitive.

Ever-new crises accompany these continuous developments. The probabilities of crises and crisis-like phenomena are increasing [11]. A crisis is a difficult situation or situation with destructive development trajectories [12]. Crisis-like phenomena are disturbances, conflicts, risks, and disasters. The nature and characteristics of these crises, and thus their impact on the supply chain, vary widely. The most recent crisis are the semiconductor crisis and the corona crisis. The latter does not affect any specific sector, industry or geographic area. It affects global supply networks in different areas, at different times and intensities. The German economy e.g., was hit with − 4.9% GDP drop of economic output in 2020, 74.5% fewer air passengers traveled which caused major airlines to struggle, Consumers spending dropped 4.6% while online retail experienced a rose of 27.8% [13]. Unique to the corona crisis is especially the influence of the crisis from both sides (demand and supply) of the supply networks. This creates lasting effects and bi-directional (forward and backward) disruption propagation [14]. Often the problem was not the change in the total demand, but the demand shift to another type of similar product (e.g., flour, yeast, toilet paper, etc.) [15]. Since many international suppliers could no longer deliver, it led to global material and supply shortages. Major suppliers were unable to produce in part due to regulatory requirements, which led to a production shutdown. Capacity utilization on the one hand and capacity overload on the other, led in part to a bullwhip effect. The capacity utilization was countered by extra shifts, reactivation of idle resources and postponement of lower-

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priority orders [16]. Because of the corona crisis, global supply chains have come under criticism [17]. A study presented in [18] investigates the short- and long-term impact of epidemic outbreaks on supply chains using simulation models – showing the potential in this technology to cope with these types of disruptions.

Partly triggered by the corona crisis, also a global semiconductor crisis developed. During corona, many vehicle productions came to a standstill, demand dropped. However, suddenly the industry picked up again, which led to a bullwhip effect. Semiconductor manufacturers need a certain amount of time to ramp up production again. OEM and the suppliers did not have this problem. The result was a phase shift. Semiconductor demand exceeded normal demand by far. The relatively long manufacturing times of about 170 days make it difficult to increase capacity in the short term.

One concept to cope with the above-mentioned challenges within supply chains is resilience (see also [19-23]). Rice and Caniato define resilience in today's business world as an organization's capability that describes how to respond to unexpected disruptions in order to restore normal operations [24]. Sheffi includes speed in his definition of a resilient supply chain [25]. Datta additionally defines resilience as the characteristic of being adaptable to respond sustainably to sudden and significant changes in the environment in the form of uncertain demands [26]. There are a variety of definitions of the term resilience. In general, it describes the ability to respond quickly and sustainably to disturbances. Many innovations with regard to supply chains such as resilience approaches have been investigated recently. Whereby the goal is often to increase the resilience of the network and therefore reduce total cost [27-29].

Spieske and Birkel state one of the most important resilience drivers is collaboration that means joint risk mitigation of the partners, requiring mutual trust [30]. For cooperating organizations, it is essential to be honest with each other and to have a strong commitment to the promises [31]. By taking trust and reputation into account in decision-making, companies could be incited to keep their promises, e.g., complete an undertaken order in spite of noticing a more profitable option for using free capacities. They also can be forced not to bias information and to meet the job due dates because otherwise, they would worsen their own situation (after receiving a bad rating, they are less likely to win new jobs). Making decisions based on trust and reputation also enables to differentiate between partners who are reliable and who are not. Such a framework is driven by the promises and commitments for the future, given by the participants. The main pillar of the framework is that one can believe the other's promises: if participants cannot count on these commitments, and they are not incited to keep the promises, the framework of cooperation is violated, and the efficiency of the distributed manufacturing system can decrease.

Companies state that the outsourcing of production steps into collaboration like concepts will likely increase in the future [32]. Concepts incorporating collaboration approaches like the resource sharing are enabled via recent developments like cyber physical production systems, cloud computing and digital shadows (see also [33]). These technologies support the integrated networking and the transparent data communication between every member of the supply chain and creates new possibilities for networking and cooperating between different actors and stakeholders within a supply network [34–37].

However, the benefits from a financial standpoint have not yet been investigated thoroughly, rather the discussion focusses on the technical feasibility and the behavior of such approaches. Especially when considering whether a company should join a shared resource federation network, such an investigation is of particular importance. Therefore, within this paper, in a first step a shared resource network is introduced based on previous works [38] and [39]. Within the second step, the model is complimented with a profound cost structure in order to perform a financial analysis with simulation experiments.

In the first section, a literature review is provided about collaboration and resource sharing in production networks, and a brief introduction to the resource sharing model is presented. In the second section, the costs and incomes in the platform-based resource sharing model are detailed. Here a quantitative break down approach is taken, which determines each process step in the overall production process including indirect areas and assigns cost to them. Then, the role of trustfulness in the model is introduced, followed by a financial comparison of the platform- and direct communication-based resource sharing mechanism. In this part, two financial aspects are particularly relevant: benefits due to the resource sharing, e.g., higher resource utilization and additional efforts e.g., caused by transports and management costs of the platform. Lastly, some simulation experiments are presented to investigate different use-cases.

The novelty of the thoughts presented here are the 1) general cost model for resource sharing networks, 2) investigation of financial benefits of resource sharing, 3) comparison of two resource sharing approaches from the financial perspective.

Collaboration and resource sharing in production networks

The producer-consumer relationships in production networks are changing, which gives room for increased cooperation in order to cope with such problems [37]. Authors of [40] state that as a result of globalization, first, large manufacturing companies and then small and medium-sized enterprises (SMEs) are increasingly moving from rigid, centralized organizational structures toward distributed production networks. They also present the influencing factors, challenges (e.g., uncertainty, complexity, sustainability and disruptive innovation), enablers (such as adaptability, platforms/standards, collaboration and technologies) and decision support systems (data analytics, simulation and optimization) of Global Production Networks. In addition, they identify the exploration of the potentials of digitalization and new forms of collaboration as a promising research direction, and state that resource allocation is a promising strategy to cope with nowadays' challenges. In [41] the need for new manufacturing paradigms using the technologies enabled by the fourth industrial revolution is also highlighted, and simulation as a digital technology suitable to help designing and testing these approaches is mentioned. As stated in [42], cooperation and collaboration are not optional for manufacturing companies; it is a must if they want to remain competitive. In [43], the authors distinguish between horizontal and vertical cooperation among enterprises, depending on whether they are at the same level of the supply chain in terms of value creation. Cooperation between supply chain actors is widely investigated in the literature from several perspectives: e.g., trustfulness [44] and robustness [45], but in these cases the cooperation is always vertical between participants: the relationship between a producer and its supplier(s) is investigated. In the paper, participants can have the same resource types and thus competitors of each other – they are on the same level of value creation (horizontal cooperation). Some of the methods developed for long-term customer-supplier relationships could be applied in resource sharing mechanisms (e.g. cost for penalizing inaccurate delivery time), but others have to be modified or rethought from the basics as the investigated problem is different.

Crowdsourced manufacturing was proposed by the International Electrotechnical Commission [46]. The main idea of the concept is to collaborate with each other by sharing resources via a *platform*. As mentioned in [47], for Build-to-Order (BTO) companies often keep extra capacities to be able to meet order deadlines, crowdsourcing can be an effective way to reach a high resource utilization level. This concept is also applicable for 3D printing, where offering resources on a Manufacturing-as-a-Service (MaaS) way is already in operation [48], and joining a platform could smoothen the demand fluctuations for

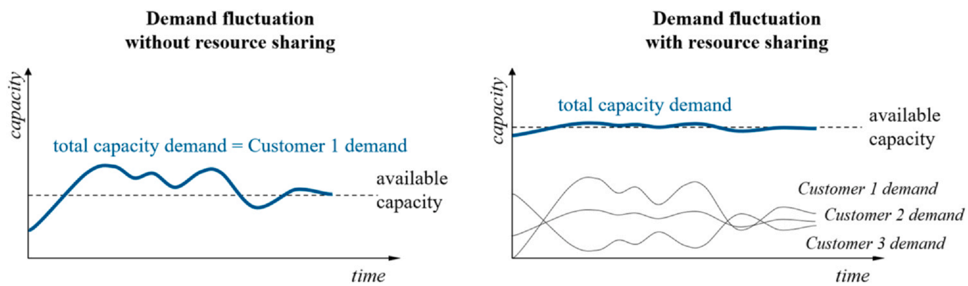

Fig. 1. Demand fluctuations without and with resource sharing.

resource offerors. This concept can be also a solution for companies having specialized, often expensive, resources, facing a problem with utilizing them on a high level. As mentioned by [49], outsourcing and crowdsourcing help manufacturers – who are facing the challenge of multi-variety and variable-batch production orders – to concentrate on their core business and share non-core business jobs with other companies. Fig. 1 shows difference between demand fluctuation without and with being part of a resource sharing federation. In the first case, the company have to face the costs of lost sales due to capacity shortage of lack of specific technology. In the second case, the company can "extend" its capacities with outsourcing some of the jobs to be able to complete more orders even from more customers, but it has to face the additional outsourcing efforts, such as transportation and organization costs.

Resource sharing can be defined as a cooperative action and has gained a lot of attention in the recent years. Users of a shared resource receive the advantages of ownership, such as availability and use, while the disadvantages, such as investments costs and environmental impact, are reduced [43]. In case of fluctuating customer demands, the company may face the problem of idle capacities (lower demand than expected) or lost sales (higher demand than expected), as shown in Fig. 2.

By sharing resources with each other, manufacturing companies can solve the challenges mentioned in Table 1.

