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journal homepage: www.elsevier.com/locate/ecraA multidimensional procurement auction for trading composite services [☆]Benjamin Blau ^{a,*}, Tobias Conte ^b, Clemens van Dinther ^a^a Institute of Information Systems and Management, Karlsruhe Institute of Technology, Karlsruhe, Germany^b Research Center for Information Technology, Karlsruhe, Germany

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ABSTRACT

Recently, static value chains have gradually been giving way to highly agile service value networks. This involves novel economic and organizational challenges. Added value for customers is created by feasible compositions of distributed service components. This work focuses on the design of a multidimensional procurement auction for trading service compositions and the analysis of strategies for service providers that participate in the procurement process. The mechanism implementation is incentive-compatible, so that it results in an equilibrium in which revealing the true multidimensional type (quality of service and valuation) is a weakly-dominant strategy for all service providers. Due to combinatorial restrictions imposed by the underlying graph topology, the winner determination problem can be solved in polynomial time, in contrast to computationally-intractable combinatorial auctions which cannot be solved this way. Furthermore, we provide a simulation-based analysis based on a reinforcement learning model of bundling and unbundling strategies of service providers that participate in the auction. Based on our results we discuss strategic recommendations for service providers depending on how they are situated within the network.

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1. Introduction

Industries are moving from vertical integration to horizontal specialization. Hierarchically-organized firms that started to cooperate in tightly-coupled strategic networks with stable interorganizational ties recently have been exploring the benefits of exploiting more loosely-coupled configurations of legally-independent firms. A prime example for such highly dynamic fields of application is the software industry. Specialized service providers are beginning to leverage their core competencies in so-called *service value networks* (SVNs) in order to jointly offer complex services. *Complex or composite services* typically involve the assembly and invocation of many pre-existing, standardized services, possibly offered by diverse enterprises to complete the functionality of a multi-step business process (Papazoglou, 2008). Business value is provided through the agile and market-based composition of such complex services from a steady, but open pool of complementary as well as substitutable standardized service modules by the use of easily accessible information technology (IT) (Blau et al., 2009). This development and the advent of service value networks are illustrated in Fig. 1.

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The logical consequence of the current trend toward *software-as-a-service* (SaaS) and Web services, combined with the emergence of SVNs, is a shift of software providers' offerings to an "Internet of services." SaaS is a software distribution model in which applications are hosted by a service provider and made available on a one-to-many basis over a network such as the Internet. Until now the term "Internet of services" has not been exactly defined in the academic world. Combining recently-provided perspectives from industry-oriented research (Ruggaber, 2007; Schroth, 2007; Schroth and Janner, 2007), we define the *Internet of services* as a global network which enables the design, retrieval, combination, trade and utilization of interoperable, electronic services in the Web.

Analogous to complex products, services will be composed of several modules provided by different partners of the underlying CVN. With the rise of highly standardized lightweight Web service technologies (Fielding, 2000), the realization of *ad hoc* compositions in an automatic fashion is simplified and manageable from a technical perspective. Due to the rapid standardization process and the renaissance of lightweight approaches, former technical problems in the context of service composition will be able to be solved (Ulkuniemi and Seppänen, 2004). Today's SaaS and Web service market already shows the way towards such an Internet of services. The market can be divided into four quadrants as shown in Fig. 2.

This typology classifies the service on-demand market by the composition *complexity* of the service and the *degree of*

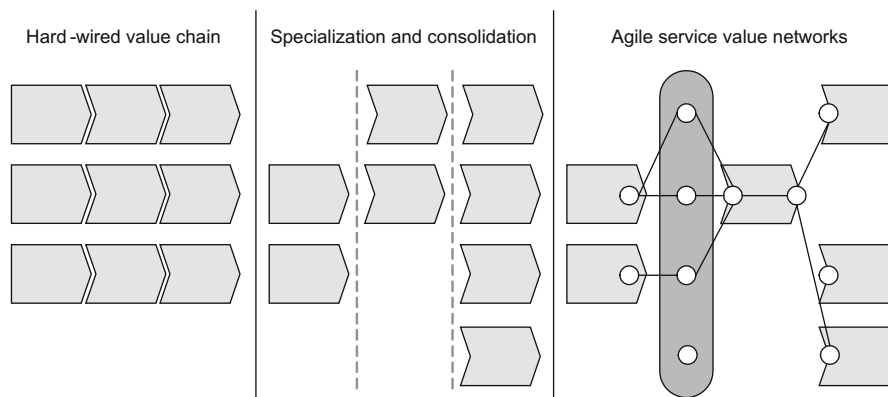


Fig. 1. From hard-wired value chains to adaptive service value networks. Note: adapted from Heuser et al. (2007).

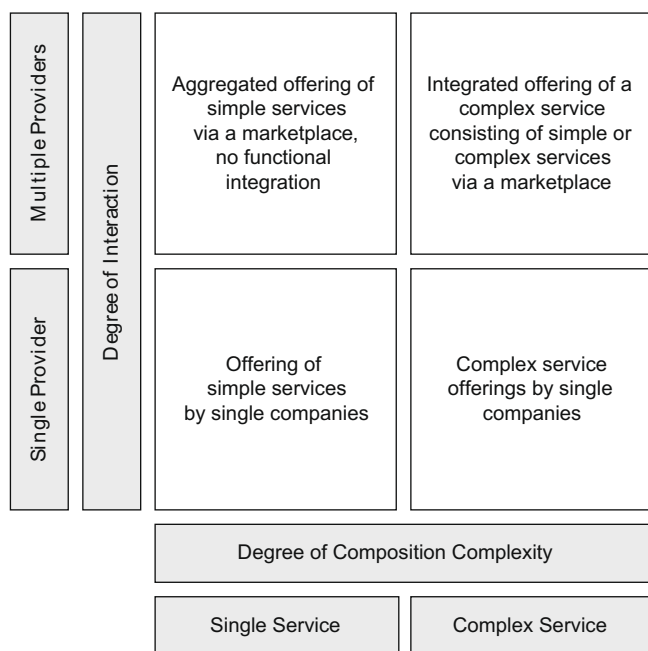


Fig. 2. Typology of on-demand services.

cross-organizational interaction when developing and offering the service. The variety of single Web services offered by individual service providers is already vast. Prime examples are services provided by Google such as Google Docs (www.docs.google.com) as a Web-based offering to create and share work online or Google Maps (www.maps.google.com), a map service that can be easily embedded in Web sites or service mashups. Another example that enjoys high popularity is the Amazon Simple Storage Service (S3) (www.aws.amazon.com/s3), a simple Web service that can be utilized to store and retrieve data. On the other hand, not only rather simple, but also complex services supporting multi-step business processes are offered on-demand. For instance, providers such as Salesforce.com (www.salesforce.com) or Netsuite Inc. (www.netsuite.com) successfully entered the business software market with their entirely Web-based on-demand customer relationship management (CRM) suites. Components offered within these suites can be dynamically composed to customized processes. Additionally, Web service marketplaces such as StrikeIron (www.strikeiron.com) recently have emerged, making available platforms for service providers to offer their services via joint distribution channels.

Additional infrastructural services for service providers are quite rudimentary though. Besides a catalogue of offered services and a search function, more sophisticated mediation support is not available. For instance, neither functional integration nor dynamic pricing schemes are provided. AppExchange (www.salesforce.com/appexchange), the application marketplace offered by Salesforce.com, offers a range of pre-integrated complementary services provided by third-party vendors grouped around the core service, Salesforce CRM. However, each Web service is based on a common platform and the same core application, which facilitates the provisioning of such integrated services. Again, the variety of pricing mechanisms is comparably low, lacking support involving multilateral approaches.

There is further need of research in the field of complex services that are composed of elements provided by different vendors. Thus, we aim to shed light on the Internet-based offering and coordination of composite services by means of an auction mechanism. We raise two main research questions.

First, how can we efficiently find good matches of service offerings that maximize utility across all participants? The core challenge is to handle the complexity of combining different services since a flawless service execution and the requester's valuation highly depend on the accurate sequence of its functional parts. Composite services only generate value through a valid order of their components. Auctions have proven to be particularly useful in such situations in which the conventional ways of establishing price and ownership are inadequate, because costs are difficult to be estimated and to be established (Smith, 1989). Nevertheless, traditional approaches in the area of combinatorial auctions are not suitable to enable the trade of composite services, since the sequential dependencies of services are not being considered. Besides with the mechanism design requirements of individual rationality, allocation efficiency, and incentive-compatibility, it is essential that such a mechanism solves the *winner determination problem* in polynomial time and that it is capable to aggregate different complex service attributes.

Second, how can we explain the strategic behavior of service providers? From the providers' perspective, is it beneficial to offer one single service or to offer a service bundle together with complementary services from other providers? Consequently, we study providers' strategies depending on how they are situated within the network. From the results of our analysis we derive strategic recommendations for service providers in such an Internet of services.

This paper is structured as follows Section 2 reviews of the literature. Section 3 introduces a formalization of a service value network that serves as the basis for our bidding language and mechanism design. The mechanism is presented in detail and the

properties are shown analytically. Thereafter, we present a simulation-based investigation of bundling and unbundling strategies of service providers in Section 4. Section 5 concludes with a summary and future work.

2. Review of the literature

Recently, an enormous amount of work has been done that blurs the border between game theory and computer science (Papadimitriou, 2001). This is the emerging discipline of *mechanism design*. It focuses on the problem of coordinating self-interested participants in pursuing an overall goal, and was introduced by Nisan and Ronen (2001). The authors design suitable mechanisms for standard optimization problems in the area of task scheduling and routing. In incentive-compatible mechanisms, agents are incentivized to choose the strategy of revealing their true type. Incentive-compatible mechanisms such as the celebrated Vickrey–Clarke–Groves (VCG) mechanism have been introduced and extensively investigated by Vickrey (1961), Clarke (1971), Groves (1973), and Green and Laffont (1978).

Most of the research has been done with respect to truth-telling of one-dimensional types. The knowledge associated with the design of incentive-compatible mechanisms that induce truth-telling of multidimensional properties of goods or services still lacks deep insights from research. Che (1993) and Branco (1997) have done thorough analysis and investigation in the area of multidimensional auctions and the design of optimal scoring rules. Bichler and Kalagnanam (2005) investigate the winner determination problem in configurable multiattribute auctions from an operations research perspective. They do not account for mechanism design aspects such as incentive-compatibility though. Parkes and Kalagnanam (2002, 2005) introduce iterative multiattribute procurement auctions that focus attention on mechanism design issues, in an effort to solve the multiattribute allocation problem. Preferences for multidimensional goods and multidimensional types in scoring auctions are extensively investigated by Asker and Cantillon, 2008 and extended to combinatorial auctions by Muller et al. (2008). Nevertheless, their work does not consider value chains and sequences of services, as well as their technically-feasible interrelations, in order to coordinate value generation in service networks. All of these approaches assume bundles of goods in scenarios where the sequence and order do not matter. Thus, they cannot be applied to composite services that only fulfill their objectives in the right sequence of execution.

Nevertheless, combinatorial auctions have major drawbacks regarding computational feasibility that result from *nondeterministic polynomial-hard* (NP-hard) complexity. Computational feasibility implies a trade-off between optimality and valuable mechanism properties such as incentive-compatibility. Several authors propose approximate solutions for incentive-compatible mechanisms to overcome issues of computational complexity (Mualem and Nisan, 2008; Nisan and Ronen, 2007; Ronen, 2001; Ronen and Lehmann, 2005). Path auctions as a subset of combinatorial auctions reduce complexity through predefining all feasible service combinations in an underlying graph topology (Feigenbaum et al., 2007; Hershberger and Suri, 2001 and Archer and Tardos, 2007). In their work, path auctions are utilized for pricing and routing in networks of resources involving computation or electricity services. Other application-related issues involving auctions and optimal routing have been examined too Feldman et al. (2005) and Maille and Tuffin (2007). All of these approaches deal with the *utility services layer*, according to the service classification by Blau and Schnizler (2000) and Blau et al. (2008). Hence they do not cover the problems related to elementary services and complex services.

Another well-known shortcoming of the valuable property of incentive-compatibility is that inducing truthfulness can result in arbitrary and high overpayments. A *budget balance* cannot be achieved simultaneously, according to the impossibility theorems of Gibbard (1973) and Satterthwaite (1975). Parkes et al. (2001) introduce an efficient and budget-balanced solution to overpayment issues in VCG-based combinatorial auctions. They solve linear problems subject to budget balance that yield approximately incentive-compatible solutions. Another approach to counteract the lack of a budget balance by sacrificing efficiency is introduced by Archer and Tardos (2007) in the context of path auctions. In their work they replace the efficient allocation function by a class of *minimum functions* that yield lower overpayments in certain scenarios. Nevertheless, they show that it is always possible to construct worst-case scenarios in which minimum functions perform as bad as the efficient variant.

3. Market mechanisms

We first introduce an abstract model as a formalization of a *service value network* (SVN) containing a *service requester*, *service providers* and *services*. It captures the network's characteristics and serves as the basis for our mechanism design. For the exchange of information objects, we provide a multiattribute bidding language to model service offers and service requests. We also provide our multidimensional mechanism design to allocate service providers within the network and to determine prices of complex services. For the reader's convenience, the formal notation is outlined in Appendix A. See Table A1.

3.1. Service value network (SVN)

An SVN is represented by a k -partite directed and acyclic graph $G = (V, E)$. Each partition Y_1, \dots, Y_k of the graph represents a candidate pool that entails services that provide the same business functionality in a modular and self-describing manner (Baster et al., 2001). The set of N nodes $V = \{v_1, \dots, v_k\}$ represents the set of services v , i , and j as arbitrary services. Services are offered by a set of Q service providers, denoted by $S = \{s_1, \dots, s_Q\}$ and s as an arbitrary service provider. The ownership information $\sigma: S \rightarrow V$ that reveals which service provider owns which service within the network is public knowledge. There are two designated nodes v_s and v_f that stand for the source and the sink in the network. The set of edges $E = \{e_{ij} \mid i, j \in V\}$ denotes technically-feasible service combinations, with e_{ij} representing an interoperable connection of service j with service i .

A service configuration A_j of service j is fully characterized by a set of attributes $A_j = \{a_j^1, \dots, a_j^l\}$ where a_j^l is an attribute value of attribute type l of service j 's configuration. Let c_{ij} denote costs that the service provider who owns service j has to bear for service j to be executed in an interoperable manner as a successor of service i . We intentionally exclude the representation of a detailed cost structure of service providers. Our representation of internal costs models the service providers' valuations for their services in different composition-related contexts from a game-theoretic perspective. If two services are not interoperable at all they are not connected within the network. The final outcome of value creation within a service value network is a complex service that is constituted by a composition of service components. Let F denote the set of all feasible paths from source to sink. Every $f \in F$ as a set of edges represents a possible instantiation of the complex service.

Fig. 3 shows a formalization of an SVN with services $V = \{v_1, \dots, v_4\}$. Every feasible path from source to sink represents a possible realization of the overall complex service.

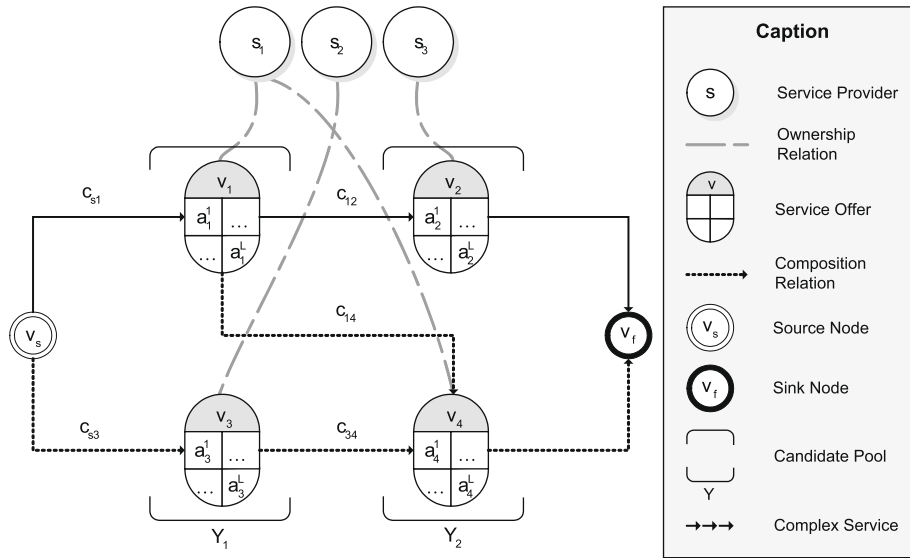


Fig. 3. Service value network (SVN) model.

In our model we focus on the core process of realizing an overall goal without going into process-related details such as parallel or cyclic components. We apply a business-oriented view addressing the question of how an overall goal can be achieved, while maximizing welfare and dynamically determining the corresponding prices. For a detailed description of presented service value network model and a differentiation from related governance forms, the interested reader is referred to Blau et al. (2009).

3.2. Bidding language

According to Lacity (2002), “successful information technology sourcing decisions require customers to identify their IT needs.” In order to describe these needs, the design of a highly expressive bidding language is required. We describe this language in this section. As a formalization of information objects exchanged during an auction process, we introduce a bidding language based on previous bidding languages for products with multiple attributes, as discussed in Engel et al. (2007). Our bidding language is aligned with multiattribute auction theory, as presented in Parkes and Kalagnanam (2002) and Ronen and Lehmann (2005). This assures compliance with the Web Services Agreement Specification discussed in Andrieux et al. (2007), which supports implementation in decentralized environments such as the Web.