Resource sharing between manufacturing companies have been already investigated from different aspects. For example, [50] examines the stability of matching resource requests with offers, [51] even highlights that it is crucial to take the costs of matching for each participant (companies and the platform) into consideration. In [44,45], the robustness of capacity allocation was studied in order to find an optimal way of outsourcing resources in a production network with the desired robustness. Authors of [52] propose a resource sharing algorithm for federated production networks and validate the concept with agent-based simulation. In [53], the strategy proofness of resource matching in crowdsourced manufacturing is investigated. In [7], the effect of considering trustfulness in resource sharing mechanisms is presented. In [54], the effects of resource occupation and decision authority decentralization on performance is investigated, [55] examines the interoperability aspects in CNC technology.

Table 2 summarizes the examples taken from the literature in order to compare them with the approach presented in this paper. In the table, the keywords in the third column mean the following:

- *trust:* trustfulness is not considered,
- *divided requests*: requests are not divisible,
- *resource constraints:* resource constraints of participants are not considered,
- *separated requesters and offerors*: service requesters and offerors are two separated groups,
- *financial aspects*: costs and incomes are not considered.

As one can see based on Table 2, the main difference in the proposed mechanism compared to the others already presented in

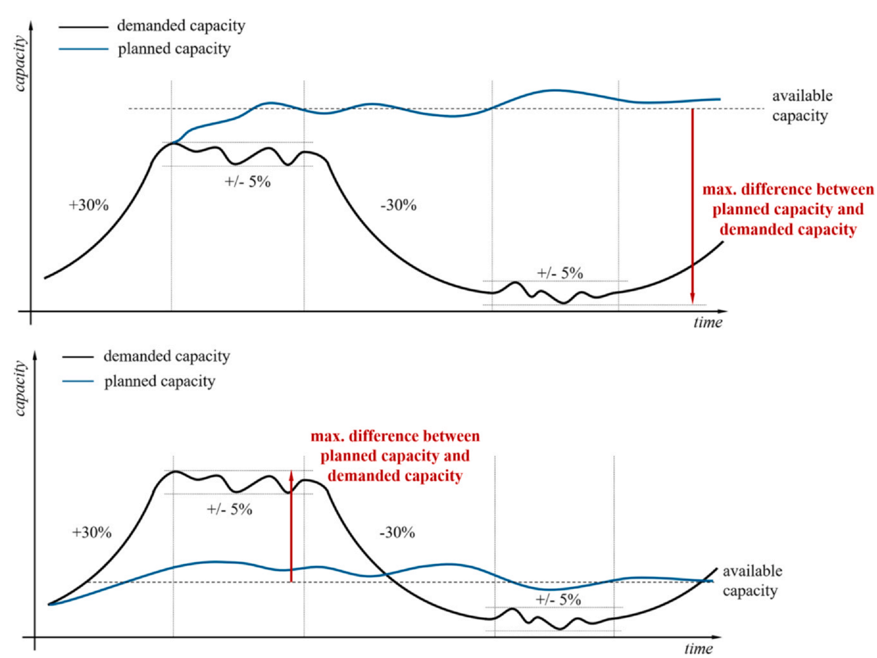

Fig. 2. Idle capacities and lost sales in case of fluctuating demands.

Table 1
Challenges solved by resource sharing.

Challenge	Solution enabled by resource sharing
Keeping extra resources in order to meet delivery deadlines of larger orders; but these may remain unused during less loaded periods	Sharing resources with each other: requesting them when having shortages and offering them when having surplus
Imprecisely predictable customer orders, disturbances in supply network causing fluctuating utilization of production system and difficult planning	
Fluctuating demand, underutilized capacities for companies having resources that can be used generally, e.g., laser cutting, 3D printing, CNC machines	Resource sharing platform where they can offer their resources, this way smoothening the demand and utilize their resources by receiving more orders
Buying specific equipment to be able to produce certain products, this way spending resources on tasks that are not the core business of the company	Outsourcing certain job phases to companies focusing on operating specialized equipment, and focusing on core business tasks that the company can complete with higher efficiency

the literature is (1) the inclusion of trustfulness, (2) the consideration of resource constraints of the participants, and (3) the financial model tested with simulation experiments.

The basics of the platform-based resource sharing mechanism and the information flow between participants have already been presented in [38] and [39]. Nevertheless, the main considerations of the model are described here for an easier understanding. One novelty of this resource sharing approach it that collaboration is not between geographic locations of the same company or between different manufacturing service provides (as in Cloud Manufacturing). In contrast, the collaborating partners are *on the same level of value creation* and their role (resource offeror or requester) depends on the specific interaction.

In the presented model, BTO companies, who are members of the federation, receive orders from customers outside the federation (see Fig. 3). An order is about producing a specific number of products and consists of some jobs that require different resource types to be completed. A job is determined by its resource requirements: type, amount and time; and the number of products that have to be produced. In the cited model, an order contains only one job, but here a more complex order composition is applied: all the jobs in an order have to be finished to complete a specific order. For example, an order can be to produce 100 windows, and specific types of equipment are needed to manufacture the glass, metal and plastic parts. A job is to manufacture the 100 handles, another is the production of the glass plates, etc. If a company that received the order has a shortage from a certain resource type that is required to keep the delivery deadline or receives an order that requires a specific resource type that the company does not have (e.g., 3D printer to manufacture a complex part), it sends a resource request to the Platform. From an information flow perspective, the Platform is in the center of the federation, and receives resource requests and offers (that companies can send in case of having underutilized resources) to match them: this way helping companies with shortages and extra resources also. The Platform could also combine offers from different companies to fulfill a request (this way, a job could be completed by different companies), and sends the list of appropriate offers or offer combinations to the company that received the order from the customer. The request sender is called *lead company*, as its role is to consolidate and manage all the jobs that were insourced and outsourced.

The presented approach is placed between decentralized and centralized production methods because the decision making (choosing between resource offers) is made by the participants

Table 2
Summary of the resource sharing related literature.

Ref.	Focus of paper	Results	Missing aspects compared to the proposed model
[50]	Stability of request-offer matching in crowdsourced manufacturing	Adaptation of the “blocking pair” concept to optimize matching stability. Computational study for matching optimization methods.	trust, divided requests, resource constraints, financial aspects
[51]	Matching costs for participants and the platform	Optimal matching strategies for decentralized, centralized and cost-sharing contract systems are presented. A cost-sharing contract effectively improves the performance of the decentralized supply chain. The cost-sharing contract does not always achieve Pareto improvement for all parties. Numerical analysis shows that the platform transaction fee and purchasing costs affect the win-win region and optimal strategies	trust, divided requests, resource constraints, separated requesters and offerors
[44]	Multi-criteria decision-making algorithm	Based on simulation results, the trust and reputation model developed is effective in resisting collusion attacks from malicious customers and filter unfair ratings. The proposed multi-criteria decision-making model helps to choose the most suitable suppliers in a supply chain	resource constraints, financial aspects
[45]	Robustness of capacity allocation	New approach for capacity allocation is proposed, validated with mathematical program	trust, financial aspects
[52]	Details of resource sharing algorithm	Resource sharing method is introduced and validated with agent-based simulation. Experimental results are focusing on the impact (service level, resource utilization) of increasing the number of participants.	Trust, divided requests, financial aspects
[53]	Strategy proofness of resource matching in crowdsourced manufacturing	Profit-sharing based crowdsourcing method is presented, computational study show that the proposed method forces greedy participants to lose their profit, and motivates them to submit true information related to resource matching.	trust
[7]	Effect of trust in resource sharing without a platform (previous work of the authors)	Considering trust and reputation in decision making (choosing between partners in resource sharing) improves the performance of the participants	financial aspects

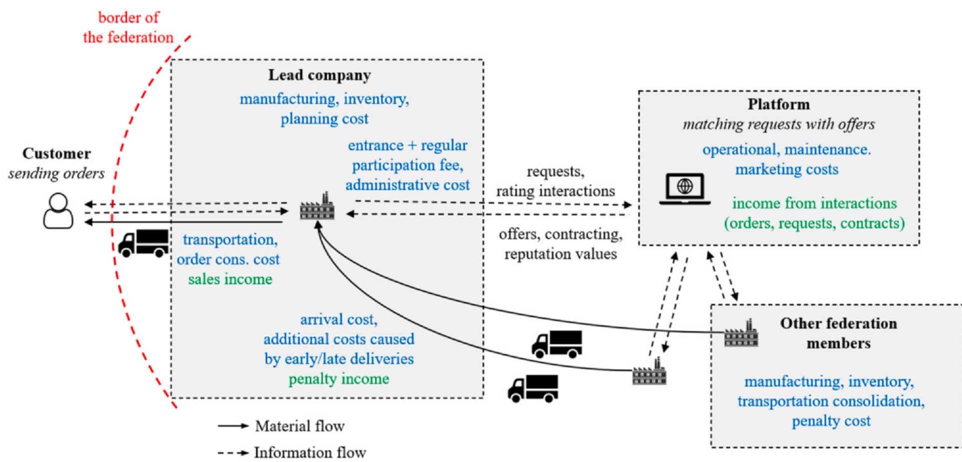

Fig. 3. Material and information flow in the federation with the costs and incomes of the participants.

locally, but the distribution of resources is supported by a central Platform whose role is to pre-filter and combine resource offers from which the requester can choose from. The lead company makes the decision based on the offer prices and it also takes the *trustfulness* of the offerors into consideration, which is based on rating each other's performance (this will be detailed in the "Considering trustfulness" subsection).

Fig. 3. depicts the material and information flow between the participants of the federation. The costs (blue color) and incomes (green color) are also visualized in this figure and will be discussed in detail in the following chapters. (A structured overview of the different cost types for federation members is presented in Fig. 4).

One can distinguish between the initial and the operation phase in connection with a resource sharing platform. At the initial phase, the main goal is to attract as many participants as possible to establish matching of resources (provide the necessary number of offers for the requesting companies and vice versa). At the operation phase, the platform should focus on ensuring the continuous communication and interactions. This paper focuses on the operation phase, and additional actions from the platform side to attract participants (e.g. reduction of participation costs) are not considered.