Imagine that a service requester wants to purchase a complex service represented by a path f characterized by configuration \mathcal{A}_f . The importance of certain attributes and prices of a requested complex service is idiosyncratic and depends on the preferences of the requester. The requester’s preferences are represented by a scoring function \mathcal{S} of the form:

$$\mathcal{S}(\mathcal{A}_f) = \left(\sum_{l=1}^L \lambda_l \mathcal{A}_f^l \right) \quad (1)$$

The scoring function \mathcal{S} represents the requesters’ preferences for a configuration \mathcal{A}_f of the complex service represented by f , which follows the definition of scoring rules given by Asker and Cantillon (2008). Their scoring rule is specified by a vector of weights $\lambda = (\lambda_1, \dots, \lambda_L)$ with $\sum_{l=1}^L \lambda_l = 1$ that defines the requester’s preferences of each attribute type l . The configuration \mathcal{A}_f of the complex service is composed of the aggregation of all attribute values of contributing services with incoming edges on the path f such that

$$\mathcal{A}_f = (\mathcal{A}_f^1, \dots, \mathcal{A}_f^L) \text{ with } \mathcal{A}_f^l = \bigoplus_{e_{ij} \in f} a_j^l \quad (2)$$

The aggregation operation \bigoplus for attribute values depends on their type. With basic aggregation operations such as a minimum operator, the bidding language also supports rich semantic approaches for more complex aggregation operations in order to deal with various non-functional service attributes. For example, services are capable of different types of encryption algorithms. If a requester prefers asymmetric ciphers, then semantic subsumption can be used to evaluate whether a complex service fulfills the requester’s requirements. This supports the determination of a score. For a detailed illustration of the expressive power of the proposed bidding language for the portfolio of supported QoS characteristics, the interested reader should see Blau et al. (2009).

$\mathcal{T}_f = \sum_{s \in \mathcal{S}} t^s$ represents the sum of all transfers to allocated service providers, which equates to the overall price of the complex service. α can be interpreted as the maximal willingness-to-pay for a perfect configuration \mathcal{A}_f with score $\mathcal{S}(\mathcal{A}_f) = 1$. In other words α defines the substitution rate between quality and price. Consequently a service request for a multiattribute complex service is defined as follows:

Definition 1 (Multiattribute Service Request). A multiattribute service request for a complex service is a vector of the form:

$$R := (\mathcal{A}, \alpha, \lambda) \quad (3)$$

such that \mathcal{A} represents the set of candidate pools within the service value network. α denotes the maximum willingness-to-pay for a configuration of score 1. The set of weights λ represents the requesters’ preferences for different attribute types l .

Having specified the bidding language for requesters, we next define notation for the provider side. A multidimensional service offer consists of an announced service configuration A_j and a corresponding price p_{ij} that a service provider wants to charge for service j being invoked depending on the predecessor service i such that $b_{ij}(e_{ij}) = (A_j, p_{ij})$. A service provider s bids for all incoming edges to every service it owns:

Definition 2 (Multiattribute Service Offer). A multiattribute service offer is a matrix of bids of the form:

$$B^s := \begin{cases} (A_j, p_{ij}), & i \in \tau(j), j \in \sigma(s) \\ (\bar{A}, -\infty), & \text{otherwise} \end{cases} \quad (4)$$

with $\tau(v)$ denoting the set of all predecessor services to service v with $\tau : V \rightarrow V$ and $\sigma(s)$ the set of all services owned by service provider s and \bar{A} being an arbitrary configuration.

3.3. Mechanism design

To design a procurement auction for complex services we follow the approach of *algorithmic mechanism design* as introduced in Nisan and Ronen (2001). Mechanism design forms a subset of game theory that focuses on solving social choice problems from an engineering perspective.

In our setting, we face the problem of maximizing welfare involving social choice by allocating the demanded services from a set of decentralized, self-interested and rationally-acting service providers. All service providers have private information about their internal costs and the quality of their services represented by the different provider types. The challenge is to design a mechanism $m = (o, t)$ consisting of an allocation function o and a transfer function t that incentivize service providers to report their types truthfully to the auctioneer with respect to all dimensions of their services. The allocation outcome of such a mechanism yields the same solution as the maximization problem in a cooperative setting pursuing the same social choice. The auctioneer has to solve the problem of allocating a path f connecting selected services within the network G that yields the highest welfare as the sum of all utilities (consumer and provider surpluses). As we mentioned earlier, the central problem in such a setting is that types are private information to service providers. Therefore the auctioneer is not capable of solving the welfare maximization problem directly. Let \mathcal{U}_f denote the overall utility of path f . Also let \mathcal{P}_f be the sum of all price bids of allocated services such that $\mathcal{P}_f = \sum_{e_{ij} \in f} p_{ij}$. Then the allocation function o evolves as follows:

$$O := \operatorname{argmax}_{f \in F} \mathcal{U}_f = \operatorname{argmax}_{f \in F} (\alpha \mathcal{S}(\mathcal{A}_f) - \mathcal{P}_f) \quad (5)$$

Let \mathcal{U}^* denote the utility of the winning path meaning the utility of a path f that maximizes the overall utility \mathcal{U}_f . Let \mathcal{U}_{-s}^* denote the utility of a path f_{-s}^* that yields a maximum overall utility in the reduced graph without every service owned by service provider s and without their incoming and outgoing edges. Every service provider $s \in S$ receives a payment or transfer t^s for all services it owns that are on the winning path.

According to the idea of a VCG-based payment scheme, each service provider that owns services allocated by o receives a transfer payment that compensates the provider for the individual contribution to the system's welfare. This monetary equivalent represents the price that service provider s could have charged without losing its participation in the winning allocation:

$$t^s := \begin{cases} \sum_{j \in \sigma(s)} \sum_{i \in \tau(j)} p_{ij} + (\mathcal{U}^* - \mathcal{U}_{-s}^*), & \text{if } e_{ij} \in o \\ 0, & \text{otherwise} \end{cases} \quad (6)$$

The goal of the mechanism design is to incentivize service providers to report their types truthfully to the auctioneer. This fosters a system-wide solution in a decentralized environment that maximizes welfare among all participants.

Corollary 1 (*The Transfer Independence Corollary*). For each service provider $s \in S$ that participates in the multidimensional procurement auction with the compensation function extension, the transfer t^s is independent of all dimensions of the bids of s (configuration and price). This means that for each service $j \in V$ owned by $s \in S$ that has an incoming edge which is allocated by o such that $e_{ij} \in o$ with $j \in \sigma(s)$ and $i \in \tau(j)$, the payoff s of the service provider is independent of all the dimensions of its bid, $b_{ij} = (A_j, p_{ij})$.

Theorem 1 (*The Bidding Strategy Theorem*). For each service provider $s \in S$ that participates in the multidimensional procurement auction with the compensation function extension, the bidding strategy $b_{ij} = (\tilde{A}_j, c_{ij})$ with $\tilde{A}_j = (\tilde{a}_j^1, \dots, \tilde{a}_j^t)$ - truth-telling with respect to all dimensions of the bid - $\forall i \in \tau(j), \forall j \in \sigma(s)$ is a weakly-dominant strategy.

Proofs of Corollary 1 and Theorem 1 are outlined in Blau et al. (2009). The solution to the allocation problem in Eq. (5) is computable in polynomial time using well-known graph algorithms, such as the Dijkstra algorithm, to determine the "shortest" path within a network. Using a Fibonacci heap data structure, the time complexity can be reduced to $O(n \log(n) + m)$, where m is the number of edges and n is the number of nodes within the graph.

According to the payment scheme in Eq. (6), the allocation must be computed twice, based on the graph with the services of the service provider receiving the payment, and without its participation. In the second case, the graph can be preprocessed and reduced by all services owned by the service provider that receives the payment. After the reduction, the shortest path can be computed accordingly, which yields the same time complexity. Contrary to the NP-complete complexity in general combinatorial auctions, this is a valuable achievement that enables the implementation of our auction mechanism in online systems.

4. Alternative strategies of service providers

In Section 3.3, we showed that under the assumption of rationality and quasi-linear utility functions, service providers act best (or at least equally good) by revealing their true multidimensional type. This has the effect of reducing their bidding strategy space to a single strategy. When the service providers' strategy horizon is expanded, it might be beneficial under certain circumstances to form coalitions and offer services in a bundled fashion. This section focuses on strategies of service providers who have the opportunity to form bundles with other providers, depending on how they are situated within an SVN.

Since a service provider's offer is only successful if one of its edges is allocated, service providers tend to find strategies to improve their situation. Two options are mainly distinguished, *unbundling* vs. *bundling*. Service providers can decide whether they wish to offer services on their own with a certain degree of interoperability with preceding offers. Such a strategy is referred to as an *unbundling strategy*. On the other hand, service providers can also provide bundled services together with service providers that own services in adjacent candidate pools (either preceding or succeeding). Two service providers from different candidate pools may combine their *complementary* offers (Levina and Ross, 2003) into a single service that aggregates both service characteristics. It is furthermore assumed that a combined service results in lower internal costs due to synergy effects that can be leverage through bundled offers. This strategy is analogous to the *independent* pattern discussed in Lee et al. (2004). This strategy is referred to as a *bundling strategy*.

There are two contrary effects and it is unclear which effect dominates in what setting:

- *Competing in quality through differentiation and flexibility*. It is reasonable to follow an unbundling strategy if a provider's services expose significantly lower prices due to lower internal costs or significantly better *quality of service* (QoS) characteristics than competing offers. Additionally, unbundled services offer more differentiated and specialized functionality that increases their flexible integration into different complex services, and thus, increase the number of possible combinations with other services from other candidate pools.

- *Competing in price through cost reduction.* On the other hand, it might be advantageous for service providers to cut costs through forming bundled offers collaboratively. To do this, they will combine their services into a service bundle that offers the functionality of both services in an integrated manner. In that case, the internal costs of the bundled services are likely to be lower compared to the sum of internal costs of two single offers.

With bundling, an aggregation of attribute values defining the service’s configuration can be done according to our approach discussed in Section 3.2. Nevertheless, bundling services results in a reduction of the degree of interoperability. A merge of services prunes incoming edges to preceding services, and this, in turn, decreases the number of complex service instances the bundled offer is part of. It is unclear which strategy is beneficial for service providers with respect to how their services are situated within the SVN. Even for services that are competitive in price and attractive for the service requesters – so they are allocated solely – forming a bundled offer with a less competitive service may be mutually beneficial for both partners. The following example illustrates the phenomenon where a bundling strategy is mutually beneficial for an allocated and a non-allocated service provider at the same time, even though there is no reduction of internal costs due to the bundling synergies that are assumed.

Example 1 (Beneficial Bundling Strategy). Fig. 4 depicts the service value network from an *ex ante* perspective. Without loss of generality, we assume that service providers only announce price bids (and not the QoS). Also, each service provider only owns a single service within the SVN. Consequently, there are four service providers s_y, s_z, s_a, s_b that own services y, z, a, b . Numbers on incoming edges to each node represent price bids placed by service providers. (Recall that according to Bidding Strategy Theorem, it is a dominant strategy equilibrium that service providers report their valuations truthfully, by announcing their internal costs.)

According to the auction mechanism, the path $f^1 = \{e_{sa}, e_{az}, e_{zf}\}$ is allocated as it yields the overall lowest price of 0.2 and therefore maximizes welfare. The second-best path $f^2 = \{e_{sy}, e_{yb}, e_{zf}\}$ yields an overall price of 0.3. According to the transfer function, payments are given to allocated service providers such that $t^{sa} = 0.1 + (0.3 - 0.2) = 0.2$ and $t^{sz} = 0.1 + (0.3 - 0.2) = 0.2$.

Focusing on the *ex post* case depicted in Fig. 5, service providers s_y and s_z have agreed on offering their services y and z as a bundle yz . As it is assumed that it is not possible to realize a cost reduction following a bundling strategy, internal costs for offering the single services add up to 0.4 for service yz .

According to the mechanism, the path $f^1 = \{e_{syz}, e_{zf}\}$ is allocated. This results in a price of 0.4. The other path $f^2 = \{e_{sa}, e_{ab}, e_{bf}\}$ yields a price of 1.0. It is assumed that service providers s_y and s_z divide their payoff according to their contribution to the alliance. This means the ratio of their internal costs determines their share. Consequently, payments to service providers evolve as follows: $t^{sy} =$

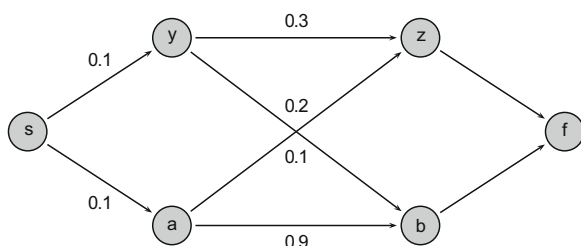


Fig. 4. Beneficial bundling strategy for allocated and non-allocated service providers: The *ex ante* case.

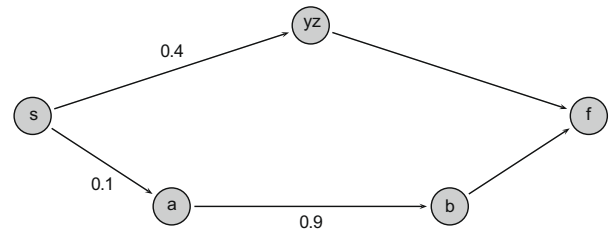


Fig. 5. Beneficial bundling strategy for allocated and non-allocated service providers: the *ex post* case.

0.75 ($0.4 + (1.0 - 0.4) = 0.75$) and $t^{sz} = 0.25$ ($0.4 + (1.0 - 0.4) = 0.25$). The example at hand shows that although there may be no cost reduction due to synergy effects when following a bundling strategy, still it might be beneficial for allocated and non-allocated service providers to jointly offer a bundled solution. In this scenario, the effect of reducing the network’s density (meaning cutting edges by merging services) also affects the number of feasible complex service instances and the composition outcome.

Both fundamental strategies imply advantageous and disadvantageous effects, and it is unclear which effect dominates. Lower costs may increase the likelihood of being part of the allocation, by offering bundled services at a lower price, but at the same time a decrease in interoperability may reduce the number of possible service combinations that involve the bundled offer. The result is a reduced likelihood to of being part of the allocation. In contrast, an unbundling strategy may increase differentiation and specialization, but it will diminish opportunities to realize synergy effects. We propose that the question whether to bundle or unbundle is the better strategy to follow depends on the service provider’s individual strategic strengths. Thus, we can distinguish this based on service providers that are part of the allocation and those which are not.

We next evaluate the following conjectures:

Conjecture 1 (The Noncompetitive Allocation Conjecture). Services that are not already allocated have a higher likelihood of being allocated when a bundling strategy is chosen instead of an unbundling strategy.

Conjecture 2 (The Noncompetitive Payoff Conjecture). For services that are not already allocated, a bundling strategy will lead to a higher expected payoff than an unbundling strategy.

Conjecture 3 (The Competitive Allocation Conjecture). Allocated services have a higher likelihood of staying allocated in the presence of an unbundling strategy than a bundling strategy.

Conjecture 4 (The Competitive Payoff Conjecture). For services that are already allocated, an unbundling strategy will lead to a higher expected payoff than a bundling strategy.

We use the terms *likelihood* or *probability* and *expected payoff* with respect to the limited set of observations. The likelihood or probability of an event refers to the relative frequency of the occurrences of that particular event. Analogously, the term expected payoff refers to the relative frequency times the mean payment observed.

4.1. Simulation model

These four conjectures will be studied following a simulation approach. We model the problem as an n -person game in which each node represents a service. Without loss of generality, we as-

sumed that service providers only own a single service within the network. Each service is characterized by an attribute value for the types *encryption* and *response time*. Dependent on the network topology, each service provider faces the decision of choosing an action *k* which is either to offer a service on its own via an *unbundling strategy* denoted by $k = u$, or to form a bundled offer with one of its successors using a *bundling strategy* denoted by $k = bf$. Thus, in each simulation round $r \in \mathcal{R}$ each node $i \in V \setminus \{v_s, v_f\}$ has to choose an action $k \in \mathcal{H}_i$.

The service provider's utility u_{ik} resulting from the action chosen is dependent on the topology of the network, the service requester's scoring function, and all other services within the network, including their quality and price. For each topology all these factors are stochastic. As such, the node's action decision does not solely control the payoff. Thus, the decision problem of the nodes is comparable to an *n-armed bandit problem*. Since reinforcement learning has proven to cope with such a model-free situation, a simple form of a reinforcement learning algorithm is applied in the present approach. Each node i assigns a fitness value f_{ik}^r to each possible action $k \in \mathcal{H}_i$. The fitness of the chosen action k is updated at the end of the period according to the update rule with the learning rate $\beta \in [0, 1]$:

$$f_{ik}^r = \beta f_{ik}^{r-1} + (1 - \beta) u_{ik}^r \quad (7)$$

Actions are chosen according to a probability choice rule based on each fitness propensity.

$$P_{ik}^r = \frac{f_{ik}^r}{\sum_k f_{ik}^r} \quad (8)$$

The action's propensity is calculated as its fitness weighted by the sum of all fitness values corresponding to the node's actions. Similar to our simulation model, the conduction of the simulation is divided in two phases: an *exploration phase* and a *simultaneous exploitation phase*. Fig. 6 displays the simulation phases and the steps of each phase. Each consists of a certain number of rounds $r \in \mathcal{R}$. Each round in the single exploration phase consists of three steps. In the first step, a single node i chooses an action k with propensity P_{ik}^r out of its action set. In the second step, the allocation is computed, as well as the mean payoffs for all allocated nodes based

on all requester types. It is important to notice that, depending on the requesters' scoring functions, the allocated services and corresponding payoffs will differ. In the third step, the fitness value of the chosen action will be updated based on the mean payoff computed based on all requester types.

After all of the nodes are trained, the simultaneous exploitation phase starts in order to evaluate settings with simultaneous decisions. Analogous to the exploration phase, each round of the simultaneous exploitation phase runs through three steps. In the first step, all nodes simultaneously choose a strategy based on P_{ik} . Note that in the training phase it is just one node choosing the strategy. When bilateral bundling decisions match, only then will the services are merged to a single node to form a bundled offer. The allocation and the mean payoffs based on all requester types are computed in the second step. Each service provider is assigned a numerical value indicating its market power within the service value network. In case two services are merged to form a bundled offer that is allocated, the resulting payoff is distributed based on the market power ratio of both service providers. The last step is again to update the fitness values of all nodes based on the mean payoff.