Costs and incomes in platform-based resource sharing

In the following subsections, the calculation of the different cost and income types applied in the model is introduced. When calculating each item, only the costs incurring and incomes generated for the federation members and the Platform, in connection with resource sharing within the federation is taken into account, focusing on the time interval when a company is a member of the federation. To help understand the formulas, the meanings of the notations are summarized in Table 5 in the Appendix.

Cost is a critical factor in the success of production, especially in today's competitive marketplace. Companies that are unable to provide detailed and meaningful cost forecasts are at a distinct disadvantage. Therefore, when considering whether a company should join a shared resource federation network, the cost and benefit aspect is of particular importance. Appropriate cost forecasts that estimate these effects in advance are necessary. A cost forecast is: "The prediction of the probable costs of a project or effort, for a given and documented scope, a defined location, and point of time in the future." [54]. The conceptual bases for this cost forecast are cost theories. They establish the relationships between costs and their determinants. The mathematical formulation of the cost hypotheses takes place via so-called cost functions. These enable the forecast of the cost amounts [55]. Due to the complexity of a production system, it is not possible/feasible to set up a single cost function. Instead, it is necessary to formulate several (partial) cost functions for subareas and combine them [55]. Generally, two techniques for costs forecasting can be used: qualitative and quantitative techniques. Qualitative techniques:

- Based on data from the past, costs of a new product are estimated
- Historical products are examined for similarities with the product to be evaluated in order to generate an estimate of the costs or at least a basis for such an estimate if there are similarities [56].

Quantitative techniques:

- The product is broken down into its components and their production processes. A subsequent analysis then evaluates the costs of these elements and adds them up.
- The sum of the resources required in the production process is formed. These methods promise more accurate results than qualitative techniques, but involve more effort [56].

Within this paper, a quantitative break down approach is taken, which determines each process step in the overall production process including indirect areas and assigns cost to them. All processes that occur during the product manufacture must be known. The processes also include non-productive efforts such as setup times. In addition to the activities, the material costs are also included in the evaluation, whereby the focus is clearly on the activities and their process times. It is a very accurate way of determining costs, which can be applied late in the product development process [56–60]. To determine the relationship between the determinant and the cost level, three steps are necessary [61].

- Determination of the factors influencing the cost level.
- Grouping of the cost-influencing factors.
- Formulation of the functional connection between the cost height and the factors.

As mentioned, the aim of this paper is the comparison of a shared resource network (RSN) and a non-shared resource network (nRSN) under a financial perspective. In order to compare these aspects a detailed structure of the relevant cost types is necessary. Within the supply chain management, various so-called cost structures were developed for this purpose. Most approaches focus on a differentiation based on the organizational units or activities similar to the SCOR-Model (see [62] for details on the SCOR-Model). Pettersson

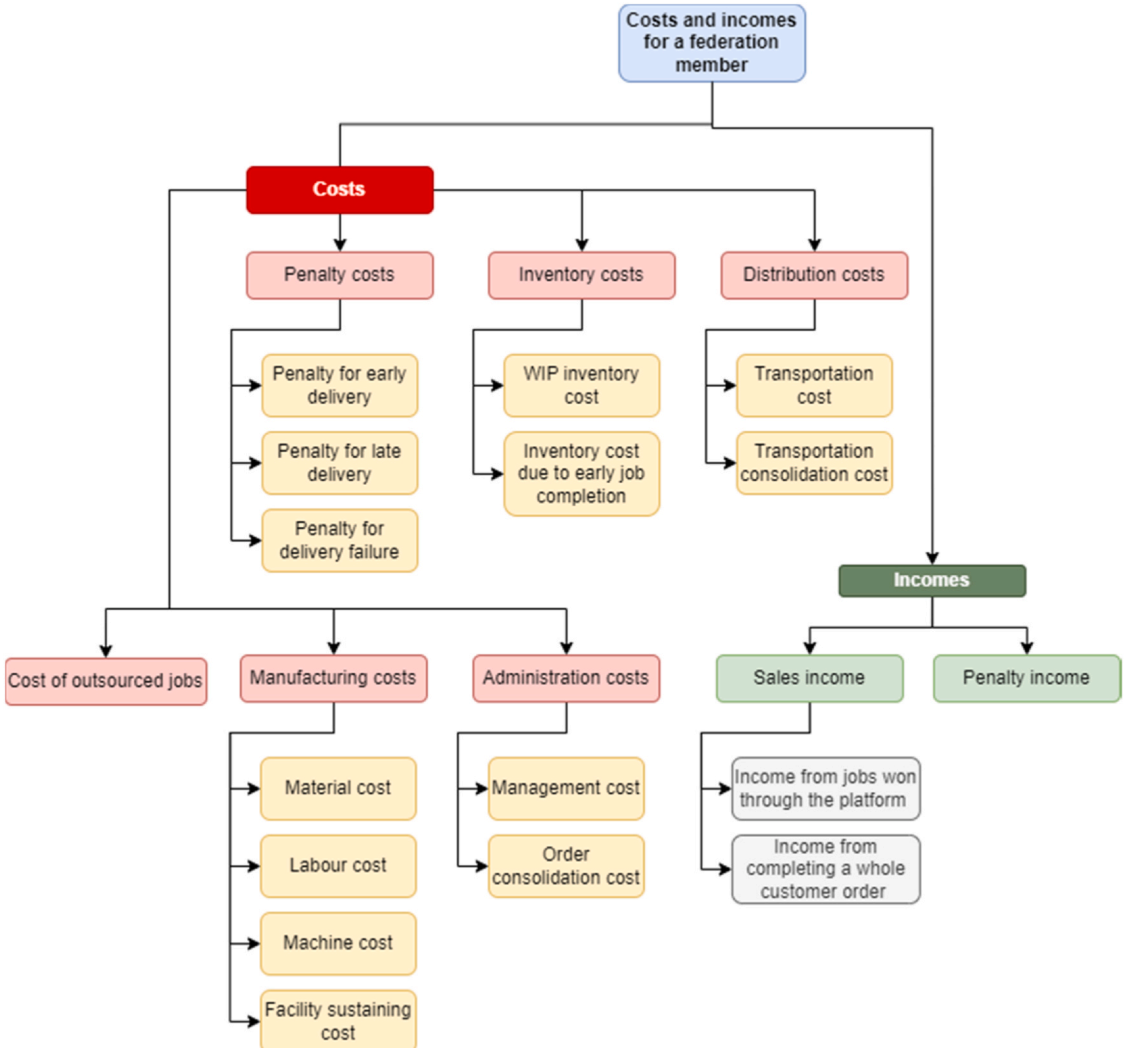

Fig. 4. Cost and incomes of a federation member in platform-based resource sharing.

et al. distinguishes manufacturing cost (including direct material, direct labor and overhead production), administration cost (including order handling and planning), warehouse cost, distribution cost (including inbound and outbound transportation), capital cost, installation cost [63]. Ustundag et al. differentiates labor cost, inventory holding cost, order cost, lost sales cost and theft cost [64]. Whicker et al. divides the costs into raw materials, production labor, production expenses, production overheads, finance and service, personal and administration, distribution costs [65]. Other researchers also consider e.g. the visibility of occurring cost and distinguish visible and invisible costs. Whereby visible costs can be directly quantified into monetary terms and invisible costs are referred to as hidden opportunity costs [66]. Sinha and Anand develop a supply chain cost model including penalty costs e.g., for failure of delivery [67]. Due to existing costs structures used in similar works being adapted to the specific use cases while missing important aspects of the SRN, there is no existing description of supply chain costs that could be used within this work. Rather, based on the afore mentioned cost structures, an adapted cost structure accommodating the relevant aspects for the comparison of SRN and nRSN is needed (Fig. 4).

For each cost type, described in the cost structure above, a cost hypothesis is derived, and a corresponding cost function is formulated within the following chapters.

- Manufacturing costs include all the costs related to manufacturing the requested number of products: the company has to pay for the materials, the labor and the machine costs, and, in addition facility sustaining costs are also considered.
- Administration costs consist of two parts: (1) management costs, which mean all the costs paid to the Platform (entrance fee, regular participation fee, sending and accepting requests and offers), (2) order consolidation costs incurring for the lead company who is managing all the jobs in an order.
- Penalty costs are defined to compensate additional costs incurring for the lead agent due to early delivery (additional inventory cost), late delivery (sales opportunity loss), and delivery failure (lost profit).
- Inventory costs can occur (1) when storing WIP products during production and (2) in case of early job completion, before delivery.
- Distribution costs are covering the transportation costs (between customers and lead companies) and transportation consolidation costs (between federation members, in case of outsourced jobs).

Manufacturing cost

[67] distinguishes between four cost types regarding manufacturing costs:

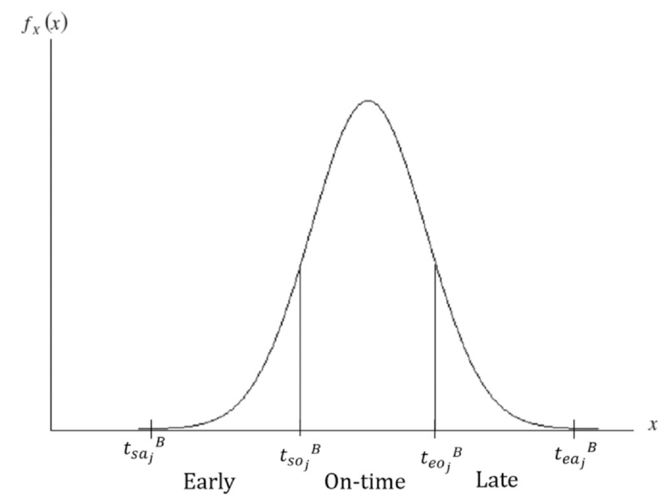

Fig. 5. Delivery window based on [67].

(1) unit-level activity costs (e.g., material, machine, and labor costs),
(2) batch-level activity costs,
(3) order-level activity costs, and
(4) facility sustaining costs.

Manufacturing costs in the presented model will be introduced by taking this approach into consideration. For simplicity reasons, batch- and order-level manufacturing costs are neglected – these raise the question of the optimal batch size that is not in focus for this paper. For a part of a job *j* that was outsourced to company B or insourced by itself, the manufacturing cost $c^B_{manuf_j}$ can be calculated by adding the $c^B_{material_j} \cdot \alpha^B_j$ material costs (material cost per product multiplied with the number of products) to the $(c^B_{machine_j} + c^B_{labour}) \cdot t^B_j$ machine and labor costs per time unit multiplied with the time that is required to complete an order:

$$c^B_{manuf_j} = c^B_{material_j} \cdot \alpha^B_j + \left(c^B_{machine_j} + c^B_{labour}\right) \cdot t^B_j \tag{1}$$

For company B, the total manufacturing cost includes the c^B_{sust} facility sustaining costs multiplied by the T time interval for which the company is a member of the federation; and the manufacturing costs of all the jobs that it has completed.

$$C^B_{manuf} = c^B_{sust} \cdot T + \sum_{j=1}^{J} c^B_{manuf_j} \tag{2}$$

Inventory cost

In the presented financial model, inventory cost can incur due to three main reasons. The first of them is when a company has to store the products during manufacturing (WIP inventory cost):

$$c^B_{WIP,j} = \frac{\alpha^B_j}{2} \cdot c^B_{inv_j} \cdot t^B_j \tag{3}$$

where $c^B_{WIP,j}$is the total WIP inventory cost for the part of job *j* that was outsourced to company B, $\alpha^B_j$is the number of parts that have to be stored, $c^B_{inv_j}$is the inventory cost per product in job *j* for company B for one time unit, and $t^B_j$is the manufacturing time of the specific job part. As a simplification, it is assumed that the number of manufactured products grows steadily during the manufacturing time, and in this case, the average number of stored products is half of the final number of them.

The remaining two of the causes for additional inventory costs are based on the early completion of a job. The first is when a resource offeror delivers the finished products to the lead company earlier than the start of the on-time interval of the specific job. In this case, inventory cost will incur for the lead company, which will recover this cost by penalizing the resource offeror with the same amount. As mentioned in the "Penalty Cost" subsection, this cost is calculated by multiplying the number of products in the specific part of the job that was outsourced to company B by the inventory cost of agent A for one product in job *j* for one time unit and by the time unit for which the products have to be stored:

$$c^A_{inv_{j,B}} = \alpha^B_j \cdot c^A_{inv_j} \cdot \left(t_{d_j}{}^B - t_{sa_j}{}^B\right) \tag{4}$$

The second reason is when the lead agent finishes an *insourced* job earlier than the start of the on-time interval determined for it and has to store the products until the whole order is finished. In this case, the additional inventory cost incurring due to the insourced job is calculated similarly as in Eq. (4).

Penalty cost

In supply chain relationships, companies have to be motivated to deliver accurately [68]. For BTO companies, which are operating a Just-In-Time (JIT) production system, excessive inventory is not an option, and inaccurate delivery times can cause serious space and cost problems [69]. In such cases, delivering products too early and too late also have to be penalized somehow. The most common way of forcing suppliers to be more reliable and to compensate the customers for the costs coming with early, late, or failed delivery is issuing a penalty cost. Authors of [70] also state that exact, cost-based performance measurement is a key aspect in connection of delivery times and measuring delivery performance, and it is closely connected to reliability. For example, in the automotive industry, Saturn levies fines of $500 per minute against suppliers who cause production line stoppages [71]. Chrysler fines suppliers $32,000/h when an order is late [72].

Several approaches can be found in the literature when investigating and modeling penalty costs in supply chains. In [73], two types of customers (agents) are differentiated: the first type accepts tardiness in the delivery of orders, the second type does not accept the tardy orders at all, and assess the tardy orders as failed. Authors of [74] mention that lower variance in delivery times improves delivery performance, thus increases customer satisfaction among the existing customer base in the short term and can lead to new customers in the long term. They define the delivery window as the difference between the earliest acceptable delivery date and the latest acceptable delivery date, as shown in Fig. 5. In the figure presented here, the nominations that are applied in the financial model have been used already. $t_{sa_j}{}^B$ is the start and $t_{ea_j}{}^B$ is the end of the acceptable delivery time interval of the part of job *j* that was outsourced to agent B, and $t_{so_j}{}^B$ is the start, $t_{eo_j}{}^B$ is the end of the on-time delivery interval where no penalty will be issued.

[75] distinguishes between four penalty cost types (the same approach is used by [67]):

(1) Penalty cost for delivery failures, which is a fixed cost, proportional to the number of delivery failures.
(2) Penalty cost caused by the sales opportunity loss, proportional to the number of products not delivered.
(3) Penalty cost to compensate extra working time that is spent to re-produce the safety stock to its nominal level.
(4) Cost of safety stock, which is proportional to the buffer size.

Here, the two abovementioned approaches are combined and at the same time focus is placed on only those penalty types that are relevant in the case of BTO companies who are sharing resources via a platform. From [74,75], cost type (1) could be applied to failed deliveries due to job cancellation or delivering outside the time window, as shown in Fig. 5. In reality, a failed delivery can cause the failure to fulfill the whole order; thus the lead company could also lose trust towards the customer, too.

Cost type (2) is for late deliveries to compensate the sales opportunity loss of the customer – but this does not include the loss of trustfulness towards the company that the customer is delivering late and a penalty that the lead company may pay for late delivery. Penalty cost types (3) and (4) are not really applicable for BTO companies operating a Just-in-Time production system, because they do not have a safety stock. The study presented in [75] does not include any penalty costs related to early delivery; however, [76] highlights that additional costs arise in connection with holding too early delivery (inventory costs), also. They present a model including nonlinear early and late delivery costs (holding/backlogging issue for the customer), which are taken as a product of a linear function of delivery lead time and a nonlinear function of the delivery lot size. They state that the efficiency of a supply chain network is greatly influenced by the reliability of the supply process, and highlight that the success of a supply chain lies beneath the proper timing of delivery of goods to the intermediate parties. They introduce a delivery tolerance period, where no penalty has to be paid, and mention that delivery time inaccuracy could come from inaccuracy of production lead time or transportation time. Here the authors are focusing on the sum of these two and assume that the earliness or lateness with deliveries is the offeror's responsibility no matter what the cause is. Nevertheless, early delivery is not only generating additional inventory costs: in the case of food or medicine, the quality of the products could decrease during the storage time period – which also has to be included in the penalty cost [77].

Taking the referenced models into consideration, by combining and extending them, the penalty costs applied in the presented financial model are the following, calculated on the basis of the delivery time ${t_{d_j}}^B$.

If ${t_{d_j}}^B < {t_{sa_j}}^B$ or ${t_{d_j}}^B > {t_{ea_j}}^B$, the delivery is *failed,* and the penalty cost will be computed by multiplying the P^o profit that could have been created by selling the products (calculation is described in the Sales income subsection) with the $c^A_{fail_j}$ failed delivery factor for company A (see Eq. (5)). Here all the additional costs, such as trust loss caused by the failed delivery, are included in $c^A_{fail_j}$. It could also happen that a resource offeror company cancels to complete a job despite the fact that it has signed the contract. For cancellation, the same penalty will be issued, but it will be penalized from the trustfulness perspective, also (description in more details can be found in the "Considering trustfulness" subsection).

$$c^B_{pen_j} = P^o \cdot c^A_{fail} \tag{5}$$

If ${t_{sa_j}}^B < {t_{d_j}}^B < {t_{so_j}}^B$, it is an *early delivery*, here $\alpha^B_j \cdot c^A_{inv_j}$ (the number of products multiplied by the inventory cost per product) and the possible $\alpha^B_j \cdot {c^A}_{qual_j}$ quality reduction costs (number of products multiplied by the quality reduction cost per product) of lead company A for the early time interval will be incurred to resource offering company B as a penalty. In the case of products whose quality do not decrease over time, $c^A_{qual_j} = 0$. Here it is assumed that the offerors do not store the products that were finished early but ship them immediately to the lead company.

$$c^B_{pen_j} = \alpha^B_j \cdot \left({c^A}_{inv_j} + c^A_{qual_j}\right) \cdot \left({t_{so_j}}^B - {t_{d_j}}^B\right) \tag{6}$$

If ${t_{eo_j}}^B < {t_{d_j}}^B < {t_{ea_j}}^B$, it is a *late delivery*, and $\alpha^B_j \cdot {c^A}_{loss_j}$ sales opportunity loss of lead company A for the late time interval will be issued to resource offering company B as a penalty:

$$c^B_{pen_j} = \alpha^B_j \cdot {c^A}_{loss_j} \cdot \left({t_{d_j}}^B - {t_{eo_j}}^B\right) \tag{7}$$

If ${t_{so_j}}^B < {t_{d_j}}^B < {t_{eo_j}}^B$, the delivery is *on-time*; thus, the penalty cost will be equal to zero:

$$c^B_{pen_j} = 0. \tag{8}$$

Distribution costs

[78] mentions that the transportation cost of an order depends on the size of the shipped batch (larger batch has a lower cost per unit), but inventory costs occur when creating too large batches as the products have to be stored until the batch size is reached. This way, an optimal batch size can be calculated. In the referenced paper, three main cost types are differentiated regarding transportation: arrival cost, inventory cost and delivery cost. Here, the focus is not on determining the optimal batch size and simplifying transportation costs, which depend mainly on the distance and transport type, the number of products delivered, and the specific company's administrative costs. Also, as one could see above, inventory costs are treated separately from shipment costs in the presented model. Regarding distribution costs, here the authors distinguish between *transportation cost* which incurs when the lead company ships the products of a completed order to the customer and *transportation consolidation cost* which incurs when the members of the federation are shipping the products of a specific job to each other.