The data of the simultaneous exploitation phase are analyzed with respect to every possible event that may occur during the conduction of the auction. Table 1 shows each possible event analyzed with respect to its relative frequency of occurrence – which can be interpreted as the likelihood of the event's realization) and its expected payoff, which is the corresponding mean payoff received times the event's likelihood of occurrence.

The conjectures are tested using a Wilcoxon signed-rank test as the number of observations is relatively small ($N = 30$). Where the data are not normally-distributed, the conjectures were tested by means of a Kolmogorov–Smirnov test. The data are based on the mean relative frequencies of each event and the corresponding expected payoffs over all service providers.

4.2. Simulation settings

As we noted previously, there are two fundamental strategic alternatives service providers have to face: focusing on differentiation and the provision of flexible services that are of highly specialized by following an unbundling strategy or focusing on cost

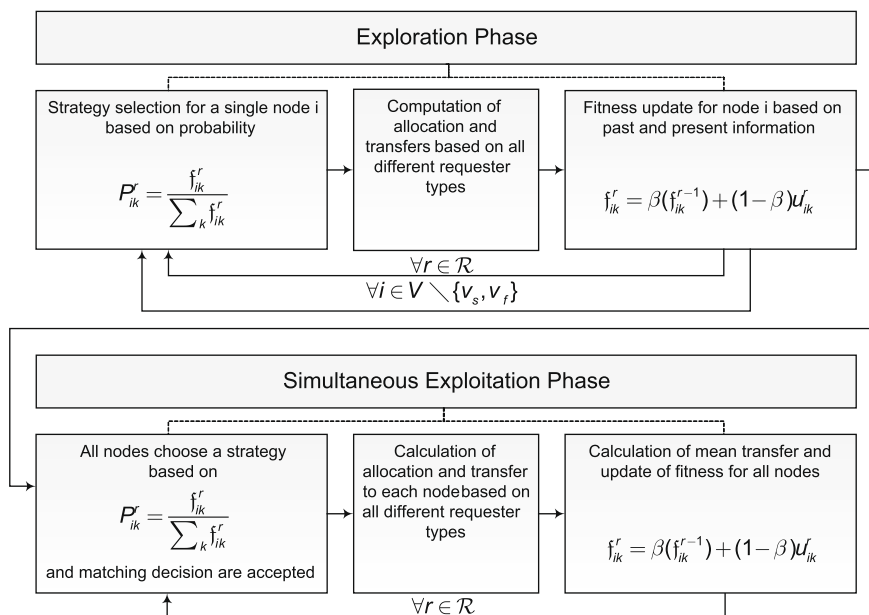


Fig. 6. Simulation model: evaluation of bundling–unbundling strategies of service providers.

Table 1
Analyzed events for the evaluation of bundling and unbundling strategies of service providers for relative frequency of occurrence and expected payoffs.

Metric	\tilde{E}_t	\tilde{E}_{t+1}	$k = b$	$k = u$
Relative	$\tilde{E}_t \neq \emptyset$	$\tilde{E}_{t+1} \neq \emptyset$ $\tilde{E}_{t+1} = \emptyset$	$P(\tilde{E}_{t+1} \neq \emptyset k = b, \tilde{E}_t \neq \emptyset)$ $P(\tilde{E}_{t+1} = \emptyset k = b, \tilde{E}_t \neq \emptyset)$	$P(\tilde{E}_{t+1} \neq \emptyset k = b, \tilde{E}_t \neq \emptyset)$ $P(\tilde{E}_{t+1} = \emptyset k = b, \tilde{E}_t \neq \emptyset)$
Frequency	$\tilde{E}_t = \emptyset$	$\tilde{E}_{t+1} \neq \emptyset$ $\tilde{E}_{t+1} = \emptyset$	$P(\tilde{E}_{t+1} \neq \emptyset k = b, \tilde{E}_t = \emptyset)$ $P(\tilde{E}_{t+1} = \emptyset k = b, \tilde{E}_t = \emptyset)$	$P(\tilde{E}_{t+1} \neq \emptyset k = b, \tilde{E}_t = \emptyset)$ $P(\tilde{E}_{t+1} = \emptyset k = b, \tilde{E}_t = \emptyset)$
Expected	$\tilde{E}_t \neq \emptyset$	$\tilde{E}_{t+1} \neq \emptyset$ $\tilde{E}_{t+1} = \emptyset$	$P(\tilde{E}_{t+1} \neq \emptyset k = b, \tilde{E}_t \neq \emptyset)$ $P(\tilde{E}_{t+1} = \emptyset k = b, \tilde{E}_t \neq \emptyset)$	$P(\tilde{E}_{t+1} \neq \emptyset k = b, \tilde{E}_t \neq \emptyset)$ $P(\tilde{E}_{t+1} = \emptyset k = b, \tilde{E}_t \neq \emptyset)$
Payoff	$\tilde{E}_t = \emptyset$	$\tilde{E}_{t+1} \neq \emptyset$ $\tilde{E}_{t+1} = \emptyset$	$P(\tilde{E}_{t+1} \neq \emptyset k = b, \tilde{E}_t = \emptyset)$ $P(\tilde{E}_{t+1} = \emptyset k = b, \tilde{E}_t = \emptyset)$	$P(\tilde{E}_{t+1} \neq \emptyset k = b, \tilde{E}_t = \emptyset)$ $P(\tilde{E}_{t+1} = \emptyset k = b, \tilde{E}_t = \emptyset)$

Note: The set \tilde{E}^s denotes the set of edges with $\tilde{E}^s = \{e_{ij} | e_{ij} \in \sigma(o, j) \in \sigma(s), i \in \tau(j)\}$, the set of allocated edges that belong to the services of service provider s .

Table 2
Simulation settings for the evaluation of bundling and unbundling strategies of service providers.

Parameter	Value
Exploration phase #Rounds	500
Exploitation phase #Rounds	500
Learning rate β	0.1
Services #	Varied
Response time a_{jt}^r	$\in U(0, 1.0)$
Encryption a_{jt}^{et}	$\in \{1.0\}$
Costs (C_{ij})	$\in U(0, 1.0)$
Market power mp	$\in U(0, 1.0)$
Service requesters #	5
α	$\frac{1}{2}K$
Type A	$\lambda_{rt} = 0.3, \lambda_{et} = 0.7$
Type B	$\lambda_{rt} = 0.4, \lambda_{et} = 0.6$
Type C	$\lambda_{rt} = 0.5, \lambda_{et} = 0.5$
Type D	$\lambda_{rt} = 0.6, \lambda_{et} = 0.4$
Type E	$\lambda_{rt} = 0.7, \lambda_{et} = 0.3$

reduction due to synergy effects in order to compete in price by following a bundling strategy.

To evaluate the success of both strategies and how advantageous and disadvantageous effects of both strategies dominate under which conditions, five different representative types of services requesters are simulated that have different preferences over different QoS attributes and prices of the complex service. Each of these five standard subjects represents a homogenous group of requesters.¹

As the results are dependent on the level of competition, multiple scenarios with different numbers of services and candidate pools are evaluated. Each scenario has been evaluated with thirty different problems sets, using thirty randomly-generated topologies based on the parameters outlines in Table 2. The exploration phase, as well as the simultaneous exploitation phase, were simulated 500 times.² Each service is characterized by attribute values for response time and encryption. Attribute values for the response time type are uniformly distributed over the interval [0, 0.1].

Encryption values are also randomly chosen and can be either false or true, as indicated by 0 and 1. Internal costs of services on each incoming edge are drawn from a uniform distribution over the interval [0, 0.1].

¹ An alternative approach is the simulation of service requesters with randomly chosen preferences. Nevertheless, this results in heavy statistical noise and hinders the convergence of service providers' fitness in an appropriate number of exploration and exploitation rounds.

² A sensitivity analysis has shown that after 500 rounds with a learning rate of $\beta = 0.1$, which avoids stagnation in local optima, the agents' fitness converges to a single best action.

Table 3
Evaluation of bundling and unbundling strategies of service providers with 20 services in four candidate pools and 0% cost reduction due to synergy effects.

Metric	\tilde{E}_t	\tilde{E}_{t+1}	$k = b$	$k = u$
Relative	$\tilde{E}_t \neq \emptyset$	$\tilde{E}_{t+1} \neq \emptyset$	0.4707	0.7269***
		$\tilde{E}_{t+1} = \emptyset$	0.5293	0.2730
Frequency	$\tilde{E}_t = \emptyset$	$\tilde{E}_{t+1} \neq \emptyset$	0.1904***	0.0355
		$\tilde{E}_{t+1} = \emptyset$	0.8095	0.9645
Expected	$\tilde{E}_t \neq \emptyset$	$\tilde{E}_{t+1} \neq \emptyset$	0.2834	0.4013***
		$\tilde{E}_{t+1} = \emptyset$	0.0000	0.0000
Payoff	$\tilde{E}_t = \emptyset$	$\tilde{E}_{t+1} \neq \emptyset$	0.1009***	0.0193
		$\tilde{E}_{t+1} = \emptyset$	0.0000	0.0000

Note: Relative frequency of possible events and corresponding expected payoffs of service providers are analyzed in $t + 1$ for bundling and unbundling strategies depending on the allocation in t . * Denotes significance at the level of $p = 0.1$, ** at $p = 0.05$. Only tested results that correspond to the conjectures are indicated. *** Denotes significance at the level of $p = 0.01$.

4.3. Results and implications

For the assessment, two different situations for a service provider's service are distinguished: it either is part of the allocation or it is not for the case that the service is solely offered. In both cases, the service provider can decide on the strategy that results in either allocation or non-allocation. As such, there are eight possible results. The probability of ending up in either of these states is the conditional probability of the described preconditions. These conditional probabilities are derived through the mean relative frequencies (over all service providers) of each event within the simulation. Table 1 displays the possible states, the conditional probabilities of these states, as well as the expected payoff in these states. As the number of effects is manifold, the analysis of protruding observations, their interpretation, and implications are structured (a) within a single competition and cost reduction scenario, (b) across different levels of cost reduction and competition, and (c) using bird's eye analysis regarding the overall provider surplus.

4.3.1. Analysis within a single competition and cost reduction scenario

Focusing on a single competition and cost reduction scenario, Table 3 shows the results in a setting with twenty services in four candidate pools with no cost reduction due to synergy effects. The results show that services that are not allocated have a significantly higher likelihood of being allocated by choosing a bundling strategy instead of an unbundling strategy which supports the Noncompetitive Allocation Conjecture (C1). Also with respect to expected payoffs, for services that are not allocated, a bundling strategy leads to a significantly higher expected payoff than an

unbundling strategy. This supports the Noncompetitive Payoff Conjecture (C2). The fact that these services are not allocated initially indicates that they are either not competitive price-wise, that their QoS characteristics are not sufficiently valuable for the service requesters, or both. Thus, by combining their offers with more attractive components – although bearing the loss of interoperability as edges to adjacent services are pruned – less competitive service providers increase their chance of being allocated and manage to increase their payoff at the same time.

Service providers that are initially capable of competing successfully within the service value networks will have unbundled services are attractive in price and expose valuable characteristics for the requesters. These providers will have a higher chance of staying allocated by following an unbundling strategy instead of a bundling strategy. Thus, the Competitive Allocation Conjecture (C3) is supported. Also with respect to the expected payoff, an unbundling strategy is beneficial for allocated service providers and outperforms a bundling strategy significantly, and this supports the Competitive Payoff Conjecture (C4).

Summarizing the results, Fig. 7 shows the corresponding decision tree for service providers participating in the auction with respect to bundling and unbundling strategies. It depicts a setting with a low level of competition and no cost reduction due to the application of bundling synergies.

4.3.2. Analysis across different levels of cost reduction and competition

On average, the results show that cost reduction due to synergy effects realized through a bundling strategy increase the likelihood of being allocated in more competitive scenarios. This effect is not observable in a setting with twenty services in four candidate pools. This is because the relatively low level of competition requires a tremendous cost reduction to outperform other substitute services. See Table 4. In other words, the spread between dominant and dominated service providers will be larger in settings with a low level of competition, which makes efforts to increase a ser-

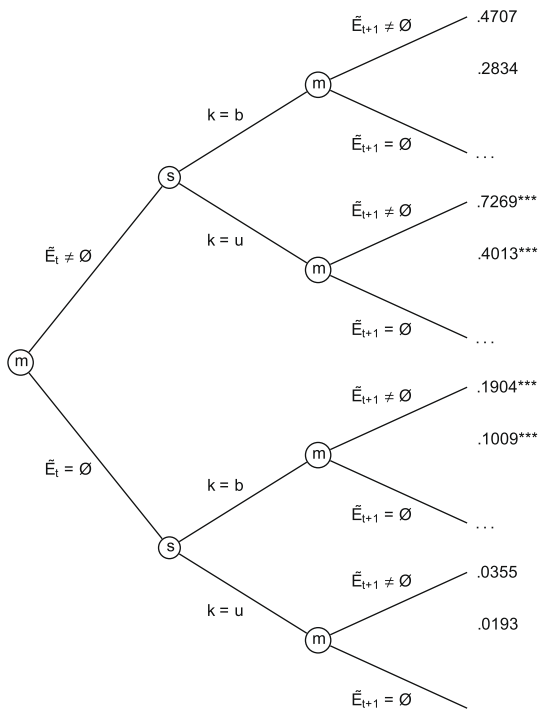


Fig. 7. Relative frequencies and expected payoffs of bundling and unbundling strategies. Note: the results are rendered for twenty services in four candidate pools and no cost reduction due to synergy effects. Nodes indicated by m denote a decision triggered by the mechanism and s a decision by the service provider.

vice’s attractiveness harder than in high competition settings. In settings with an increased level of competition (e.g., 28 services in four candidate pools) the effect is directly observable, as a cost reduction of 50% is sufficient to make service providers that previously had less attractive prices for the requesters in bundled offers.

Table 4

Evaluation of bundling and unbundling strategies of service providers with 20 services in four candidate pools and 50% cost reduction due to synergy effects.

Metric	\tilde{E}_t	\tilde{E}_{t+1}	$k = b$	$k = u$
Relative	$\tilde{E}_t \neq \emptyset$	$\tilde{E}_{t+1} \neq \emptyset$	0.3947	0.9398***
		$\tilde{E}_{t+1} = \emptyset$	0.6053	0.0601
Frequency	$\tilde{E}_t = \emptyset$	$\tilde{E}_{t+1} \neq \emptyset$	0.0502**	0.0129
		$\tilde{E}_{t+1} = \emptyset$	0.9497	0.9871
Expected	$\tilde{E}_t \neq \emptyset$	$\tilde{E}_{t+1} \neq \emptyset$	0.1553	0.4248***
		$\tilde{E}_{t+1} = \emptyset$	0.0000	0.0000
Payoff	$\tilde{E}_t = \emptyset$	$\tilde{E}_{t+1} \neq \emptyset$	0.0199	0.0052
		$\tilde{E}_{t+1} = \emptyset$	0.0000	0.0000

Note: Relative frequency of possible events and corresponding expected payoffs of service providers are analyzed in $t + 1$ for bundling and unbundling strategies depending on the allocation in t . * Denotes significance at the level of $p = 0.1$. Only tested results that correspond to the conjectures are indicated.

** Denotes significance at the level of $p = 0.05$.

*** Denotes significance at the level of $p = 0.01$.

Table 5

Evaluation of bundling and unbundling strategies of service providers with 28 services in four candidate pools and 0% cost reduction due to synergy effects.

Metric	\tilde{E}_t	\tilde{E}_{t+1}	$k = b$	$k = u$
Relative	$\tilde{E}_t \neq \emptyset$	$\tilde{E}_{t+1} \neq \emptyset$	0.4396	0.9275***
		$\tilde{E}_{t+1} = \emptyset$	0.5604	0.0725
Frequency	$\tilde{E}_t = \emptyset$	$\tilde{E}_{t+1} \neq \emptyset$	0.1127***	0.0128
		$\tilde{E}_{t+1} = \emptyset$	0.8872	0.9872
Expected	$\tilde{E}_t \neq \emptyset$	$\tilde{E}_{t+1} \neq \emptyset$	0.1274	0.4556***
		$\tilde{E}_{t+1} = \emptyset$	0.0000	0.0000
Payoff	$\tilde{E}_t = \emptyset$	$\tilde{E}_{t+1} \neq \emptyset$	0.0509***	0.0040
		$\tilde{E}_{t+1} = \emptyset$	0.0000	0.0000

Note: Relative frequency of possible events and corresponding expected payoffs of service providers are analyzed in $t + 1$ for bundling and unbundling strategies depending on the allocation in t . * Denotes significance at the level of $p = 0.1$, ** at $p = 0.05$. Only tested results that correspond to the conjectures are indicated.

*** Denotes significance at the level of $p = 0.01$.

Table 6

Evaluation of bundling and unbundling strategies of service providers with 28 services in four candidate pools and 50% cost reduction due to synergy effects.

Metric	\tilde{E}_t	\tilde{E}_{t+1}	$k = b$	$k = u$
Relative	$\tilde{E}_t \neq \emptyset$	$\tilde{E}_{t+1} \neq \emptyset$	0.4396	0.9275***
		$\tilde{E}_{t+1} = \emptyset$	0.5604	0.0725
Frequency	$\tilde{E}_t = \emptyset$	$\tilde{E}_{t+1} \neq \emptyset$	0.1127***	0.0128
		$\tilde{E}_{t+1} = \emptyset$	0.8872	0.9872
Expected	$\tilde{E}_t \neq \emptyset$	$\tilde{E}_{t+1} \neq \emptyset$	0.1274	0.4556***
		$\tilde{E}_{t+1} = \emptyset$	0.0000	0.0000
Payoff	$\tilde{E}_t = \emptyset$	$\tilde{E}_{t+1} \neq \emptyset$	0.0509***	0.0040
		$\tilde{E}_{t+1} = \emptyset$	0.0000	0.0000

Note: Relative frequency of possible events and corresponding expected payoffs of service providers are analyzed in $t + 1$ for bundling and unbundling strategies depending on the allocation in t . * Denotes significance at the level of $p = 0.1$, ** at $p = 0.05$. Only tested results that correspond to the conjectures are indicated.