Transportation cost

Transportation cost $c^{AC,o}_{transport}$ for an order *o* is computed by multiplying the d_{AC_o}distance between lead company A and customer C, with the ${c_{transport}}^o$ cost factor for a specific transport type per product, and the α^onumber of products in the specific order. In addition, a fixed shipment sending ${c_{shipment}}^A$cost incurs for the lead company A for each order:

$$c^{AC,o}_{transport} = d^{AC} \cdot {c_{transport}}^o \cdot \alpha^o + {c_{shipment}}^A \tag{9}$$

Transportation consolidation cost

Transportation consolidation cost is calculated similarly to transportation cost, but for shipment of products in case of outsourced jobs between federation members: d^{AB} distance between lead company A and resource offeror company B is multiplied by the $c_{transport_j}$cost factor for a specific transport type per product and by the α^B_j number of products in the specific part of job *j*. In the case of each outsourced job, ${c_{shipment}}^B$ fixed shipment sending cost also incurs for company B. For lead company A, only the fixed ${c_{arrival}}^A$ arrival cost incurs in case of each outsourced job part.

$$c^{B,j}_{tr.cons} = d^{AB} \cdot c_{transport_j} \cdot \alpha^B_j + {c_{shipment}}^B \tag{10}$$

$$c^{A,j}_{tr.cons} = {c_{arrival}}^A \tag{11}$$

Of course, transportation consolidation costs do not appear in the case of insourced jobs. Nevertheless, the higher number of parts the Platform separates a job (because one company does not have the required resource load), the more transportation consolidation cost will incur for the companies.

Administration costs

Management cost

Management costs cover the different cost types that incur for federation members related to the Platform and the planning costs when sending requests and offers:

(1) *entrance fee* that incurs when the company is joining or re-joining the federation (c_{entr}),
(2) *participation* fee that has to be paid regularly after a certain time unit (c_{part}),
(3) *administrative costs* (paid to the Platform) of sending one offer ($c_{offer,a}$), one request ($c_{request,a}$) and establishing a contract ($c_{contract}$), multiplied by the number of offers, requests, and contracts (${n_{offer}}^A$, ${n_{request}}^A$, ${n_{contract}}^A$),
(4) *resource planning costs* of sending offers ($c_{offer,p}$) and requests ($c_{request,p}$).

The c^A_{man}total management cost of federation member A is calculated by summarizing the entrance fee, the participation fee multiplied with the T time interval since when the company is a member of the federation, and the abovementioned administrative costs:

$$c^A_{man} = c_{entr} + c_{part} \cdot T + (c_{offer,a} + c_{offer,p}) \cdot {n_{offer}}^A + (c_{request,a} + c_{request,p}) \cdot {n_{request}}^A + c_{contract} \cdot {n_{contract}}^A \tag{12}$$

Order consolidation cost

Order consolidation cost is incurring for the lead company as a cost for administrating the consolidation of different jobs and job parts in connection with each order. The total order consolidation cost for lead company A is calculated by summarizing all the consolidation costs for the jobs that are part of the orders that company A received:

$$c^A_{ord.cons} = \sum_{j=1}^{J} c^A_{ord.cons_j} \tag{13}$$

Incomes of the participants

The authors distinguish between the following income types for the federation members: *sales income*, *penalty income* and *order completion income*.

Sales income, profit

In the model, the authors distinguish between sales income that is received after completing an outsourced *job*, and lead companies also receive an income after a *whole order* is completed and the finished products are delivered to the customers.

The first type of sales income in connection with a specific job j is paid by the lead company to the resource offeror company and means the selling price of the products that were delivered (${I_{sales_j}}^B$) to the lead company. It is calculated by multiplying the sum of ${c_{manuf_j}}^B$ manufacturing cost and $c^B_{WIP,j}$ WIP inventory cost of the job, by the$1 + p^B$ profit margin of company B (if its profit margin is 10%, the company receives the 110% of these costs as sales income).

$${i_{sales_j}}^B = ({c_{manuf_j}}^B + c^B_{WIP,j}) \cdot (1 + p^B) \tag{14}$$

Profit generated by company B from completing (a part of) job j:

$$P^B_j = ({c_{manuf_j}}^B + c^B_{WIP,j}) \cdot p^B \tag{15}$$

Before selling the whole order to the customer, first lead company A pays for the outsourced jobs. Here the authors assume that the profit generated directly from these jobs, in general, is equal to zero, as after paying for the manufacturing, logistics, inventory, administration costs – even if the partner company works less expensively – it is not realistic to gain a considerable profit directly from these interactions. Consequently, the lead company can generate direct profit mainly based on the additional value of the in-sourced parts. Nevertheless, income is also generated from consolidating all the jobs and delivering the whole order to the customer or assembling the parts that other partners provided. This income is proportional to theα^o number of products in the order, and also with factor i^oadditional income per product. In total, the ${i_{sales}}^{A,o}$ sales income received by lead company A after selling order o is equal to the sum of the income that is proportional to the size of the whole order ($\alpha^o \cdot i^o$) and the income that is generated by the in-sourced jobs.

$${i_{sales}}^{A,o} = \alpha^o \cdot i^o + (1 + p^A) \cdot \sum_{j=1}^{J} ({c_{manuf_j}}^A + c^A_{WIP,j}) \tag{16}$$

The profit for company A in connection with order o is calculated as follows:

$$P^{A,o} = \alpha^o \cdot i^o + p^A \cdot \sum_{j=1}^{J} ({c_{manuf_j}}^A + c^A_{WIP,j}) \tag{17}$$

Penalty income

Penalty income is paid by resource offerors to the lead company to compensate costs due to early or late delivery. This is equal to the cost that was described in the “Penalty Cost”.

subsection: the penalty income for lead company A in connection with the job part that was outsourced to company B (${i_{pen}}^{A,B}_{\ j}$) is equal to the penalty cost that company B has to pay in connection with the same job (${c_{pen}}^B_j$).

$${i_{pen}}^{A,B}_{\ j} = {c_{pen}}^B_j \tag{18}$$

Incomes and costs of the platform

In the presented financial model, the incomes of the Platform are equal to the management costs paid by the federation members to the Platform (sum of management costs incurring for the companies, without resource planning costs):

$$i^{Platform} = \sum_{k}^{K} (c^k_{entr} + c^k_{part} \cdot T + c^k_{offer,a} \cdot n^k_{offer} + c^k_{request,a} \cdot n^k_{request} + c_{contract} \cdot n^k_{contract}) \tag{19}$$

The costs of the Platform consist of the marketing costs (c_{mar}) to attract a higher number of participants, and the operational and maintenance costs of the IT system of the Platform (c_{op} and c_{maint}, e.g., maintenance of server and web page). The Platform could be profitable if the number of participants is high enough to compensate these costs.

$$c^{Platform} = c_{mar} + c_{op} + c_{maint} \tag{20}$$

Considering trustfulness in decision-making

In supply chains, penalty cost-based motivation of suppliers to be accurate can be considered for long-term relationships. In [69], the authors mention that many U.S. firms have used competitive pressure to influence suppliers and their performance by allocating portions of their purchases of an item to multiple suppliers. Authors of [79] even state that they signed contracts that can be terminated in a moment. In contrast, Japanese build on long-term trust, and they help their suppliers develop themselves. In the resource-sharing federation case, an incentive mechanism for the mixture of short- and long-term relationships has to be created, as two participants are not constantly working together (the base of cooperation is lack or surplus of resources), but they may cooperate several times due to different jobs. Here an extended approach is needed that makes the occasional partner selection (choosing the best option from resource offers) more effective, also. In long-term supplier relationships, the main aim of penalty costs is to compensate additional costs of the customer caused by inaccurate deliveries. In contrast, in the resource sharing federation, contracts are made occasionally, and penalty costs are necessary to compensate additional inventory costs (early delivery), or the cost of lost sales opportunity (late delivery). But, in addition, a rating could also be defined that helps resource requesters to distinguish between reliable and non-reliable partners – as it was shown in [7], the performance of a resource sharing federation could increase if trustfulness is considered.

In the presented model, trustfulness is included by using two ratings calculated on the 0.100 scale, called *trust* (which is an internal rating about a specific partner, similar to an own opinion) and *reputation* (which is a public rating, aggregating all the ratings sent by partners about a specific company, and updated by the Platform). The authors here apply an updated version of the rating presented in [39]. There the basis of the ratings was the percentage lateness with the deliveries, canceling offers and contracts were also considered, but early delivery was neglected. In the updated and extended trust model, the $r_{t,j}^{A,B}$ rating given in time point t about a specific interaction (between lead company A and resource offeror company B, about job j) is calculated in the following way. Here the authors are using the same notations that were described in the "Penalty Cost" subsection.

If the delivery is *on-time*, $r_{t,j}^{A,B} = 100$, i.e., company B gets the maximum possible rating. If the delivery is *early* or *late* (arrives inside the *delivery acceptance* interval, but outside the *on-time* interval), the rating about the interaction is computed based on the extent of earliness or lateness that is nominated with δ_j. If the delivery is early, $\delta_j = t_{so_j}{}^B - t_{d_j}{}^B$, if it is late $\delta_j = t_{d_j}{}^B - t_{eo_j}{}^B$. In these cases, the rating is calculated as follows:

$$if \delta_j < L_j \; r_{t,j}^{A,B} = 100\left(1 - \frac{\delta}{L_j}\right)\cdot\gamma\cdot\mu_j \tag{21}$$

$$if \delta_j \geq L_j \; r_{t,j}^{A,B} = 0 \tag{22}$$

where L_j is the length of the job in time, γ is the penalty factor applied on federation level to penalize inaccurate deliveries to a higher extent ($0 < \gamma < 1$), and μ_j is the quality factor that makes it possible to rate not only the delivery accuracy but the quality of the resource offeror's work about job j ($0 < \mu_j < 1$).