*** Denotes significance at the level of $p = 0.01$.

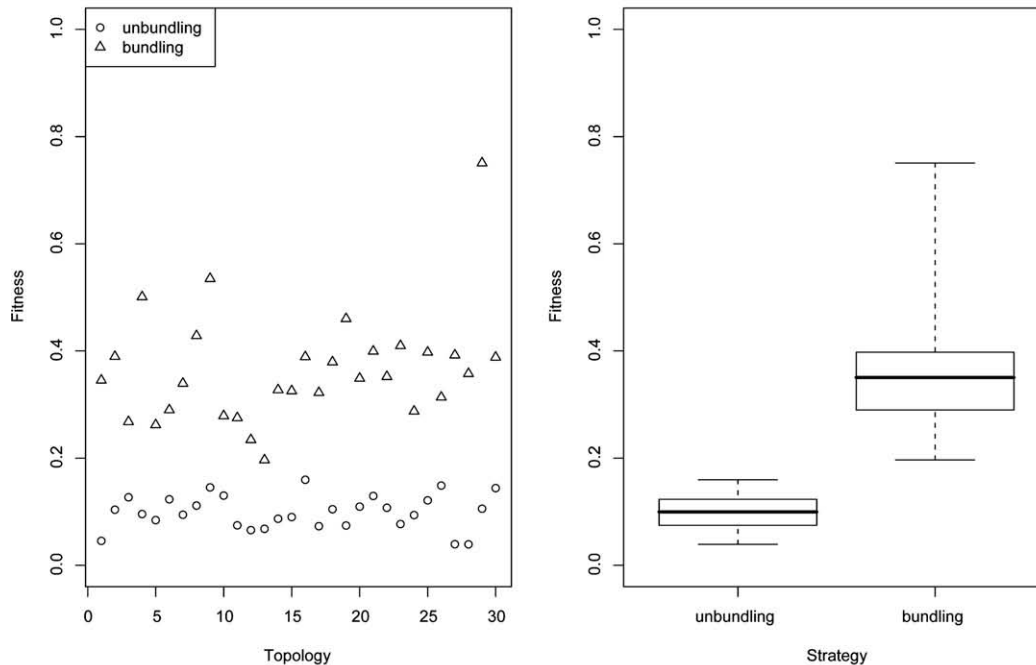
For a comparison of the results, see Table 5, which shows a setting with an increased level of competition and no cost reduction. Table 6 shows results assuming a 50% cost reduction for a bundling strategy.

As shown in the Bidding Strategy Theorem, it is a weakly-dominant strategy for service providers to bid truthfully. This implies that reducing costs results in a reduced price which service providers charge for their offerings. Nevertheless, the Transfer Independence Corollary shows that when it is involved in the allocation, the service providers' payoffs are independent of their bids. As a result, contrary to an increased likelihood to become allocated, a cost reduction does not influence the agent's payoff.

In contrast to a setting with twenty services in four candidate pools and no cost reduction, the Noncompetitive Payoff Conjecture (C2) is not supported in settings with a high level of competition and no cost reduction. See Table 5 again. With an increase of the number of services, interdependencies and feasible complex services, a bundling strategy results in a tremendous loss of interoperability.

The more preceding and succeeding services and the higher the number of interdependencies between services, the higher the loss of interoperability incurred through a merge of single offers within a service value network. In the setting with 28 services in four candidate pools and no cost reduction for bundled services, the likeli-

(a) No Cost Reduction Due to Bundling Synergies



(b) 50% Cost Reduction Due to Bundling Strategies

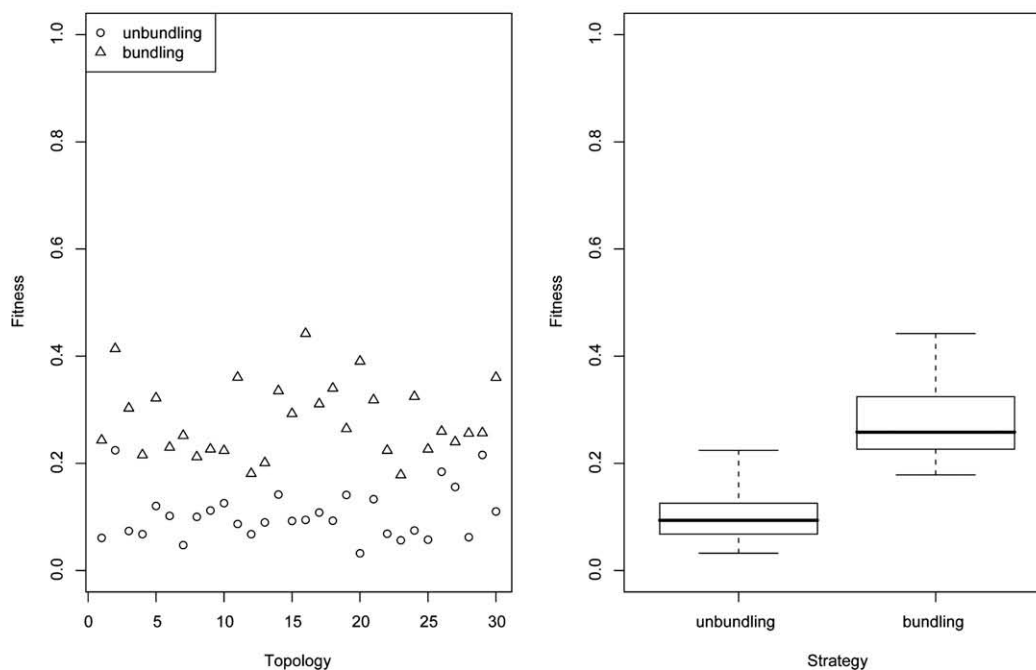


Fig. 8. Strategy fitness in different cost reduction scenarios with 20 services in four candidate pools.

hood to get allocated is still higher when following a bundling strategy. This finding is supported at a significance level of $p = 0.05$. Nevertheless, the expected payoff that results from that strategy is not significantly better than for the case of unbundling. Thus, when the service providers' services are not allocated when there is a high level of competition and are no synergy effects that reduce costs for bundled offers, they will be indifferent between a bundling and an unbundling strategy. As a result of the higher level of competition, the critical values for service providers will generally be lower. Also, in the case of bundling, both service providers will have to share their payoffs according to their market power. This again will tend to decrease the payments they will receive if they are allocated.

4.3.3. Bird's eye analysis regarding the overall provider surplus

Recall that in the simulation model, service providers maintain a fitness table for each bundling and unbundling strategy. Fitness values indicate the degree of success of feasible strategies based on the payoff received when choosing a particular strategy (e.g., higher fitness values indicate beneficial strategies). Thus, fitness values for each strategy are closely related to the payments gained as feedback for the actions triggered by service providers. Mean fitness values over all service providers for each problem set are depicted in Figs. 8 and 9 in scenarios with different levels of competition and different levels of cost reduction.

In general, bundling strategies seem to outperform unbundling strategies in fitness value terms. Nevertheless, this is only true for