Choosing between offers is based on trustfulness and price; thus, the ratings given after each interaction are cumulated. To assign smaller weights to older feedbacks, a modified exponential smoothing is applied, similarly to different trust and reputation systems [44]. The $w(T, t)$weight – that is assigned to a rating given in time point t in order to calculate the cumulative rating in time point T – is calculated as follows, where θ is the decay factor used to affect the shape of the function:

$$w(T, t) = \frac{\theta}{\theta + (T - t)} \tag{23}$$

The cumulative trustfulness in time point T is calculated according to Eq. (24), where all the ratings given earlier are included:

$$\varphi^{A,B}(T) = \frac{\sum_{t \leq T} w(T, t)\cdot r_{t,j}^{A,B}}{\sum_{t \leq T} w(T, t)} \tag{24}$$

The rating described in Eq. (21) is created after each interaction, and (1) sent to the Platform to update the offeror company's reputation, and (2) the internal trust value is updated on the lead company side. When choosing between offers, a company takes the cumulative trust and cumulative reputation (provided by the Platform) of the offeror company into consideration, also, in addition to the price of the offer.

This way, a company could be penalized for bad performance, but its bad rating also could be changed in the long term, in case of improvement in delivery or quality accuracy. It can also happen that a company cancels an offer or a request that has been already sent to the Platform before matching. This is only penalized from the trust and reputation perspective, with a 1% decrease of the cumulated value (and, of course, the company has to pay the management cost of sending an offer/request). Companies can also cancel a contract; this is penalized to a greater extent, which means a 5% decrease, and after the third time, the company gets banned from the federation.

Another important aspect is the honesty of federation members. In the model, the authors suppose that the companies are providing ratings honestly and do not try to influence other companies' decision making by giving lower ratings to a partner than it deserves.

By applying the penalty costs in addition to trustfulness rankings, a penalty structure for occasional cooperation was created to penalize additional costs incurred due to inaccurate delivery time, and also that helps in decision making (when choosing partners who are performing better and do not generate additional costs with being inaccurate) in the long run.

As mentioned, in the presented model, choosing between offers is done by the individual companies. They decide between offers based on price, the actual trust and reputation level of the offeror (see Eq. (25)). In the case of each offer o, requesting company A determine a fitness value ($F_o{}^A$) by calculating the weighted sum of the actual rating of offeror company B ($\varphi^{A,B}(T)$) and the price of the offer o sent in connection with job j ($price_{j,o}^B$). Weights $w_{rating}{}^A$ and $w_{price}{}^A$are determined by the specific company; this way they can be modeled with a preference of price or trustfulness.

$$F_o{}^A = w_{rating}{}^A\cdot\varphi^{A,B}(T) + w_{price}{}^A\cdot price_{j,o}^B \tag{25}$$

Comparison of platform-based and direct communication-based resource sharing

As it has been already investigated in different studies, there is a common understanding that resource sharing generally improves the performance of the collaborating companies [45,50-52]. Here, it is discussed on which way it is more efficient to share resources: by communicating directly with each other or through a Platform. In the first case, a company sends resource requests to its partners if it has shortages, and they send offers as a response, if they have free and appropriate resources. In [38], a comparison is presented between these two approaches (by applying a less complicated order composition logic, as an order contained only one job), and it is shown that platform-based resource sharing could come with a *higher resource utilization level due to the more complex matching logic*, and reduces the communication load of the companies, as well. In addition, the companies have to share information with the Platform only, instead of other (possibly competitive) companies.

In order to be worth joining the Platform, the additional income generated by the higher resource utilization level (i.e., being able to complete more incoming orders and completing jobs outsourced by others) has to cover the additional costs that incur due to Platform-based resource sharing.

According to the model, additional income can be generated by:

- Completing additional orders due to the more complex matching logic of the Platform. Here, as mentioned in the "Incomes of the participants" section, income is generated by (1) insourced jobs and (2) order completion.
- Completing additional jobs outsourced by other companies, by regularly sending offers to the Platform. As the Platform can combine offers from separate companies to fulfill one request, smaller amount of offered capacities could be matched with requests, also.
- Penalty income in case of a partner delivers inaccurately (note: this will be spent on covering the additional inventory costs or lost sales).

Additional costs are:

- Management costs including entrance fee, regular participation fee, and administrative costs of sending messages (requests, offers, contracting).
- Manufacturing, inventory and distribution costs caused by completing additional incoming orders and jobs outsourced by other federation members.
- Additional penalty cost might be paid due to inaccurate job completions.

If a company wants to decide whether it worth joining the platform, it has to consider the following aspects:

Completing additional orders

Does the company receive orders (that can be completed only with outsourcing a part of them) often enough? Do the other federation members have the appropriate resource types to complete the outsourced orders? Do they have enough free capacity to offer their resources?

Completing outsourced jobs

Does the company have additional resources it can regularly offer? Do the other federation members receive orders that could require these resources? Can these resources be offered on the appropriate price level? Is the company reliable enough in terms of delivery accuracy?

Balance between incomes and costs

As described above, higher resource utilization level and additional incomes come with additional platform-related costs, also. A company, which wants to decide whether it is beneficial to join or leave the federation, has to analyse the incoming orders and interactions with others from the past and make forecasts for the future to be able to calculate the possible benefits.

Simulation experiments

There are many definitions of the term agent, but it is generally accepted that agents are intelligent and autonomous entities, acting on the basis of observations of their dynamically changing environment and thus having an impact on their environment [80]. This paper is aimed at investigatin the behavior of manufacturing companies with these characteristics and the dynamic resource sharing between them. Thus, the agent-based modeling method proved to be particularly suitable for the implementation.

As [81] mentions, *simulation modeling* is an efficient technology for designing and evaluating a manufacturing system due to its low cost, quick analysis, low risk and meaningful insight that it may provide. It is also proven to be a powerful tool in case of investigations inside (e.g. material flow, layout planning simulation) and outside the factory (supply chain, design and planning of manufacturing networks).

Due to the dynamic interactions between the participants, analytical methods are not suitable to investigate the mechanism, and therefore experimental runs using a multi-agent simulation model were used to test the proposed mechanism. Multi-agent systems have been widely used in the literature for studies that focus on the interaction between participants in a system and how they respond to inputs coming from their environment [82].

To investigate the financial model for the resource sharing federation, some use cases were created using a model implemented in AnyLogic simulation software where both the companies and the Platform are modeled with agents (see Fig. 6).

Agent-based simulation model

During model running, the companies are receiving a continuous order stream that triggers performing several pre-defined functions: e.g., checking own capability to complete a job, composing and sending offers/requests, matching logic of the Platform, etc. The Platform stores the received and not matched requests and offers in its database, which is continuously updated during the simulation run.

In an agent-based model, each agent must have one or more clear goals, to be accomplished through specific actions, driven by decisional rules.

The goals of *Platform agent* are the following:

- Generate income during operation paid by companies.
- Receive and handle all incoming requests and offers from companies.
- Provide up-to-date reputation values to companies for easier decision-making.

Action items are:

- In case of an incoming request: not to select the best solution but to pre-filter the offers that are meeting the resource and reputation constraints and send them to the requester.
- In case of an incoming offer: to try to find matching requests by checking already received ones, in addition, to continuously monitor the incoming requests for a possible match.
- React to incoming messages (offers, requests) as quickly as possible and update the databases containing requests and offers continuously.
- Penalize companies which are canceling offers or already undertaken jobs, to create a reputable environment that the companies can use for planning.

The goals of the *company agent* are:

- Maximize its own resource utilization and profit.
- Minimize penalty costs occurring because inaccurate delivery.

Action items are:

- Send offers and request to the platform (or in the direct exchange-based case, to other companies).
- Select external resources according to own preferences (e.g. lowest price, highest reputation).
- Rate other companies based on their performance.

Fig. 6. Simulation model in AnyLogic.

- Create and continuously update own production plan based on incoming orders, accepted offers and available resources.

Table 3 summarizes the main input parameters for simulation experiments. For the parameters determined by using a truncated normal distribution, the mean and sigma values are included in the table (for the constant ones, sigma is 0). In these cases, the difference between the lower and upper bounds of the distribution from its mean is sigma/2. Regarding the partner selection, we expect best results if companies of a same region and with a similar product portfolio take part in a resource sharing cooperation. This way, both transportation and machine setup efforts are minimized and lead to less additional costs [43]. Thus, in the model, 10 companies – located in county seats in Hungary on the map – were implemented, and all of them had 16 different resource types out of the required 20 that were used to compose the orders. One order included 3 job types that can require different resource types to complete. Resource type for a job was chosen randomly from the 20 possibilities.

As indicated in Table 3, each company received an order every day that included 3 jobs, consisting of in average 400 products and requiring 4 pcs. of resources (e.g. 3D printers) for in average 12 time units. The Platform could combine a maximum of 3 offers to fulfill the requirements of a request in order to reduce administrative and logistics costs. The planning horizon, i.e., the length of the time interval for which the companies could offer their resources in advance, was 40 time units. The on-time delivery (2 time units) and the delivery acceptance (4 time units) intervals are applied as follows: the middle of the interval is the accurate delivery time in the contract, as it can be seen in Fig. 5.

Regarding the cost parameters, the entrance fee that had to be paid when entering the federation was 10 monetary units, the regular fee was 5; the latter was paid after every 20 time units. The experiments were run for 1000 time units. In the case of outsourced jobs, it was assumed that the manufacturing cost per product for the outsourced jobs were 90% of the insourced ones – meaning the partner companies work less expensively, as outsourcing in reality often happens towards a company whose core business is the specific job type and thus can operate its resources in a more efficient way.

After running the model using the parameters introduced in Table 3, cumulated costs and incomes of Company1 after are shown in Fig. 7.

Experiment 1 – effect of changing order interarrival time

In the first experiment, a realistic scenario was investigated, when a company is continuously a member of the federation, but it receives a lower number of orders for a specific time period due to a temporary demand decrease. The aim was to examine the effect of this on the company from the monetary perspective to see how its profit is affected by this fluctuation.

For one of the 10 companies (Company1) the order interarrival time was increased temporarily at time unit 200 from the original value 1, meaning the company received orders less frequently for

Table 3
Input parameters for simulation experiments.

Parameter	Mean	Sigma	Unit
General simulation parameters			
Order interarrival time	1	0	tu*
Incoming order length	12	6	tu
Incoming order resource quantity	4	2	pcs.
Number of products in one order	400	200	pcs.
Number of jobs in one order	3	0	pcs.
Max. number of offers to be combined by the Platform	3	0	pcs.
Planning horizon	40	0	tu
Probability of canceling an order (for all companies)	2	0	%
Simulation time	800	0	tu
Length of on-time delivery interval	2	0	tu
Length of delivery acceptance interval	4	0	tu
Cost parameters			
Entrance fee to join the federation	10	0	mu**
Regular fee for federation members	5	0	mu
Regular fee payment time interval	20	0	tu
Initial capital for companies	100	0	mu
manufacturing cost per product for the outsourced jobs compared to insourced ones	90	0	%
Profit margin for all companies	10	0	%

*time units, ** monetary units.

200 time units; and from 400 time units, it was set back to 1. One can see in Fig. 8 that in the first two cases (order interarrival time is 1 or 2 time units), the revenue of the company continuously increased. In contrast, when it was receiving orders less frequently (order interarrival time is 3 or more time units) it can be noticed that for the short term, it is not worth for the company to be the part of the federation because of the decreased incomes (due to lower resource utilization) are not covering the management fees. However, in the long term, it is worth joining the federation because the overall balance is positive on the horizon of 1000 time units.

The experimental results confirm that accurate demand forecasts are highly important to the companies. Up to a certain order frequency limit, it is worth it to be a member of the federation, but of course, the Platform cannot solve the problem of large-scale demand decrease: in this case, if a company may exit the federation temporarily not pay the participation fee for this period of time. Nevertheless, one goal for the Platform is to motivate the companies not to quit, for example, by raising the entrance fee that has to be paid again when re-joining.

Experiment 2 – effect of the price of outsourced jobs

In real industrial environments, companies outsource a job only if the manufacturing cost of the job is that much less expensive to cover the additional management, transportation consolidation and inventory costs. Of course, in some cases, it is reasonable to undertake an order even if the profit related to it is negative, not to lose trust towards the customer, and to have a long-term successful relationship.

In the next experiment, another federation member, Company2 was tested, and the extent to which the manufacturing price of the outsourced orders are less expensive was investigated. Here it was assumed that companies outsource a job in any case when they cannot complete an order by their own resources, without regarding the financial balance of doing so. As one can see in Fig. 9, in case of this ratio is 90%, it is worth it to be a member of the federation and outsource orders, but as the ratio increases, the company becomes lossmaking. If the partners are using the same unit prices as the

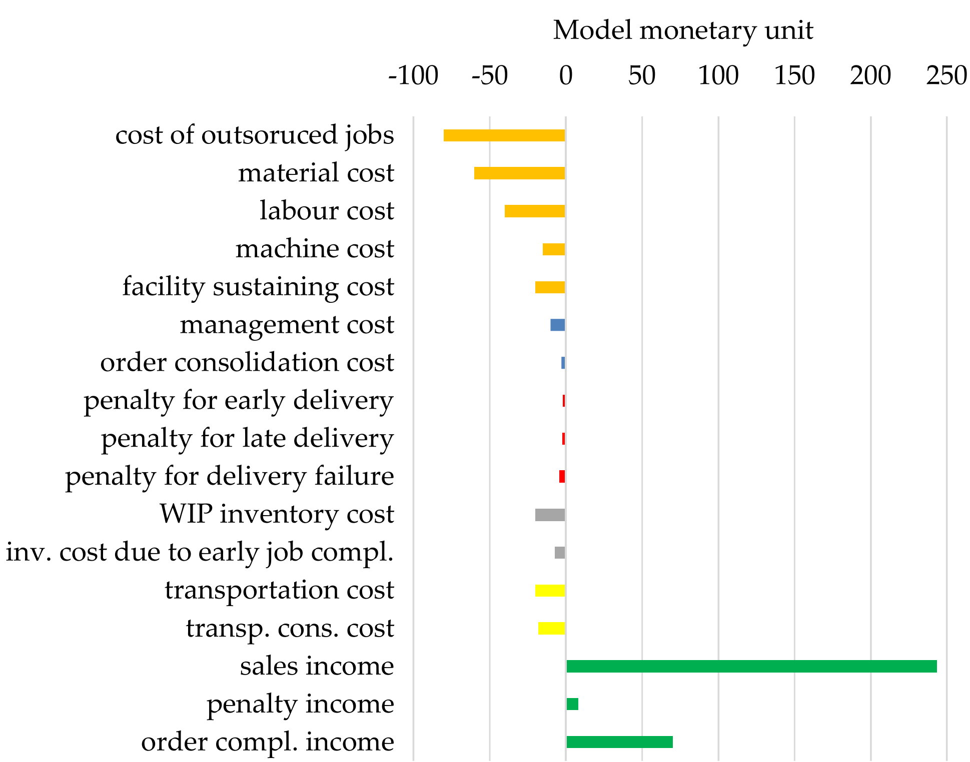

Fig. 7. Costs and incomes of Company 1 in a test case.

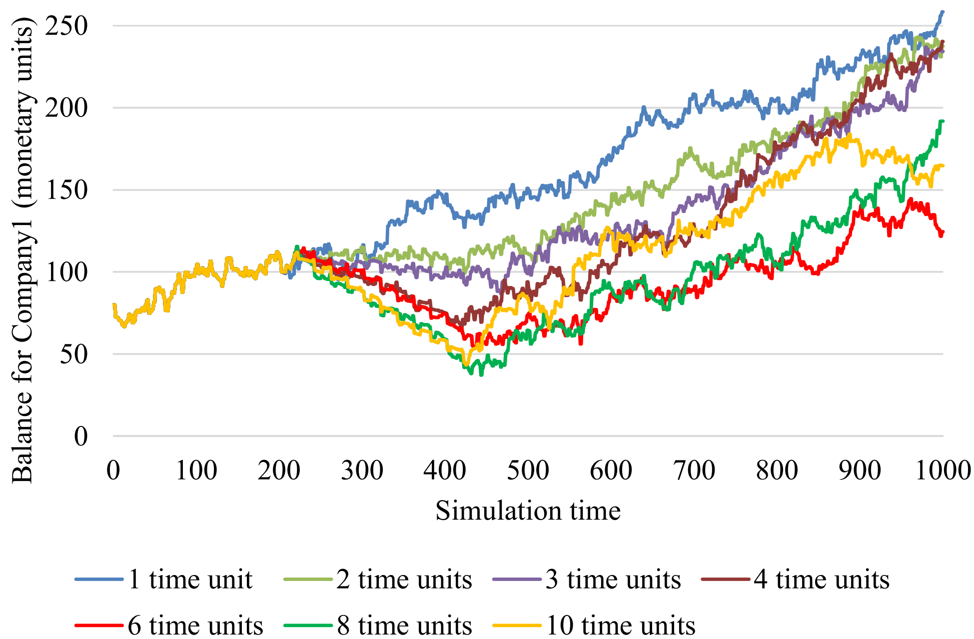

Fig. 8. Effect of changing order interarrival time temporarily.

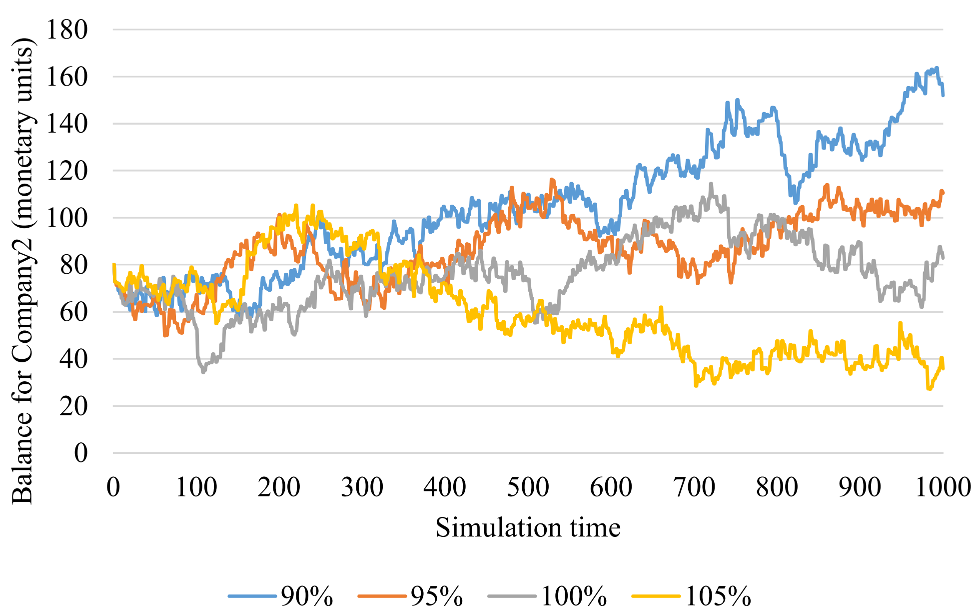

Fig. 9. Effect of price of outsourced jobs.

resource requester company (100%), depending on the contents of the orders, there are time intervals where the income is positive (higher number of insourced jobs), but in other cases the income is negative (higher number of outsourced jobs, loss is created). In such a resource sharing federation, depending on the extent of the additional costs, a company could find the specific cost level where it is reasonable to outsource orders, taking the loss of trustfulness towards the customers into consideration.