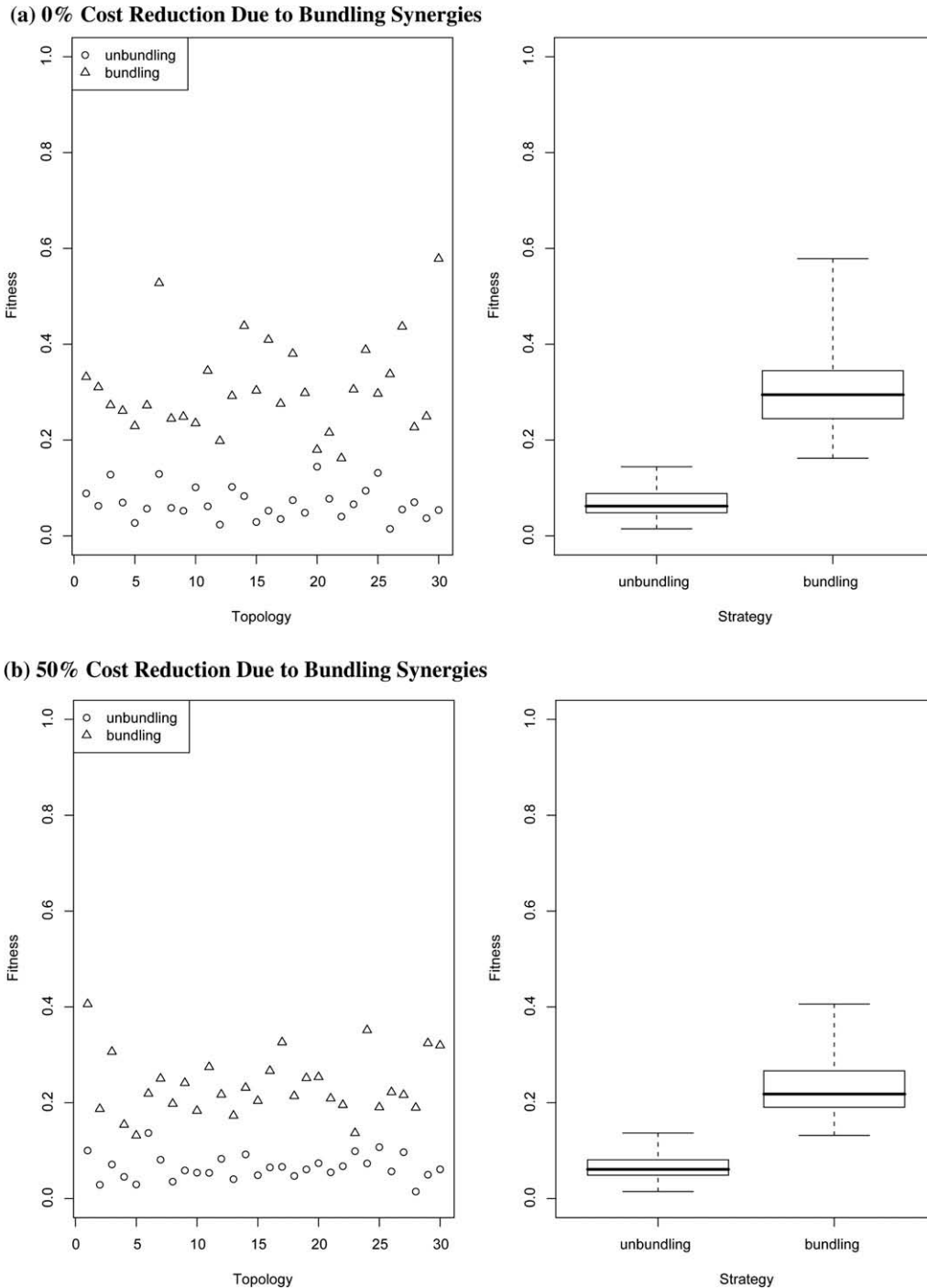


Fig. 9. Strategy fitness in different cost reduction scenarios with 28 services in four candidate pools.

the collectivity of service providers. It is important to notice that there are fewer allocated services than non-allocated services and service providers that own services within each group value each strategy differently. As we already have shown, following an unbundling strategy generally is not beneficial for providers that offer less competitive services. This is likely to be true for the majority of participants. Hence, the fitness values for an unbundling strategy for service providers that offer less competitive services will be close to zero which in turn strongly decreases the mean fitness for that strategy.

A fundamental effect is observable when comparing scenarios with no cost reduction due to missing synergies as illustrated in Fig. 8a and with large synergy effects as depicted in Fig. 8b. The higher the synergy effects realized through bundled offers, the lower the mean fitness value for that strategy. Recall that fitness values are closely related to the payments gained by following a particular strategy. Thus, a decrease in the mean fitness value for the bundling strategy reflects the fact that service providers receive lower payments when realizing synergy effects. Synergy effects reduce costs for service provision. A reduction of costs is directly reflected in the bid prices as shown in the Bidding Strategy Theorem. Consequently, by simultaneously realizing synergy effects and reducing costs, service providers face stronger price competition that will constantly impact and decrease their payoffs. Looking at service providers as a group, realizing synergy effects by offering bundled solutions will decrease the overall provider surplus.

4.4. Strategic recommendations

Based on the results that we described in Section 4.3, the following coarse-grained strategic recommendations regarding single services and bundled forms can be derived. For less competitive services, a bundling strategy leads to a significantly higher expected payoff than an unbundling strategy and increases the likelihood of being allocated if synergy effects can be realized. Less competitive service providers offer services that either are not competitively priced, or whose QoS characteristics are not sufficiently valuable for the service requesters. Thus, by combining their offers with more attractive components – although bearing the loss of interoperability as edges to adjacent services are pruned – less competitive service providers can increase their chance of being allocated and manage to increase their payoff at the same time. Service providers that are initially capable of competing successfully within an SVN have a higher chance of staying allocated and also face a higher expected payoff by following an unbundling strategy instead of a bundling strategy even though the synergy effects will not materialize. When this occurs, the loss of interoperability through the merger of one provider's services with another's will not be advantageous, even if it is compensated by a reduction of costs. The reason is that it increases the risk of service requesters viewing the offering as less favorable, diminishing the likelihood it will be chosen.

5. Conclusion

We proposed a multidimensional procurement auction for trading composite services in networked business settings. We presented a graph-based model that captures the main components and characteristics of service value networks. Based on this model, we introduced a mechanism design that enables allocation and pricing of service components that together form a requested complex service.

Auctions for composite services are much more complex than simple procurement auctions, in which the suppliers themselves

offer a full solution to the procurer. In composite services, this is not the case, as flawless service execution and the requester's valuation depend on the sequence of the activities in the auction process. This means that contrary to service bundles, composite services only generate value through a valid order of their components. The allocation is computed based on the requester's score for quality of service characteristics of the complex service. At the same time, the mechanism is capable of handling a wide range of aggregation operations for service attributes, and of supporting rich semantic approaches for dealing with complex non-functional service specifications. Due to the combinatorial restrictions imposed by the underlying graph topology, the related winner determination problem can be solved in polynomial time. This is a crucial issue when it comes to implementing auction online systems.

We further showed that our proposed mechanism is individually rational, allocatively-efficient and incentive-compatible with respect to QoS characteristics and prices of services. Hence, reporting the true type regarding configuration and price is a weakly-dominant strategy for all service providers. This is a valuable property, as it lowers strategic complexity for service providers and fosters a trustful requester-provider relationship.

Based on our analytical results regarding the mechanism's properties, we also investigated bundling and unbundling strategies of service providers by expanding their strategy space from pure bidding strategies to decisions about establishing strategic alliances with competitors. In an agent-based simulation, we showed that this decision depends on how service providers are situated in the network. Service providers that are not allocated by the mechanism increase their probability of being allocated as well as their expected payoff by forming strategic alliances. Service providers that have already been allocated, it turns out, are better off by following an unbundling strategy.

Table A1

Modeling notation for mechanism analysis and implementation.

Notation	Meaning
$G = (V, E)$	Service value network
$V \setminus \{v_s, v_f\} = \{v_1, \dots, v_N\}$	N services with $i, j, \in V$ are arbitrary services
$v_s, v_f \in V$	Source and sink node
$\tau: V \rightarrow V$	Predecessors function
$\mathcal{Y} = \{Y_1, \dots, Y_K\}$	Candidate pools
$E = \{e_{ij} i, j \in V\}$	Technical feasible combinations of services
$f \in F$	Feasible path from source to sink that is an instantiation of a complex service f
u_f	Overall utility of complex service f
$S = \{s_1, \dots, s_Q\}$	Q service providers
$\sigma: S \rightarrow V$	Ownership function
$A_j = \{a_j^1, \dots, a_j^L\}$	Configuration of service j with a_j^l is the attribute value of type $l \in L$
c_{ij}	Interoperability costs of service j as a successor of service i
p_{ij}	Price charged for service j being invoked as a successor of service i
\mathcal{P}_f	Sum of prices charged for complex service f
t^s	Transfer to service provider s
\mathcal{T}_f	Sum of transfers to service providers
$\mathcal{A}_f = (\mathcal{A}_f^1, \dots, \mathcal{A}_f^L)$	Configuration of complex service f with \mathcal{A}_f^l is the attribute value of type $l \in L$
$\mathcal{S}: \mathcal{A} \rightarrow [0, 1]$	Scoring function of service requester
$A = (\lambda_1, \dots, \lambda_L)$	Preference structure of service requester with λ_l is the weight for attribute type $l \in L$
α	Willingness to pay of service requester for a complex service f with $\mathcal{S}(\mathcal{A}_f) = 1$
R	Service request
B^s	Service offer bids of service provider s
$m(o, t)$	Mechanism with allocation function o and transfer function t

Table A2
Modeling notation for simulation model.

Notation	Meaning
$k \in \mathcal{K}$	Action
$b \in \mathcal{K}$	Bundling action
$u \in \mathcal{K}$	Unbundling action
$r \in \mathcal{R}$	Simulation round
$f_{ik} \in \mathcal{F}$	Fitness of node i regarding action k in round r
$p_{ik}^r \in \mathcal{P}$	Propensity of choosing action k of node i in round r
$\beta \in [0,1]$	Learning rate

For further research, we plan to investigate solutions to counteract overpayments, as our mechanism design is not budget-balanced. Nevertheless, this is a crucial property from a requester perspective. Up until the present, the resulting prices for complex services are unbounded and hardly predictable. Budget-balanced solutions can be enforced by adequate payment rules (Parkes et al., 2001). We also encourage the evaluation of payment rules that are budget-balanced, approximately incentive-compatible, and incentivize service providers to strengthen compatibility ambitions.

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Appendix A. Mathematical notation

Tables A1 and A2.

References

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