Discussion

Using the platform-based resource sharing mechanism, the associated trustfulness rating system and financial model presented in this paper, a web-based platform can be created in reality. It can act as a virtual capacity extension of companies to assist them in operating more efficiently and utilizing their resources as much as possible, particularly in the cases of fluctuating or unforeseeable customer orders. With the presented financial model, companies can decide if it is worth it for them to join a platform-based resource sharing community, based on the influencing factors (e.g., incoming orders, price of outsourced jobs). Due to the evolution of manufacturing and production informatics in recent years, the information technology background needed to operate these platforms has become available [31]. In previous studies, as indicated in Table 2, resource sharing and crowdsourcing was investigated from a different perspective (e.g. stability of matching, matching costs, robustness of the model, strategyproofness), neglecting important aspects such as trustfulness, financial considerations or resource constraints. Other studies often include numerical analysis instead of a simulation model that is able to assess dynamic processes between participants – this way making the results more realistic.

With simulation experiments using the proposed model, it is possible to justify the viability of the resource-sharing mechanism from the financial aspect, too – which is unique in the literature.

The limitations of the work presented here are the following. It was assumed that all the participants are honest and does not try to influence the system with false ratings. Also, in the investigated cases the price of the resources was fixed – in reality, a company usually increases its prices when noticing high demand for its resources.

Conclusion and outlook

Driven by complex supply networks and reoccurring disruptions like the corona crisis, supply chain resilience and flexibility have gained increasing attention. The aim is to increase performance in high uncertainty environments and therefore reduce overall total cost of the supply network. As a key enabler, collaboration among the network participants was identified and has since been incorporated in different supply network concepts. One promising concept in terms of a holistic collaboration approach is a platform based shared resource network. Even though they have been investigated from a technical standpoint, a financial investigation was yet missing.

Therefore, this paper applies a cost and benefit model in a trust-based resource sharing platform, in order to investigate its financial behavior. Within this network, the manufacturing companies are collaborating with each other by sending requests (in case of resource shortage) and offers (in case of resource surplus) to a central Platform to match them, this way utilizing their resources and exploit their business opportunities on a higher level. Companies can also rate the performance of their partners based on their trustfulness, which is, besides the price, the basis of the decisions made locally between offers provided by the Platform after combining and pre-filtering them.

The financial model consists of the description and formulation of costs related to resource sharing, such as manufacturing, administration, penalty, inventory and distribution costs. Incomes from sales and penalty are also introduced, and the financial issues for the Platform are investigated. In the presented model, resource offering companies are penalized in the short term for being inaccurate with delivery deadlines (penalty costs), and choosing the most reliable partner is supported by trust and reputation rankings in the long term.

In the paper, platform- and direct exchange-based resource sharing are compared from the monetary perspective, and the advantages and disadvantages of joining the Platform are discussed. By using agent-based simulation, the effect of changing order inter-arrival times and the impact of the price of outsourced jobs are investigated. With simulation experiments, it was shown that (1) despite possibly being loss-making in the short term, it can be profitable to join the federation, (2) the price of outsourced jobs strongly affects the incomes of the participants and (3) there is a limit for the price above which it is not worth outsourcing.

In future works, the model is planned to be extended with dishonest companies who are trying to influence the resource sharing mechanism by sending fake offers, and could learn using artificial intelligence algorithms based on the responses received from the Platform (e.g., what resource types are rare in the federation, and offer them more expensively). This research direction – not in connection with resource sharing platforms, but regarding trust and reputation systems in general – has been already highlighted in [83]. Other future direction is to apply a more complex multi-criteria decision-making algorithm in the decision-making and assignment processes. Another planned extension of the model is to include more complicated orders including interdependent tasks, which – in case of outsourcing – require offers from a complete supply chain, not only from independent suppliers.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix. List of notations

See Tables 4 and 5.

Table 4
List of notations in the trust model.

Notation	Meaning
$r_{t,j}^{A,B}$	rating given in time point t about a specific interaction between lead company A and resource offeror company B, about job j
δ_j	time difference between the delivery deadline and the real delivery time in case of job j
L_j	length of job j in time
γ	the penalty factor applied on federation level to penalize inaccurate deliveries to a higher extent
μ_j	quality factor to rate the quality of the resource offeror's work about job j
$w(T, t)$	weight that is assigned to a rating given in time point t in order to calculate the cumulative rating in time point T
θ	decay factor used to affect the shape of the *w(T,t)* function
$\varphi^{A,B}(T)$	cumulative trustfulness calculated by lead company A about resource offeror company B in time point T

Table 5
List of notations in the financial model.

Notation	Meaning
All cost types	
A	resource requesting (lead) agent
B	resource offering agent
subscript j	job index
superscript o	order index
superscript C	index of customer outside the federation
α^o	number of products in order o
α_j^B	number of products in the part of job j that was outsourced to company B
Manufacturing costs	
C_{manuf}^B	total manufacturing cost for company B
c_{sust}^B	facility sustaining cost for company B, per time unit
T	length of time interval when company B is a member of the federation, in time units
$c_{manuf_j}^B$	total manufacturing cost of the part job j that was outsourced to company B
$c_{material_j}^B$	material cost for one product in job j for company B
$c_{labour_j}^B$	labor cost per time unit in job j, for company B
$c_{machine_j}^B$	machine cost per time unit in job j, for company B
t_j^B	time interval required to complete the part of job j that was outsourced to company B
Inventory costs	
$c_{WIP,j}^B$	WIP inventory cost for the part of job j that was outsourced to company B
$c_{inv_j}^B$	inventory cost of agent B for one product in job j, for one time unit
t_j^B	manufacturing time of the part of job j that was outsourced to company B
$c_{inv_{j,B}}^A$	total inventory cost that incurs due to early completion for lead company A for the specific part of job j that was outsourced to company B
Penalty cost	
$c_{pen_j}^B$	penalty cost for resource offering company B in case of job j
$c_{inv_j}^A$	inventory cost of agent A for one product in job j, for one time unit
$c_{qual_j}^A$	quality reduction cost of agent A for one product in job j, for one time unit
$c_{loss_j}^A$	sales opportunity loss for agent A for one product in job j, for one time unit
c_{fail}^A	fixed failed delivery factor for agent A
P^o	profit generated by selling order o
${t_{sa_j}}^B$	start of *delivery acceptance* interval of the part of job j that was outsourced to agent B
${t_{ea_j}}^B$	end of *delivery acceptance* interval of the part of job j that was outsourced to agent B
${t_{so_j}}^B$	start of *on-time* interval of the part of job j that was outsourced to agent B
${t_{eo_j}}^B$	end of *on-time* interval of the part of job j that was outsourced to agent B
${t_{d_j}}^B$	delivery time of the part of job j that was outsourced to B
Transportation cost	
$c_{transport}^{AC,o}$	transportation cost of order o between company A and customer C
C^o	customer (outside the federation) of order o
d^{AC}	distance between agent A and customer C on the road
${c_{transport}}^o$	cost factor for specific transport type in case of order o, per product
${c_{shipment}}^A$	fixed shipment sending cost for lead agent A
Transportation consolidation cost	
$c_{tr.cons}^{B,j}$	transportation consolidation cost for resource offeror company B, in case of job j
$c_{tr.cons}^{A,j}$	transportation consolidation cost for lead company A, in case of job j
d^{AB}	distance between agent A and B on the road
$c_{transport_j}$	cost factor for specific transport type in case of a specific job
${c_{arrival}}^A$	arrival (administration) cost for company A
${c_{shipment}}^B$	shipment sending (administration) cost for company B
Management cost	
c_{man}^A	total management cost for company A
T	length of time interval when company A is a member of the federation, in time units
c_{entr}	one-time entrance fee of the platform
c_{part}	regular participation fee of the federation, per time unit
$c_{offer,a}$	administrative cost of sending an offer (paid to the Platform)
$c_{offer,p}$	resource planning cost of sending an offer to the Platform
${n_{offer}}^A$	number of offers sent to the platform by company A
$c_{request,a}$	administrative cost of sending a request (paid to the Platform)

(*continued on next page*)

Table 5 (*continued*)

Notation	Meaning
$c_{request,p}$	resource planning cost of sending a request to the Platform
${n_{request}}^{A}$	number of requests sent to the platform by company A
$c_{contract}$	administrative cost of contracting in case of a match
${n_{contract}}^{A}$	number of contracts signed by company A
Order consolidation cost	
$c^{A}_{ord.cons}$	total order consolidation cost for company A
$c^{A}_{ord.cons_j}$	order consolidation cost of job j
Sales income, profit	
${i_{sales_j}}^{B}$	sales income for company B for completing (a part of) job j
${c_{manuf_j}}^{B}$, ${c_{manuf_j}}^{A}$	manufacturing cost of (a part of) job j for resource offeror company B manufacturing cost of (a part of) job j for lead company A
p^{B}, p^{A}	profit margin of resource offeror company B and lead company A
${i_{sales}}^{A,o}$	additional income for completing order o
i^{o}	additional income per product for order completion
P^{B}_{j}	profit generated by company B from job j
$P^{A,o}$	profit generated by company A from order o
Penalty income	
${i_{pen}}^{A,B}{}_{j}$	penalty income for lead company A in connection with the job part that was outsourced to company B
${c_{pen}}^{B}_{j}$	penalty cost for resource offering agent B in case of job j
Incomes and costs of the Platform	
$i^{Platform}$	total income of the Platform
k	federation member index
K	number of members in the federation
$c^{Platform}$	total costs of the Platform
c_{mar}	marketing costs of the Platform
c_{op}	operating costs of the Platform
c_{maint}	maintenance costs of the Platform

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